UNDERSTANDING URBAN DEVELOPMENT AND WATER QUALITY THROUGH SCENARIOS

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ABSTRACT

TRACY HADDEN LOH: Understanding Urban Development and Water Quality Through Scenarios
(under the direction of Yan Song)

The Clean Air Act establishes a framework for regions to target environmental outcomes related to air quality in long-range transportation planning in the United States. Similarly, the Clean Water Act establishes a framework for regions to improve their environmental performance regarding water quality standards when regulating land development. However, these policy and planning frameworks do not reflect the well-established relationship between transportation and land use. Is this a problem? I applied the land use/transportation model TRANUS in parallel with the EPA's Storm Water Management Model (SWMM) to simulate the water quality outcomes of two alternative long-range transportation plans for Mecklenburg County in North Carolina. I found that alternative regional urban forms can significantly influence only the spatial pattern of stormwater runoff.

This finding departs substantially from previous research suggesting that development strategies that promote densification can reduce per capita stormwater runoff. These results suggest that regional growth management strategies developed to meet air quality goals are not optimal for meeting watershed protection goals. Parallel and competing planning processes for land use and transportation produce suboptimal outcomes. In the context of a region, municipalities and planners have multiple goals at

different scales which are sometimes in conflict. Achieving full transparency about tradeoffs

between alternatives is particularly fraught because the costs and benefits inherent in these

competing goals are not experienced at the same spatial scale, or by the same localities or

classes of people. With regard to environmental performance, the federal government plays

a unique role in mandating planning and promoting best management practices. The results

of this study suggest that there is a real opportunity for the EPA and USDOT to integrate

transportation and land use planning through regulatory requirements and incentives.

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INTRODUCTION

As of 2008, the United Nations estimates that half of the world's population will live in cities. At the same time, there is growing global concern about the impact of human activities on the ecology of our planet (Grimm et. al. 2008). The concept of sustainability sits at this crossroads – can humans find a way to live by which our local, regional, and global resource and energy flows are in balance? Or will we simply consume raw materials and produce non-recyclable waste until our planet is used up? This is a fascinating and exciting moment in the history of cities. Cities of the past have churned with goods and capital while enthusiastically exchanging with each other, relying on the surrounding region to house excess population, absorb waste, and input food, water, and energy. As city sizes spiral larger and larger, the capacity of surrounding areas to support unprecedented global metropolises is stressed. In this, the first majority urban century, can we find a city of the future that is more self-sustaining? Can we urbanize and remain in balance? This project will look at one piece of this puzzle – water quality.

Across the United States, watersheds in urbanizing areas are poised on the brink of a major change. Currently, healthy watersheds provide critical ecosystem services like clean drinking water, fishing and swimming opportunities, erosion control, and flood protection. However, as of 1994 the Environmental Protection Agency (EPA) has identified the development and expansion of the urban built environment as the greatest threat to the

continued functioning of these essential processes (EPA 1994). American cities are facing a question with no known answer: can we manage growth in a way that preserves the health and functionality of watersheds? In order to answer this question, our understanding of how regional growth impacts watersheds must deepen. At the most fundamental level, changing American streams and rivers of today show us the negative impact that urbanization can have on watershed health.

This basic correlation is mediated through interventions known as best management practices (BMPs). Many of these practices are implemented at the site level, through features that alter the hydraulic characteristics of a developed site in order to reduce peak flows and remove contaminants from stormwater runoff. As more and more localities require the use of BMPs through building and subdivision design codes, these treatments are becoming an increasingly common sight. Familiar urban BMPs may include green roofs, detention basins, and swales (Claytor 2006 p. 340-1). A large body of research evaluating and quantifying the effectiveness of these BMPs has empowered regulators and developers to improve the environmental outcomes of development.

Best management practices are not confined to the site level, however. For example, street sweeping can remove accumulated contaminants before they are mobilized into the surface water system through stormwater runoff and become nonpoint source pollution. There is increasing awareness that in addition to improving the quality of new development with regards to stormwater management, the nonpoint source pollution problem must also be addressed through such regional strategies. In particular, advocates such as the Chesapeake Bay Foundation, the Natural Resource Defense Council, and the Riverkeeper

Alliance have all argued that regional growth management tools should be applied for stormwater management. Research to evaluate the usefulness of such complex, long-term policy intervention could help demonstrate whether regional growth management can be a best management practice.

The goal of this research is to test the hypothesis that alternative regional urban forms can significantly influence water quality outcomes. Previous research has clearly established a relationship between impervious area and nonpoint source pollution. However, there are many metrics of urban form beyond imperviousness. This research demonstrates that alternative regional urban forms may have the same total impervious area, but different water quality outcomes. Other aspects of urban form, including directly connected impervious area (distinct from total impervious area) and the spatial pattern of imperviousness, are key to accurately specifying the relationship between urbanization and water quality. This research identifies these variables and elucidates the spatial and scale dynamics of the role they play in the processes that produce urban form and nonpoint source pollution.

In the field of regional planning, there is currently little consensus on what constitutes an ideal urban form (Batty 2008). Theorists and activists advocate for various archetypes of urban form, such as the strictly monocentric city or the radial polycentric city, often using arguments based on assumed environmental performance. In reality, however, there is very little conclusive evidence regarding the impact of regional design on the environment. This is especially true with regards to water quality, because the relationship between land use and water quality is complex and scale-sensitive. Though human

settlements rely on the natural hydrology around them for essential ecosystem services, including management of ever-increasing volumes of stormwater runoff, most research comparing urban archetypes has focused on transportation. American cities as diverse as New York, NY and Cary, NC are applying divergent growth management strategies to protect water resources, with essentially no hard information about the comparative advantages of each strategy. Therefore, the objective of this project is to understand the water quality consequences that emerge at the regional, watershed scale from widespread incremental development decisions in land use and transportation over long periods of time.

Within the planning community, there is widespread interest in regional approaches to stormwater management. Regional planning agencies like Chicago's Metropolitan Planning Council are looking for ways to improve water quality because they want to reclaim urban waterfronts to improve the quality of life of urban residents and harness the economic development potential of these areas. Regional water utilities want to be partners in these efforts, and additionally are subject to the National Pollutant Discharge Elimination System (NPDES) permit program (created by the EPA to implement the Clean Water Act) that regulates Municipal Separate Storm Sewer Systems (MS4s). The cost of compliance can be very steep – for example, the Long Term Control Plan (LTCP) required as part of Washington, DC's NPDES permit comes with a price tag of $1.2 billion, mostly for stormwater infrastructure[1]. The Environmental Protection Agency's guidance on this program includes a list, known as the National Menu of BMPs, which can be used by urban areas to comply with the NPDES. The motivation for this research project is to provide

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[1] http://www.dcwater.com/workzones/projects/pdfs/ltcp/Executive_Summary.pdf

quality data analysis to support decisions about the very serious financial and environmental consequences of NPDES compliance, including what strategies cities and regions choose, how new development is regulated including what metrics or benchmarks are used as standards, and what strategy elements the EPA will promote in the National Menu of BMPs or allow in individual regions' LTCPs.

Planners and decision-makers need this research not only to improve the quality of the decisions they make about stormwater management, but to inform the public about the costs and tradeoffs involved in potential strategies. The high cost of improving and maintaining a stormwater system is forcing many municipalities to create new sources of revenue, such as stormwater utility fees. Ratepayers want to know what these fees are for and be convinced that such charges are necessary and beneficial. This research is a critical evaluation of the assumption that regional growth management can make a difference for water quality. It serves the needs of consumers and planners for evidence to "make the case" for land management decisions and new infrastructure. In addition this research tests the hypotheses of smart growth advocates and quantifies the benefit that regions can derive from attempting to connect regional urban form and water quality outcomes.

Previous research has attempted to meet these needs through a variety of modeling approaches. The consistent theme of these studies is the assumption that at higher densities of development, per-capita imperviousness will decrease, and thus per-capita runoff. While this is clearly true at the site level, this project improves on previous research by modeling both the land market's and the watershed's response to regulation of density at the regional level. This project departs from previous research by acknowledging that urban

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development patterns are actually the result of a process, not primarily pre-determined by planners. This is a critical distinction that speaks directly to the ability of the methods applied in this research to effectively answer the research question for policy makers. This greatly improves the test validity of the research design, and thus the value of the research to consumers.

This project uses Charlotte, NC and surrounding Mecklenburg County as the study area. Mecklenburg County is home to 235,530 households as of 2000 and nine incorporated municipalities (Figure 1). The county is dominated by the city of Charlotte, which is the
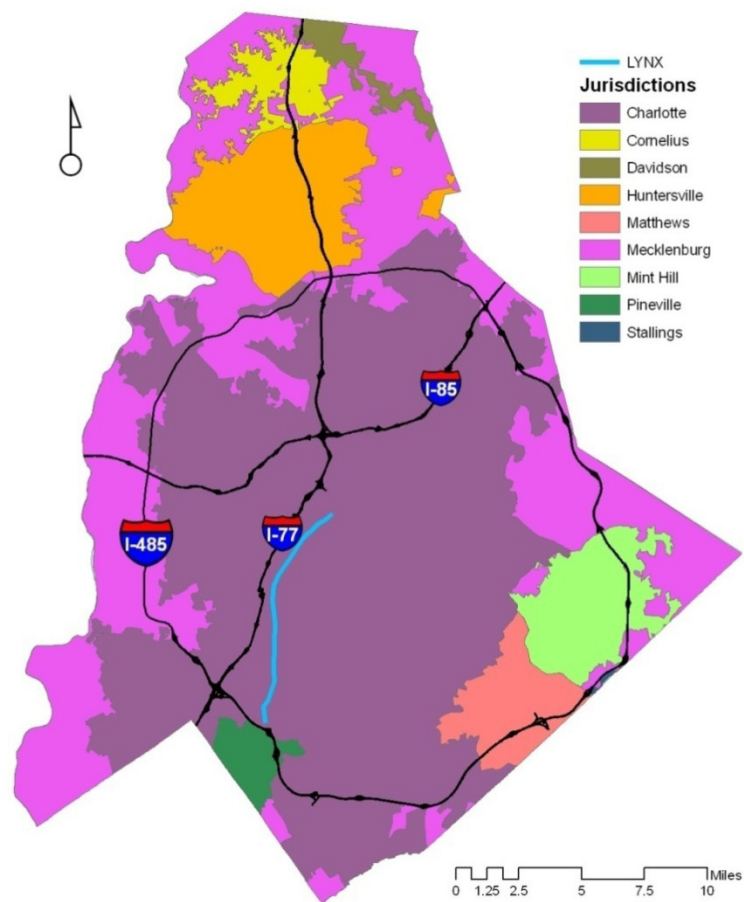
Figure 1: Project Study Area

largest city in North Carolina. As of 2007, Charlotte is the fifth-fastest growing major metropolitan area in the U.S., according the U.S. Census. The Catawba River provides drinking water for 1.5 million North Carolinians, and in 2008 was designated America's Most Endangered River by American Rivers, primarily because of the water quality threat posed by urbanization. The parts of the Catawba/Yadkin River basins that form the study area are located just north of the North Carolina/South Carolina border in the Piedmont region. Protecting the water resources of this area is vital to the life and future of Charlotte and North Carolina. However, it is clear that the same population and economic growth that underpins the prosperity of this community may threaten its potential if the decision-makers of the region do not have the information they need to manage development in a sustainable way.

The rapid growth in Mecklenburg County since 1980 has been characterized primarily by low density residential development. However, commercial development has remained largely concentrated in the higher density urban core of Charlotte, where employment in the area is still centralized. Local municipalities and the county have undertaken a number of local and regional planning efforts to improve the way in which new development is accommodated.

The region is currently involved in a number of major transportation investments that will change the way residents of the county travel. These investments include the completion of a beltway, the construction of toll lanes on that beltway, and an initial investment in fixed-guideway transit in the form of a new light rail line, the LYNX. The relative newness of the beltway ring around the city has resulted in a radial-corridor regional

structure, with employment highly centralized in the CBD, where the Bank of America and other major employers have their headquarters. Over the next few decades, the area will face significant challenges related to managing development, including water scarcity, congestion, and rising housing costs. These challenges will be driven by two fundamentals – which land is developed where, and travel behavior.

The challenge in predicting the environmental performance of long-term and/ or regional-scale development alternatives is threefold. First, typically there are a large number of unknowns in terms of the baseline state (impervious surface inventory; local travel demand; current environmental performance). Second, the dynamics by which these patterns and processes change are extremely complex. Third, the future is inherently uncertain, and the longer the time horizon of the "future" that one seeks to explore, the more impossible it is to say what it will be like. Previous research on the environmental performance of land development alternatives has been hindered by each of these challenges.

This research confronts each of these three obstacles using a three-pronged strategy. First, the study area of Mecklenburg County is a particularly data-rich region, and various city, county, and regional agencies contributed data to the project. Many attempts to study the intersection of land use, transportation, and water quality are limited by the nonexistence of critical and highly detailed spatial data such as the location and size of building footprints, roads, continuous precipitation records, or stream gauges. Mecklenburg County was an outstanding study area not just because of the appropriateness of evaluating long-term transportation and land use management strategies in the context of watershed

health given the current planning context of the area, but because the necessary rich data existed and the relevant agencies were willing to share it.

Any research design investigating the outcomes of long-term land use change must make decisions about how to model this change. The suitability and sophistication of the modeling approach determines the internal and external validity of the findings. There are merits and drawbacks at each end of the spectrum between simple, transparent models and complex, data-intensive models. On the one hand, research that is easily replicable in other study areas, and applies a methodology that readers from different disciplines and levels of training can understand is valuable to policy-oriented research. On the other hand, planning for the most part concerns large and complex established systems. In the American context, individual stakeholders or agencies can only influence the margins of these systems. Finding real margins of opportunity and estimating the correct sign or direction of those opportunities requires rigor and nuance. For this reason, this project models long-term land use change and hydrological response using a pair of computer simulations whose data demands and calibration are extremely labor-intensive and complex, but whose theoretical underpinnings stand on a mature understanding of the process dynamics in question.

Talking about the future is an endeavor inherently fraught with assumptions, driven by values, and burdened by unknowables. These are precisely the conditions that computer simulations cannot control for. Therefore, this project combines data and computation with a scenario planning approach that incorporates assumptions, values, and unknowns in to the research design. By building multiple simulations of plausible, but different possibilities

within a scenario space, this methodology captures both the qualitative and the quantitative

aspects of asking and attempting to answer questions about the future.

This project's primary contribution to the body of research on environmental

planning is methodological. The novelty of the methods has two major components –

the intensive and sophisticated qualitative and quantitative effort put in to developing

the scenarios, and the statistical techniques used to build computer simulations of

unprecedented data richness. The model results clearly expose the tradeoffs between

alternative development management approaches, and the policy adjustments and

additions necessary to guide current trends in one direction or the other.

CHAPTER 2

LITERATURE REVIEW

This project is fundamentally interdisciplinary, drawing on ideas and methods from city and regional planning, economics, environmental science, geography, and computer science. This review will describe the current state of the relevant literature from these areas relating to land use change, water quality, scenario planning, and computer simulation. Part A will describe the current state of knowledge concerning the relationships between urbanization and water quality, in order to show the position of the research question of this project on the frontier of existing knowledge. Part B reviews different scenario planning methods in order to establish a suitable and "good" approach for addressing the research question. In Part C, major avenues within urban growth modeling research are reviewed in order to explain the use of TRANUS in the research design. The outcome variable in this research is water quality. Therefore Part D describes the state of the art of water quality modeling relating to land use, including model selection criteria. Finally, Part E reviews recent comparable research investigating land use and water quality relationships to compare and contrast with this project.

Impacts of Growth on Water Quality

A general connection between human-made land use changes and decreasing water quality is widely known (Smith et al. 1987; Tong & Chen 2002). Substantial research concerned with protecting water resources has focused on identifying specific urban form

characteristics related to water quality, and on elucidating the connections between these characteristics and a cornucopia of water quality constituents (Kayhanian et al. 2003; LeBlanc et al. 1997; Rhodes et al. 2001). The broad range of quality indicators includes turbidity, levels of nutrients (nitrogen and phosphorus), measures of oil, grease, and metal particle contamination, bacteria densities, dissolved oxygen levels, temperature, and biotic measures like fish or microorganism counts. However, the benchmark Nationwide Urban Runoff Program, conducted by the EPA from 1978 – 1982 to collect urban runoff quality characteristics at 28 locations in the US found that flow volume is the single most important parameter predicting urban runoff loads (Athayde et al. 1983, Tsihrintzis & Hamid 1997). Stormwater runoff volume, then, is a key indicator of quality.

The direct agent that produces stormwater runoff is impervious surface. Surfaces that cannot be infiltrated by water include rooftops, streets, sidewalks, driveways, parking lots, sewer piping, and even gravel paving and compacted soil from construction sites and landscaped lawns. The runoff from these surfaces degrades streams through pollution contamination, and through altering stream channel structure by changing stream volume and flow. Pollution contamination threatens public health and the health of aquatic species, while changes to channel structure accelerate erosion and destroy habitat. Measures and thresholds for impervious surface cover in a watershed have been declared the key to understanding and mitigating the impact of runoff (Arnold Jr. & Gibbons 1996). However, not all impervious surfaces are equal.

The function or use of the impervious surface is a significant factor in resulting impact on water quality. Transportation-related imperviousness is especially notable for its

greater association with multiple severe indicators of stream degradation (Schueler 1995).

Automobile transportation-related coverage includes highways, streets, parking lots, and

driveways. One survey of areas with different dominant land uses concluded that, generally,

transportation-related imperviousness accounts for 63% - 70% of total imperviousness (City

of Olympia 1994). For many land use configurations, therefore, transportation infrastructure

is not only associated with problematic, non-biodegradable pollutants, but it composes are

larger share of the total surface area of concern, and thus may make a larger contribution

to runoff volume. Increasing road density has been linked to increased concentrations of

chemical pollutants associated with truck stops, gas stations, and road salt, including oil,

grease, and ions (Rhodes et. al. 2001). Furthermore, increasing annual average daily traffic

on highways has been correlated with higher pollutant concentrations for most indicators,

though a limited number are associated with less-traveled agricultural areas (Kayhanian et.

al. 2003).

The physical connection between an impervious area and proximate urban water

systems also plays a major role in determining the damage done by runoff from that area.

Most studies do not distinguish between impervious area directly linked to water bodies

via an impervious stormwater system and those that may drain to pervious areas (Brabec

et al. 2002). In one case, however, Lee and Heaney (2003) attempted to measure directly

connected impervious area (DCIA) and total impervious area (TIA) and their relative impacts.

Their results indicate that though TIA may cover approximately twice the DCIA area, DCIA

contributes 72% of total runoff volume. In addition, DCIA is the imperviousness responsible

for combined sewer overflows (CSOs), a serious water quality problem. Furthermore,

they estimate that 97.2% of DCIA is transportation-related imperviousness. In the case of

non-DCIA, the proximity of the impervious area to the water system is crucial. The size of the riparian buffer between human-intensive land uses and water bodies is a significant mediator for water quality (Houlahan & Findlay 2004, LeBlanc et. al. 1997). These results suggest that there is significant need for context-sensitive modeling of the mobilization of contaminants via imperviousness in models of stormwater runoff.

A complete enumeration of types of impervious surface cannot be obtained by considering only paved surfaces. Though many measures of imperviousness only consider building and transportation structures, the infiltration ability of much of the open space in urbanizing areas has been called into question. Construction activities often compact soil through grading and the weight of heavy equipment. Landscaping often removes topsoil, small plants, and trees, causing severe erosion. The open space or lawn remaining after these activities have ended often produces just as much runoff as paved surfaces in terms of volume (Schueler, 1995). These surfaces cannot be relied on to provide infiltration services to a watershed; rather, they must be counted as impervious surface, and the runoff from these surfaces cannot be assumed to be free from contamination.

In essence, stormwater runoff volumes and chemistry are influenced by the amount of impervious surface, the use that impervious surface is subject to, and the presence or absence of the mediating influence of pervious surface. This dynamic is well understood at the site level. However, at the regional scale, drivers beyond imperviousness that are not typically associated with water quality may have a major impact on water quality outcomes through mechanisms that are unregulated and poorly understood. For example, Michael Huston (2005) traced three phases of land-use change through history: agrarian, industrial,

and information, each of which was associated with different drivers. In the agrarian phase, land use change was driven by primary productivity of land. Land was developed if it was productive for farming. In the industrial phase, access to transportation was the key factor, while in the information phase aesthetics come to the fore. Water quality is not a consideration in any of these models of land use change, except possibly the last, even though each model has serious effects on it.

The second implication of the limitations of impervious surface as a measure at the regional scale is that because the relationship between imperviousness and water quality is ambiguous at the regional level, it may be a good thing that it is largely unregulated at this scale. Other measures of urban pattern, such as edge density, road density, and patch size have been found to be much stronger predictors of water quality (Alberti and Marzluff 2004, Rogers and DeFee 2005). Therefore, as urbanization increases in a watershed, water quality is affected by variables at the site and regional level. This suggests that a hierarchical model considering both scales could contribute to an understanding of threats to water quality. Figure 2 presents a proposed theoretical model of the relationship between urban form and water quality, considering both scale and linkages.

Figure 2 shows constructs of urban form and how they are connected to water quality. This figure summarizes key insights of the literature. At the regional level, water quality is determined by the amount of developed land (impervious surfaces) and the amount of undeveloped land (natural land cover), and how these two types of land are arranged spatially. The regional development pattern is the ultimate driver. However, stormwater runoff, and thus nonpoint source pollution, is generated locally, one raindrop
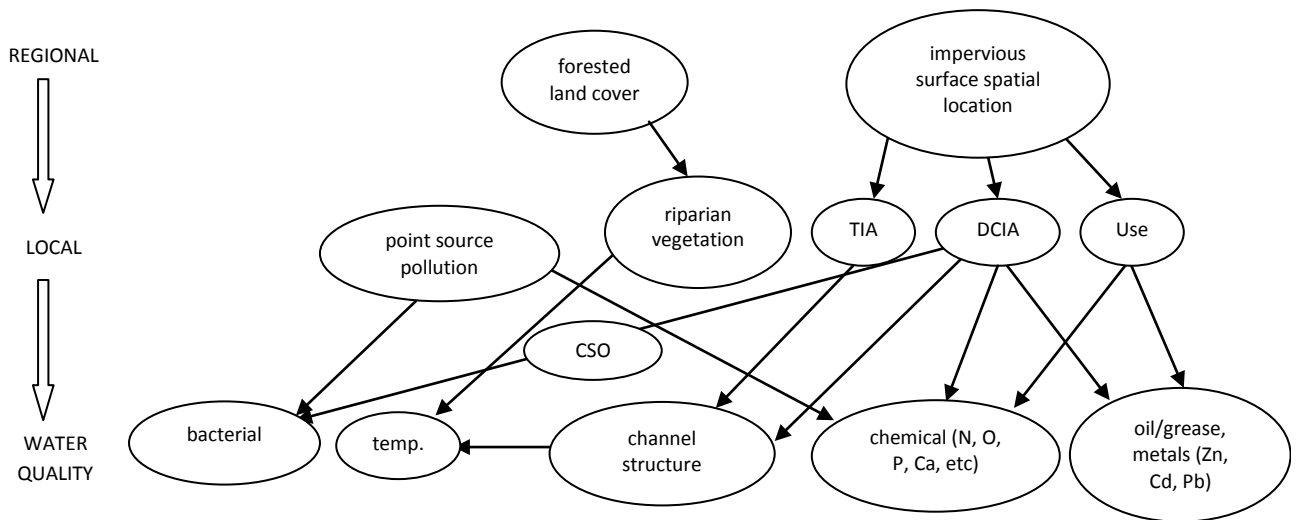
Figure 2: Theoretical Model of Interactions Between Urban Form and Water Quality

at a time. Therefore at the local level, the water quality outcome is mediated by whether

the impervious surface is directly connected and what the use of the impervious surface is,

in addition to the quantity of imperviousness. The outcome is also mediated by pervious

riparian areas. Total impervious area (TIA), a directly measurable construct, is just one

aspect of this dynamic. Urban form measures like edge density, road density, and patch

size may approximate or correlate with the construct of directly connected impervious area

(DCIA).

Land use intensity is also a key construct in the relationship between land use

and water quality. This construct is often measured by density. However, there is limited

consensus or hard evidence as to exactly what role density plays in the water quality story.

High-density urban development has long been associated with negative environmental

impacts. Industrialization, with all the point-source pollution inherent in its activities, is

historically highly associated with urbanization. Intuitively to some, development density is

associated with the disappearance of trees, channeling of water into culverts and sewers,

and separation from nature by pavement. On the other hand, some planners believe that conventional low-density development is fundamentally automobile- and thus pavement-oriented, and that this form of development prioritizes wide roads, parking, and compacted, landscaped lawns and golf courses over low-impact development principles (Schueler 1995).

Scenario Building

Scenario planning represents the next evolution in planning practice from the conventional rational comprehensive planning model, as well as a powerful research design for investigating planning questions. The roots of scenario planning paired with complex modeling are deep in the transportation planning community, primarily because of the Federal-aid Highway Act of 1962, which required both alternatives analysis and projections about how a facility would operate in the future (Bartholomew 2006). Despite its roots, the use of scenarios appears to have gained increasing acceptance in planning practice as a different form of rationality that relies on incremental planning (Guhathakurta 1999; Xiang and Clarke 2003). New applications of scenario planning in regional transportation planning differ from past alternatives analysis in that the scenarios explore varying future arrangements of both land use and transportation, rather than assuming a static land use pattern (Zegras et. al. 2004). Keith Bartholomew recently reviewed 80 American scenario planning projects from over 50 metropolitan areas, documenting how widespread scenario planning has become in the US (Bartholomew 2005).

When initiating a scenario planning process, the "alternative futures" process developed by Carl Steinitz (2003) begins with the question of representation: "how should the state of the landscape be described in content, space, and time (p. 13)?" In the scenario

planning literature as applied to urban planning, there are three over arching models for

describing urban futures. Abdul Khakee (1991) identifies the first framework as placing the

"emphasis on the physical-spatial," through maps and descriptions of alternative urban

forms, as embodied by H. Wentworth Eldredge's work. Khakee proposes an alternative

framework that emphasizes socioeconomic variables, with the scenario planning process

driven by social goals like equity, employment, or conservation. A third framework can

be found in the work of Lewis Mumford (1938). While engaged in the physical-spatial

framework debate of his day, Mumford placed special emphasis on extrapolating the

cultural and political implications of varying urban forms. He was interested what values

different urban form choices represented, and his "Stages of City Development" from The

Culture of Cities traced the moral outcomes of varying manifestations of urbanization. These

frameworks are summarized in Table 1.

In the Eldredge framework, the planning focus is on producing housing and other

infrastructure. Land use issues and comprehensive master planning are dominant. A

scenario planning process in this framework would assume strong economic growth,

because otherwise there would be no need for additional infrastructure and no way to

pay for it. In Khakee's framework, the planning focus is on dealing with great political and

economic uncertainty, emphasizing plan implementation (the connection between distant

Table 1: Urban Futures		
Framework	Representation Model	Examples
Eldredge	Physical-spatial	Metropolitan central city, satellite cities
Khakee	Socioeconomic	The racially integrated city, city of employment opportunity
Mumford	Cultural and political	Eopolis, tyrannopolis

future and short- and medium-term policy) and review. With Mumford, the emphasis is on the structure of the economy and the planning process, i.e. demarcation of land by role in the economy, public participation, and regional relationships, all restricted by financial resources. Correspondingly, there is a different role for urban planners in each model. In the Eldredge model, planners strive to provide services and achieve system performance goals based on projections. In the Khakee model planners are facilitators of development, working to achieve economic and social goals based on analysis of existing human capital and social infrastructure. Planners potentially have an even grander role in Mumford's model, where the goal is to achieve an ethical spatial alignment of the environment, political structures, and the economy in order to shape culture.

Harold Becker (1983) describes the selection of the representation model simply as selecting the "basic characteristics," which are "the few conditions most important to shaping the system...being studied (p. 100)." The representation is contingent upon our understanding of the system we are studying. In the case of water quality, do we understand water quality as primarily an outcome from a physical-spatial system, or is it shaped by social goals like conservation, or does it vary based on cultural and political climate (capitalist vs. socialist, etc)? While all three models may offer productive frameworks for understanding water quality, the literature on water quality as an outcome of the physical-spatial system is the most fully developed (Brabec et. al. 2002). Therefore, this project applied the Eldredge model. This implies that the "basic characteristics" as from Becker will include physical and spatial measures, such as urban form pattern metrics. These physical-spatial characteristics are what Becker would call "key drivers" of water quality.

Furthermore, selecting this representation model means that each scenario is visualized as a spatially explicit map.

In the scenario planning literature, there are a number of common criteria proposed to define what makes a "good" scenario. The literature consistently emphasizes the importance of plausibility (Avin and Dembner 2001, Becker 1983, Coates 2000). However, de Jouvenel (2000) poetically emphasizes that the future is "yet to be created." It is a realm of freedom, power, and will, not just probabilities, a realm where there is room for audacity, creativity, and action. Xiang and Clarke (2003) capture this exciting sense of possibility and combine it with the plausibility criterion in their concept of plausible unexpectedness. While scenarios must be believable, they must also challenge the boundaries of belief, or scenario planning falls into the trap of simply exploring familiar parts of the scenario space over and over again. Therefore a good scenario set has diversity, inconsistency between scenarios, and surprise. Within each scenario, the development of a narrative describing the chain of events that produces the scenario will establish a test of plausibility. Comprehensiveness also contributes to plausibility; to achieve this, the scenario set as a whole must cover the range of possible internally consistent instances of the Becker scenario space.

Xiang and Clarke posit two additional criteria: informational vividness and cognitively ergonomic design (effective and safe). A scenario is vivid when it is "(1) emotionally interesting, (2) imagery provoking, and (3) proximate in a sensory, spatial, and temporal way (p. 893)." Urban growth scenarios can be made emotionally interesting by using the narrative to link each scenario to individual and community values, as well as contemporary issues. Physical-spatial scenarios are imagery provoking because each is fully visualized as a

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map and a story. Scenarios are proximate when they are based on a real area (as opposed to a hypothetical one). Extending scenarios very far in the future (for example, to 2050), however, is a proximity problem. This is a common paradox in applying scenario planning to regional planning. At this scale, changes in land use, transportation, travel behavior, the economy, and so forth happen gradually, with substantial shifts only becoming apparent over decades. However, the scenarios will not be interesting, diverse, or comprehensive if they do not expand to a time-scale that can illustrate these potential differences. Therefore, additional effort to make regional planning scenarios proximate in other ways must be made. With regards to the final criterion, cognitively ergonomic design, scenario sets can achieve this by restricting the size of the scenario set and identifying each scenario with a unique theme that does not overlap with other scenarios. A cognitively ergonomic design should also include an explicit statement of assumptions. This contributes to plausibility, and avoids creating unrealistic expectations, by explicitly establishing limits.

One point of contention in the literature with regards to "good" scenarios is the concept of the "surprise-free" scenario. Shearer advocates for the inclusion of an alternative that embodies "the future that can be anticipated if there are no significant changes." The idea is that the surprise-free scenario can function as "a platform" on which "conventional thinking" and subconscious assumptions can be recognized, serving as a "reference point" or "baseline" for users who are new to scenario planning (p. 72). On the other side of the argument, Avin and Dembner argue against 'straw men' that are not based on an analysis of the driving forces in a system. Their essential point is that the relevance of scenario planning is its special ability to manage uncertainty and rapid change. However, if those two things exist, then by definition the surprise-free alternative that assumes no changes is implausible.

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A 'surprise free' alternative can be distinguished from a mere trends-extrapolation scenario. This scenario can simply include future changes which are widely expected. In the case of water quality, the full implementation of Clean Water Act Phase II requirements is an example of a widely expected change.

This project fully responds to the challenges set by the literature with regards to creating two scenarios that are first and foremost plausible, based on rich local data and real, active planning endeavors extant in the study area. This is critical to the face validity of the research and central to the research motivation. One scenario represents a "surprise-free" alternative based on the published work of the region's metropolitan planning agency and its fiscally constrained long-range transportation plan. The other scenario represents a more visionary approach to planning for the future of the region, including some more ambitious changes in land use regulation and transportation infrastructure. Both meet Xiang and Clarke's criteria for vividness in that each is both a narrative communicating a specific perspective on the study area and how to plan for it, and can be visualized as maps of a variety of different descriptive and outcome variables.

Urban Growth Modeling

Computer simulations are key tools that enable exploration of the behavior of large, complex systems. Both research scientists and policy makers have long-standing interests and agendas regarding land use change related to urbanization (Agarwal et. al. 2002). The prospects of large-scale land use change models and their place in policy have risen, fallen, and risen again since the advent of computing (Wegener 1994). This review will summarize the current state of the art in urban growth modeling, with attention to theoretical

structure, implementation, and suitability. There are quite a few more extensive historical

or analytical reviews in the literature (e.g. Agarwal 2002, Berling-Wolff & Wu 2004, EPA

2000); this review will simply outline the major themes and approaches that remain current

in the field, and diagram the advantages and disadvantages of each approach. There are

four major approaches in urban modeling that represent the current frontiers in the field:

hybrid spatial interaction, cellular automata, agent-based, and reduced-form. Each of these

modeling approaches will be discussed in turn.

i. Spatial interaction models

Basic spatial interaction models have the longest history, and are notable for

their effort to integrate land use and transportation. These models are rooted in the

application of Lowry-style gravity models. Models such as DRAM/EMPAL accomplish this

by aggregating space into zones. Each zone contains some amount of households and jobs,

and the interaction between any two zones is a function of the 'mass' of the zone and the

connectivity between the two zones. Thus, land use (locations of households and jobs) and

transportation (flows between zones) are modeled simultaneously. This model can then

be used to test the impact of changes to the attractiveness of a given zone or zones (for

example, increased accessibility from a transportation improvement), or the effect of an

exogenous increase in population. This approach assumes equilibrium, in other words that

the supply of locations is able to meet the demands of all existing households and jobs.

Hybrid spatial interaction models improve on the basic approach by incorporating

behavioral and economic theory in addition to gravity theory. Thus, models like TRANUS

use nested multinomial logit models of location choice for different activity sectors. These

models respond to price signals from the land market, which are calculated based on

the relative supply and demand for land in each zone. Demand for land in each zone is in

part a function of the accessibility of the zone. These models are also called spatial input-

output models because they use an input-output matrix that is exogenously initialized to

represent the demand relationships between activity sectors. This matrix is then applied

to space by inputting basic, exogenous activities and using the input-output matrix to

impute endogenous (induced) production. The land market is cleared at each iteration by

applying discrete location choice models to the activity sectors. The model achieves market

clearance for all other markets by allowing demand in one zone to be satisfied by production

in another zone, depending on price, for all sectors except land. Tracking these flows

reveals the demand for travel. This establishes an iterative equilibrium between the land

use pattern and transportation flows that further integrates land use and transportation.

TRANUS and MEPLAN are the most widely used and validated of these integrated land use-

transport models internationally, with TRANUS being somewhat easier to calibrate (Hunt

et. al. 2005). The framework and implementation of TRANUS are described by de la Barra

(1989) in detail.

ii. Cellular automata models

Cellular automata (CA) models apply the principles of complexity theory to urban

modeling. The CA approach is based on the idea that cities are unself-conscious, organic

systems composed of modular, hierarchical elements (Batty 2005). Simple rules that govern

local, observable processes explain the emergent, seemingly chaotic and unobservable

patterns and behavior of the total system (Batty & Torrens 2005). A major attraction of CA

models is that they are relatively simple to calibrate and parameterize, and straightforward

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to explain. A typical CA model is composed of a grid of cells, each of which has a current state. There is some finite set of possible states that the cells can exhibit. In addition to the current state, each cell has some set of characteristics that describe the cell. Simple transition rules, either deterministic or stochastic, use the characteristics of the cell and the immediately adjacent neighbor cells to move each cell from state to state. Thus, while the description and behavior of any one cell is simple, the patterns that emerge through time from the iterative interactions of each cell with its neighbors can be quite sophisticated. Depending on the initial state and the transition rules, the system may or may not ever converge to a steady state; in other words, equilibrium is not an assumption of CA models. Cellular automata models provide a framework for applying hierarchical patch theory from landscape ecology to built human systems.

The two most widely used urban development CA models are the Land use Evaluation and impact Assessment Modeling (LEAM) framework developed at the University of Illinois Urbana-Champaign (Deal 2001) and the SLEUTH model developed by the USGS and the University of California, Santa Barbara (Herold et. al. 2003, Jantz et. al. 2003). In general, there are significant limitations in applying these models to land use change; namely, it is difficult for a CA model with a finite number of states to represent the full spectrum of urban form. This is also true because these models, since they are grid-based and cover large geographic areas, are typically initialized using remote sensing land cover data (e.g. LANDSAT), which does not distinguish between types of developed land. Therefore CA models are best suited for studying land cover change, and are significantly less useful in studying land use change.

iii. Agent-based models

Agent-based models represent a significant theoretical advance in the modeling of land use change. Urbanization in the United States is by and large a process caused by many separate, distributed individuals making decisions and taking action, only marginally influenced by central policies. Agent-based models are similar to CA models in that they are used to model systems that are emergent; in other words, the cumulative product of many separate, parallel events. There are two basic data structures in an agent-based model. First, there must be some kind of representation of the 'space' in which the agents interact. This may literally be some explicit representation of physical space, or it may be a representation of a conceptual space in which agents interact, like a market. Second, the agents themselves are represented as individual instances that have some characteristics (possibly including a specific location in the 'space'), and whose behavior is governed by rules. Each type of agent has some discrete set of possible actions related to interacting with the 'space' and/or with other agents. These rules will vary based on agent type; however, agents of the same type can be expected to behave differently at any given time-step because these rules depend in part on the current characteristics of the individual instance of the agent. Furthermore, the rules may be stochastic and/or adaptive. The theoretical structure of agent-based models, comparative strengths, and current research applying these models to land use change have been discussed by Parker et. al. (2003).

The congruence between agent-based models and the way development actually occurs in the United States suggests a good fit between the theoretical structure of the model and, hypothetically, the reality that available data have been measuring. It is for this reason that UrbanSim, the most theoretically sophisticated land use change model currently

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extant, has consistently moved towards an agent-based approach with each redesign of the model. UrbanSim is actually framework that combines several models, including (in some instances) spatial interaction model for travel demand. However, households, firms, and developers are all represented as agents in the sub-models of UrbanSim. Thus, they are modeled separately from the space that they occupy, and their behavior is not solely determined by the state of that space. Furthermore, for these agents, 'space' is represented using the property parcel as the unit of analysis. This provides a theoretically rigorous and clear accounting of the agents, markets, and geography that are all involved in the urbanization process. In this sense, UrbanSim is a "microsimulation," because it minimizes aggregation of these conceptual units. This disaggregation has the further advantage of freeing the model from any requirement to achieve a cross-sectional equilibrium in order to obtain a solution. Furthermore, this dynamic microsimulation establishes a full range of feedback between land use and transportation systems. The primary drawback to such an approach is the monumental amount of data required to initialize and calibrate such a set of models. While UrbanSim uses an open-source distribution model and a sophisticated GUI to help minimize the cost (data, labor, etc) of applying the model, it is still infeasible for a single planner or experimenter to attempt UrbanSim alone. The most recent documentation of UrbanSim is available online at http://cuspa.washington.edu/. UrbanSim has been described and reviewed in the literature several times (Hunt 2005, Waddell 2002, Waddell 2003, Waddell 2007).

iv. Reduced-form models

Reduced-form models take a strictly empirical approach to modeling land use change. Rather than attempt to divine the theory and mechanisms driving land use change,

these models apply the methods of econometrics to estimate multinomial logit models that predict the likelihood of development for a given site based on a set of independent variables (e.g. Newburn & Berck 2006, Zhou & Kockelman 2008). While other models use multinomial logit to model location choice or other variables as part of a more elaborate modeling framework, this approach is distinct in that the model looks directly at land use change. Goodness-of-fit and error can be calculated, bringing a level of statistical rigor to this approach that is not available in any other model type reviewed here. The California Urban and Biodiversity Analysis Model (CURBA) developed by Landis, et. al. (1998) is a prominent example representing the application of random utility theory to urbanization. CURBA and other reduced-form models typically use a grid-based representation of the landscape, and can thus be paired with CA models in a more complex modeling framework. The multinomial logit model is conditioned using historical data from two time periods (thus showing change). The likelihood of development in the future is then estimated for each cell. However, this probability is only based on the characteristics of that cell. Therefore the model does not look at development drivers that are not rooted in space, such as household or employment-based demand for locations.

A major limitation of these models is that while the model may have an excellent fit for the historic data, applying a strictly empirical model like this to the future depends on the assumption that change in the future will happen just as it did in the past. In essence, this is a trend-extrapolation approach that cannot be used to explore multiple scenarios for future development. There is no feedback in applying the model to multiple timesteps, and so congestion and crowding externalities are not modeled. Thus, when attempting to use the future probabilities of development to actually allocate population growth, the forecast

may be highly dubious. The primary strength of these models is in identifying which specific areas are likely to undergo land cover change. This is very useful for impact assessments that are driven by land cover inventory, such as farmland, wetland, or habitat preservation. Reduced-form models are substantially less useful for predicting land use driven impacts, such as congestion or impervious surface coverage.

<u>Water Quality Modeling</u>

While impact assessment at the site level is well established, there is growing policy and research interest in developing models and methods for conducting impact assessment at larger spatial scales. This practice is already established in transportation planning, where regional planning is mandated by the federal government. Similarly, in the case of nonpoint source pollution, growing awareness of the need to understand watershed-scale impacts, spurred by the requirements of the Clean Water Act, has motivated the development of computer simulation models to quantify the relationship between land use and water quality. Various research groups and government agencies have developed many such models, using a variety of methodologies. The EPA has played a leading role in coordinating these efforts through the Better Assessment Science Integrating point and non-point Sources (BASINS) framework. Through BASINS, the EPA seeks to provide decision support systems for use by states conducting Total Maximum Daily Load (TMDL) analyses of select constituents. This literature review will compare the theoretical structure, operational details, and applications of five select hydrologic models, several of which are included in BASINS. In general, these models were selected for review based on their level of acceptance and use in the scholarly and environmental policy communities. However, one very new model, MUSIC, is included for its novel approach. These models are tools for

exploring the water quality implications of land use change. Other concerns like climate change tracking, flood control, and water supply management also motivate some of these simulations. This review will evaluate each model both in theory and in application with an emphasis on land use.

The Hydrologic Simulation Program in Fortran (HSPF) is a widely used hydrology model with water quality submodels that is supported by the EPA. The Soil and Water Assessment Tool (SWAT), developed by the US Department of Agriculture, is another widely used watershed simulation with a different theoretical approach. The Long-Term Hydrologic Impact Assessment (L-THIA) model is theoretically similar to SWAT, but with some different hydrological assumptions. L-THIA is also fairly simple to calibrate and apply, and is often used by policy analysts. The Storm Water Management Model (SWMM) was created around 1970 for the EPA, and has been updated since. This model's long history makes it one of the most widely used. In addition, a relatively new Australian system, the Model for Urban Stormwater Improvement Conceptualization (MUSIC), is included for its original and contrasting theoretical approach and implementation.

The correlation between human-made land use changes and decreasing water quality is well established. A simulation model representing this relationship must make more specific decisions than a regression model about how to represent land use and how to connect land use to water quality. The land use data requirements, the role of land use in the model, and the model of hydrology are typically distinguishing characteristics of a simulation. Watershed hydrology, especially groundwater movement, is a complex subject that is not so well understood that it can be perfectly represented by computer and

equations. Furthermore, hydrology is challenging to model in that it is essentially a moving

target. Rain falls, groundwater flows, and water evaporates, and a model must somehow

render discrete these continuous movements across a watershed through time. Therefore,

a model relating land use to water quality must contain some simplified representation of

hydrology and time at some geographic scale. Simplifying assumptions about the functions

of the water budget through time have consequences for the geographic appropriateness of

the specific model.

Water quality is a broad concept that can be modeled in a variety of different

ways. Modelers may consider any number of a cornucopia of water quality constituents.

The broad range of quality indicators includes turbidity, levels of nutrients (nitrogen and

phosphorus), measures of oil, grease, and metal particle contamination, bacteria densities,

dissolved oxygen levels, temperature, and biotic measures like fish or microorganism

counts. Each of these contaminants is mobilized by stormwater runoff through land use in a

different way. The many dimensions of water quality are part of the challenge of modeling

the impact of any given source. Each model discussed here has different data requirements,

calibration options, and operational details that factor into how the simulation is run and

what it does. Output, of course, also varies. How the model has been applied and with what

success suggests a set of planning questions that each model is most useful to address.

i. Hydrologic Simulation Program – Fortran (HSPF)

The principles and technical foundations of the HSPF model are described in

Bicknell et al. (2001). Land use categories in HSPF are user-defined, which allows the

user to incorporate whatever level of detail is desired to distinguish between land uses.

However, each category is defined only by percent impervious cover. No other distinguishing characteristics of land uses are incorporated in the model. A watershed basin is represented as a collection of internally uniform land segments (with the exception of soil type and canopy cover), which are pervious land, impervious land, or stream reaches/reservoirs. A land segment is composed of zones, each of which is a volume of storage, with inflows and outflows. HSPF is a continuous model, which simulates hydrologic and bio- and geo-chemical movements and interactions in a timestep of as little as one hour. In other words, runoff volumes and pollutant loads are tracked using a process-based approach, rather than empirical estimates. Water quality constituents modeled by HSPF include: sediment, dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, fecal coliform, nitrogen, phosphorus, and key biota (phytoplankton and zooplankton). This comprehensive process-based modeling approach is unique to HSPF.

The operational details of HSPF are complex. A number of supplementary tools have been developed to assist with developing the necessary configuration to run HSPF, including the Non-Point Source Model (NPSM), WinHSPF, the HSPF Parameter Database (HSPFParm), and the HSPF EXP-ert system (HSPEXP) for calibration. The model requires meteorological and land use/land cover topography as inputs, as well as observed streamflow and water quality monitoring data for calibration. In spite of this complexity, HSPF has been applied in a wide variety of studies because of its theoretical completeness. Application of the HSPF model to the Gwynns Falls watershed in Maryland produced strong results compared to historic data (Brun & Band 2000). Application to the Polecat Creek watershed in Virginia also found good agreement between observed and simulated streamflow and water quality

indicators (Im et al. 2003). These results suggest that HSPF is a useful and powerful tool for modeling runoff volumes and water quality in urbanizing watersheds.

ii. Soil and Water Assessment Tool (SWAT)

Since 1998, SWAT has been integrated into the EPA BASINS framework. The behavior and operation of the SWAT model is detailed in Arnold et al. (1998). In SWAT, a watershed basin is represented as a grid of cells or subwatersheds. Within each cell, the hydrology, soil, land use, and topography are assumed to be homogenous. Land use and soil type for each cell are represented in tandem using the Soil Conservation Service (SCS) curve number (CN) method, also known as TR-55 (USDA-NRCS 1986). In the CN method, a constant is estimated for each combination of land use type and soil type, which is then used in a larger equation to estimate runoff volume. The CNs and the equation that relates them to runoff volume are empirically derived, based on observations from sample landscapes. The CN representation captures the variation in evapotranspiration and stormwater runoff generation between land cover types. The CN method also allows the option of accounting for whether the area connects to a drainage system, or outlets to pervious area.

Land use is a part of the model only in how the land use, through impervious area, affects the volume of stormwater runoff. Within water quality, sediment, nitrogen, phosphorus, and pesticides are all modeled by SWAT. Bacteria transport was added in 2000 (Arnold & Fohrer 2005). However, loads for these constituents are all estimated using only runoff volume and soil data. The model does include comprehensive submodels to account for agricultural land management, including tillage, irrigation, fertilizing, pesticide application, and grazing. The hydrology model is also comprehensive, including a complete

water budget with precipitation, runoff, evapotranspiration, percolation, and return flow. SWAT has a sophisticated approach to modeling flows, including separate calculations for lateral subsurface flow, ground water flow, snow melt, ponds, and channel and reservoir routing for the sediment and chemical constituents. The model is continuous-time, operating on a daily time-step, and does not require any calibration from local gauge data (though it is an option).

The emphasis on fairly large subbasin-cells and agricultural land management in the SWAT model suggests that this model is most appropriate to simulate the impact on changing farming practices on water quality in watersheds where land use is mostly agricultural. In the appropriate setting, SWAT can be a powerful tool, given the completeness of the model and its minimal data requirements (weather data, soils, CNs, agricultural practices). Srinivasan et al. (1998) applied SWAT to a watershed in the upper Trinity River basin in rural north-central Texas. Results for streamflow and sedimentation were very good, but the chemical constituent submodels were not tested. The advanced weather model that simulates precipitation events in SWAT has attracted additional research activity. The model has been successfully applied in several studies of climate change impacts on water supplies (Hotchkiss et al. 2000; Rosenberg et al. 1999; Stonefelt et al. 2000). Despite these successes, it should be noted that an attempt to apply the SWAT model to a watershed in southern Illinois yielded very poor results (Muleta & Nicklow 2005). In this case, the authors cite limited data for verification as a possible explanation for the failure of the experiment; it is also unclear what the characteristics of the study watershed are, and how suitable the SWAT model is for that system.

iii. Long-Term Hydrologic Impact Assessment (L-THIA)

The L-THIA model is similar to SWAT in that it is also based on the empirical TR-55

curve number method. The emphasis in the development of L-THIA was to produce a simple

model relating land use to water quality that had basic, widely available data requirements

for use by local planners (Harbor 1994). Both web- and GIS-based applications of L-THIA

are freely available. In order to simplify the modeling process, L-THIA makes a number of

additional assumptions beyond those of SWAT. Snowfall is not considered, or the effects

of freezing ground. In addition, antecedent moisture conditions (how wet the watershed

is prior to precipitation) are ignored. These simplifying assumptions limit the power of the

model, but they also make the model easier to apply. A comprehensive list of water quality

constituents are considered in L-THIA. These include nitrogen, phosphorus, suspended

solids, lead, copper, zinc, cadmium, chromium, nickel, pesticides, BOD, chemical oxygen

demand (COD), oil/grease, fecal coliform, and fecal strep. The breadth of useful output

from the model is especially attractive to researchers and decision-makers comparing the

water quality outcomes of alternative development scenarios (Greenberg et al. 2003; Tang

et al. 2005). Since different urban forms may be associated with the production of different

constituents, comparing scenarios across a wide variety of indicators is necessary to obtain a

fair and accurate comparison.

iv. Storm Water Management Model (SWMM)

The Storm Water Management Model (SWMM) was the first urban runoff quality

model (Donigan & Huber 1991). The model's capabilities and requirements are documented

in Rossman (2005). This model is intended for application to storm sewer systems that

drain urban areas; SWMM is a simulation of the hydraulics of storm sewers rather than just

watershed hydrology. However, SWMM does include a simple hydrology model that includes precipitation, evaporation, snow, interception, infiltration, percolations, groundwater flow, and reservoir routing of overland flow. Buildup of pollutants on impervious subcatchments is simulated, followed by precipitation event-based wash-off and drainage through gutters, storm drains, and a sewer system (storm sewer, combined sewer, or natural drainage). Simulations in SWMM can also be run continuously as a repeating cycle of build-up and wash-off. The Extran Block component of SWMM is a complete set of dynamic flow routing equations that can model a number of hydraulic phenomena found in sewer system management like backwater, surcharging, looped sewer connections, and other hydraulic structures (pumps, weirs, BMPs, etc).

Water quality constituents are user-specified in SWMM. Users input concentrations for each pollutant in rainfall and groundwater, and a decay coefficient. Land use categories in SWMM are also user-specified. The rate of build-up of a given constituent is set for each land use. Note that this allows SWMM to model pollutant contributions from rainfall, as in "acid rain," as well as from air deposits on surfaces and soils. Additionally, in this model both surface runoff volume and constituent concentrations vary by land use. In SWMM, land use is more than just imperviousness. The model enables users to define their own land use categories, and the associate these definitions with different relationships to pollutants. Through subarea routing, the model also distinguishes between directly connected impervious area and total impervious area. This is a critical difference between SWMM and other models.

In part because of its longevity, SWMM is the most widely used model of its type, and it has been repeatedly independently validated (Donigan & Huber 1991). The number of user-defined parameters in SWMM, however, is clearly a roadblock to the model's general use. For a catchment with little monitoring, it may be impossible to apply SWMM without trial-and-error guessing of some parameters. However, a decision support system incorporating inference models and optimization techniques may be one way to overcome this obstacle and calibrate SWMM accurately (Choi & Ball 2002).

v. Model for Urban Stormwater Improvement Conceptualization (MUSIC)

The Cooperative Research Centre for Catchment Hydrology of Melbourne, Australia, released the Model for Urban Stormwater Improvement Conceptualization (MUSIC) for commercial use in 2003 (CRCCH 2005). Model theory and operation are presented in Wong et al. (2005). The primary motivation for developing a new model tool was a need to better simulate the role of stormwater treatment best management practices (BMPs). Through SWMM can represent some of these measures, others are ignored, such as wetlands. MUSIC can run as a continuous or event-based simulation, with a user-defined timestep appropriate to the scale of the simulation. The model can represent a range of scales, from individual sites to watersheds. MUSIC represents an advance from previous models in that it incorporates theory of the hydraulics and treatment behavior of stormwater management measures. MUSIC was designed as a decision support system for catchment managers in public and private practice. The model uses an icon-driven graphical user interface that emphasizes ease of use. However, the model is available only by paid license (or limited free trial), and there has been little public research activity surrounding the model beyond the model's developers.

Land use plays two roles in MUSIC. Each land use is assigned a percent-imperviousness, which is used in runoff volume calculations. In addition, land use variation is represented in the model by the varying empirical distributions of each pollutant attributed to each land use type. Other environmental variables are included in the model, including soils and topography. In addition to imperviousness, the built environment can be modeled in MUSIC through is inclusion of stormwater treatment measures in the model configuration. Model options include buffer strips, vegetated swales, wetlands, infiltration systems, ponds, rainwater tanks, sedimentation basins, gross pollutant traps, and a user-defined option.

Reflecting its specific orientation to urban areas, MUSIC does not model water quality constituents commonly associated with agriculture, such as pesticides. The only constituents considered in this model are total suspended solids (TSS), total phosphorus, and total nitrogen. The model compiles summary statistics for each constituent in each simulation, including daily mean, daily maximum, and daily sample (random). In the simulation, the effect of each BMP on constituent loads is regulated by a kinetic decay equation specified by two parameters, background concentration and rate of decay. These parameters can be calibrated by the user, though each constituent has unique default values for these parameters for each type of treatment measure in MUSIC.

vi. Comparative Synthesis

The approach of a "design" model like SWMM contrasts with that of "planning" models like L-THIA (Bhaduri et al. 2001). Design models provide a detailed simulation of each storm event and the resulting flows, tracing the movement of water

quality constituents through the system. Planning models, on the other hand, make pragmatic hydrologic assumptions and use empirical shortcuts when possible in order to get an adequate overall assessment at the lowest possible cost. The question is, how different are the results of the two approaches? A comparison of annual average runoff predictions by SWMM and L-THIA found that L-THIA could be calibrated to mimic SWMM output through the strategic selection of CN values (Bhaduri et al. 2001). However, constituent load estimates were not examined, and no algorithm for calibrating CNs was proposed.

Each model presented here has some unique features that suggest varying usefulness to different applications (Table 2). Beyond the distinction between design and planning models, each model has different strengths and weaknesses in the representation of land use, model of hydrology, and what water quality constituents are considered. No one

Table 2: Summary of Water Quality Models		
Model	Description	Application
HSPF	A process-based, ecological simulation of watershed response to precipitation.	Watersheds where constituents of concern are dominated by ecological reactions. Watersheds where land management is of concern (logging, development, drought).
SWAT	Complex modeling of hydrologic implications of agricultural practices.	Rural watersheds where dominant land use is farming/grazing. Water quality impact of land cover & climate change.
L-THIA	Curve number approach. Web- and GIS-based interfaces. Comprehensive inventory of pollutants modeled.	Basic assessment of overall implications for water quality of simple land use scenarios.
SWMM	Hydrologic and hydraulic modeling of flows in managed watersheds. User-defined land use categories with varying imperviousness and pollutant generation.	Urban/urbanizing watersheds. Watersheds impacted by a diverse variety of urban land uses.
MUSIC	Simulation of the role BMPs play in water quality.	Site planning, supplement to other models.

model includes every theoretical feature. For a given study area, model selection is about understanding the scope of the problem or question at hand.

<u>Related Research</u>

This project focuses on exploring the connections between urban form and water quality at the landscape scale. Researchers in a variety of disciplines have conducted scenario-based experiments to test relationships between land use and water quality. The debate has primarily been organized around the relative impacts of low- versus high-density development patterns, where density refers to the number of housing units per acre. These studies typically employ some combination of simulations of development, stormwater runoff volume, and/or contaminant loads to evaluate these development alternatives. In this way, the simulation experiment can be used to evaluate alternative urban forms and understand water quality impacts.

Most recently, Jacob and Lopez (2009) applied a simple spreadsheet model to demonstrate the watershed-scale regional water quality outcomes of high density versus low density development. Their research design was a simple thought experiment in which the residential density of a hypothetical study area was doubled to create an alternative high-density scenario. Their spreadsheet model applies a simple equation expressing a functional relationship between water quality and runoff, runoff event mean concentration (EMC), and land area, where runoff itself is a function of rainfall and an imperviousness ratio. Simply adjusting the parameters for imperviousness ratio and EMC to reflect two alternative land use scenarios allowed the authors to illustrate the watershed-scale cumulative outcomes determined by the relationships expressed in the functional

equations. The study found that per capita loadings and runoff decreased markedly with density increases.

Similarly, Richards et al. (2002) used the Smart Growth Water Assessment Tool for Estimating Runoff (SG WATER) to simulate runoff volumes under hypothetical two residential development scenarios. Their conclusion was that high-density development was better for watershed health because it disturbed less land in total and housing units share more impervious infrastructure. This conclusion was based on the fact that though the high-density scenario produced more runoff per acre, it produced about 40% less runoff per housing unit. Greenberg et al. (2003) used Huntingdon County, NJ, as a study area. They predicted the runoff pollutant load under two different growth scenarios for the county: one with 8000 new housing units at 8 units per acre, and one with 3758 new housing units at 2 units per acre. These scenarios were based on the assumption than 20,000 new residents would move to Huntingdon County, all of which could be accommodated under the high-density scenario, and only about half of which could be accommodated under the low-density scenario due to the limited amount of land. They applied the Long-Term Hydrologic Impact Assessment (LTHIA) model to estimate changes in runoff pollutant load for each scenario. Interestingly, they found that the pollutant loadings across fourteen indices, with the exception of nitrogen, did not vary much between the two densities. However, they concluded that the high-density scenario posed a less serious threat to water quality because it accommodated twice as many households while still leaving some land untouched by development.

Though these simulations have tried to demonstrate the relative sustainability of high-density development, the strength of the conclusions of these studies is limited by the representation of urban form in the research design. In the Jacob and Lopez and SG WATER models, only residential density varied. In the LTHIA model, residential densities and distributions of other land use categories are considered. Essentially, these models forecast runoff volume assuming no urban form variation within broad land use categories. However, as the theoretical model presented in Figure 2 illustrates, subtle nuances of development configuration, far more obscure than residential density, including directly connected impervious area and size of riparian vegetation buffers, are major determinants of a particular urban form's impact on water quality. In fact, recent research has found that density-neutral alternative approaches to subdivision design, as well as basic land use, have significant water quality implications (Nassauer 2004).

The simplistic reduction of the complexities of urban form to a matter of residential density or even TIA measures can be dangerous, leading to false conclusions. One can argue that urban forms featuring compact development may have higher percentages of DCIA due to integrated sewer services, making this form less sustainable. On the other hand, it is just as easy to hypothesize that low-density development implies more transportation-related imperviousness per household, making this form unsustainable (Goonetilleke et. al. 2005). Brun and Band (2000) found that impervious surface cover up to 20-25% was a threshold for runoff ratios using the Hydrologic Simulation Program – Fortran (HSPF). However, the arrangement of impervious cover at the site and regional levels within this threshold is completely undetermined.

In this vein, scenario-based studies that vary growth rates but not land management alternatives, such as Wang et. al. (2005), Tang et. al. (2005) and McColl and Aggett (2007), show that the research design is just as important as the methodology when attempting to relate research to decision-making. These studies pair modern land use change and water quality models, and produce findings demonstrating the existence of thresholds in the relationship between urbanization and water quality. In all cases the authors argue that their model can be used by decision-makers for planning purposes. However, research has demonstrated that the possibility of misinterpreting and misapplying research relating to impervious surface thresholds is substantial (Moglen & Kim 2007). The issue is that while these research designs have technically legitimate findings, the dependent variable is the quantity of population or economic growth, something that most communities have little control over. The models then use simplistic or static representations of urban form (especially density) and/or land use policy, even though this variable is key to the actual choices and tradeoffs that local communities have the power to act on. This mismatch between design and reality can imply policies that are ineffective and even harmful.

The key to producing results that can inform policies governing development is that the representation of land use type, pattern, and change must be data-rich and reality-based. A recent study by Costanza et al. (2002) developed and applied such a model to the Patuxent River, Maryland, watershed. This study simulated land use change with an economic land-use conversion (ELUC) model that used inputs of property values, ecological features, existing infrastructure, and government policies to output conversion likelihoods. The influence of transportation was represented by a road gravity weight (proximity to transportation infrastructure). Another study, by Hulse et. al. (2000), used the

Steinitz alternative futures model of scenario planning to develop five scenarios through a participative process for the Muddy Creek watershed in western Oregon. These scenarios were tested for diverse water quality impacts using a curve number-based GIS model, including suspended solids, phosphorus, nitrates, and a separate biodiversity model.

This design represents the gold standard in exploring landscape-scale land use and water quality relationships. Currently, studies like these, which generate future land use scenarios using theoretically sophisticated models based on rich local data, are the exception rather than the rule. More typically, hypotheses are generated by educated guesses based on broad policy guidelines (Greenberg et al. 2003; Im et al. 2003; Richards et al. 2002). The results of future efforts in this area can increase their relevance to policy makers with more sophisticated alternative-scenario generation, and by employing theory- and data-driven models of land use change.

For example, the strong relationship between land use and transportation patterns is well established (Dueker 2002; Ewing & Cervero 2002). In spite of this, however, this relationship is not well modeled in even the most advanced studies simulating the impact of urbanization on watersheds, such as the Patuxent River ELUC model. One sign of progress is the efforts of Alberti and Waddell (2000) to integrate UrbanSim, a comprehensive land use-transportation change simulation, with a process-based nutrient cycle model to simulate changes in nitrogen and phosphorus loads under alternative development scenarios. However, both the UrbanSim project and the Patuxent River study focus exclusively on one kind of water quality constituent, nutrients.

This project builds and improves on prior research by applying a rigorous and original modeling methodology that exploits large fine-grain datasets of environmental, economic, and infrastructure data. While this limits the external validity of the research by tightly tying the model to local data, and hugely increasing the breadth and intensity of effort required to build the model, this maximizes the internal validity of the design to authoritatively test the research hypothesis about regional land development patterns and stormwater outcomes. The outcome variable of this project's model, stormwater runoff volumes, is the most widely monitored and regulated indicator of water quality, which usefully serves the research motivation.

CHAPTER 3

CONCEPTUAL FRAMEWORK

The conceptual framework of this study is to explore the relationship between urbanization and water quality not by seeking out correlates, but by explicitly measuring and simulating spatially the processes that shape urban form and produce stormwater runoff. Urbanization is a process shaped by many complex, multivariate drivers. Thus, there are many ways of measuring urban form. Only some of these are significant in the stormwater runoff process. In order to operationalize a design addressing the research question, the conceptual framework must identify the key constructs and variables. Most of these, for example directly connected impervious area, have already been identified by the literature and called out in Chapter 2. However, one key gap in the literature is the current treatment of density in research on nonpoint source pollution.

Density is a widely considered variable in the overall literature of urban environmental performance, including water quality. Urban density is a multi-faceted construct that can be operationalized in many different ways. Extant models define density in human, social, psychological, environmental, ecological, economic, and behavioral terms, each predicting different drivers and outcomes along a density gradient (Newman and Hogan 1981). Residential density can be created at a variety of scales. Richards et. al. (2002) suggest measuring density at the one-acre, lot, and watershed scales. Current common zoning and subdivision ordinances, implemented over time, produce "wall-to-wall

subdivisions" that form a constant, flat, low-density gradient at all three scales: one-acre, lot, and watershed (Arendt 2006 p. 453).

In watershed protection terms, this outcome is not necessarily the product of an absence of planning, though it might be. Rather, it is also the result of a historic perspective that when it comes to water quality, "dilution is the solution to pollution (Tarr p. 12)." If impervious surfaces created by development produce stormwater runoff that harms watersheds, then one way to allow development while trying to minimize this harm would be to spread the damage evenly over the landscape. By capping one-acre, lot, and watershed-scale development at a low density, total imperviousness within the watershed will remain below the thresholds that studies have suggested indicate impairment (Brun and Band 2000, Richards 2002). Thus, in this conventional urban form the only low-impact design strategy is enforcement of impervious surface thresholds, through density regulation at all scales.

In contrast, conservation subdivision theory takes a different approach to regulating density. In this paradigm, density is maximized at the one-acre scale, held constant at the lot scale, and conventionally regulated at the watershed scale. The central goal of conservation subdivision design is to preserve patches of open space untouched by human intervention (e.g. grading, landscaping, etc). Density is increased by increasing proximity of housing units to each other within a given lot. Given a several-hundred acre lot to convert from farming or fallow use to housing, Randall Arendt advocates a "density-neutral" approach in which the number of housing units permissible will be calculated based on the current zoned maximum for the whole lot. The conventional low-density approach, then, would be to

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simply distribute the allowed housing units uniformly over the site, maximizing the size of each individual housing plot.

As an alternative to this approach, conservation subdivision theory restricts the housing lots to 50% or less of the total lot, reducing the average housing plot size but creating open space within the acreage that is available for all residents, as well as native wild plants and animals, to use. Areas for development and areas for conservation are identified through a suitability analysis that considers ecological factors (and many other factors) (Arendt 1996 p. 11 – 12). In terms of environmental benefits, Arendt advocates the conservation subdivision approach as a way to preserve natural topography/drainage, which minimizes erosion; buffer riparian areas, providing natural filtration of stormwater runoff, shade to regulate stream temperature, and reduced necessity for stormwater detention basins; protect pervious open space, which allows aquifer recharge; and finally, provide area for on-site wastewater treatment through "spray irrigation" or shared septic (Arendt 1996 p. 13 – 15).

It should be noted that conservation subdivision theory is analogous to the "spatial solution" theory advanced by Forman and Collinge (1997) as applied at the site level. Compared to conventional low-density urban form, conservation subdivisions represent a quantum leap forward for incorporating low impact design strategies. However, the approach is limited in that the only urban form structural features that vary from conventional development are one-acre scale density and shared open space.

Regional densification represents a much more ambitious alternative to conventional low-density urban form. This paradigm is present in regional planning movements such as

"Smart Growth" (Nisenson 2005) and New Urbanism (Duany 2002). For example, the New Urban Transect theorizes a density gradient from high to low extending from city center to rural preserve (Duany 2002). Depending on which sector of the Transect a development project falls in, varying lot and one-acre densities will be called for. In the urban sectors of the Transect, there is a consistent emphasis on increasing both one-acre and lot scale densities as opposed to conventional development. Rather than allowing development to occur all over the watershed, then, this approach concentrates development in certain areas regionally. Under New Urbanism, within developed areas, there is a further compaction of development (increase in one-acre density) to create room for shared open and public spaces (Berke et. al. 2003).

The general principle behind regional densification is that per-capita land consumption is reduced, so that sensitive areas can be protected. In addition, by compacting development there should be additional room for implementing best management practices (BMPs). While the goal in conservation subdivision is to reduce or eliminate the need for BMPs by creating buffers and minimizing paved infrastructure, this strategy relies on relatively low densities. Therefore, at the higher densities of regional densification, BMPs are still necessary. Results found by Greenberg et. al. (2003) emphasize the critical importance of creating room for BMPs. In comparing a low-density development with a high-density alternative, the study found that there was little difference in the stormwater runoff pollutant loads predicted by their model. Therefore, the high-density alternative that allows room for BMPs becomes the key to watershed protection. This is confirmed in Berke et. al. (2003), which found that New Urbanist developments were more likely to protect sensitive areas and implement BMPs than conventional developments.

New Urbanists also advocate compacting and mixing land uses and housing types. It has been theorized that mixing uses will reduce demand for auto travel, which could mean smaller parking lots (Berke et. al. 2003). Furthermore, diversity will reduce per capita impervious surface by increasing the amount of roads, parking, and rooftops that can be shared. Conservation subdivisions promote this sharing within the subdivision, but New Urbanism greatly increases it through compaction at the watershed scale (as opposed to the just the lot scale), including multifamily housing, and by combining uses within buildings. Richards et. al. (2002) and Jacob and Lopez (2009) demonstrated this principle using simulation of alternative development scenarios that varied by density, but contained the same total number of housing units. However, Girling and Kellett (2002) found New Urbanist developments actually increased peak flow more than "status quo"-style development, perhaps because their model accounted for the type of drainage system. Clearly watershed protection performance is highly contingent on the regional design as a whole.

There are competing views within the planning community about the benefits of large-scale regional density. On the one hand, Smart Growth advocates promote urban compaction and densification through infill development as a way of spatially restricting the changes in stormwater runoff brought about by urbanization (Nisenson 2005 p. 17). The urbanized region becomes a sacrifice zone where negative water quality impacts are confined. On the other hand, there is growing dubiousness in the planning community about the environmental benefits of strict, large-scale regional density and compaction (Grant et. al. 1996, Gordon and Richardson 1997, Van Der Waals 2000).

At the root of this confusion is the fact that the relationship between water quality and urban form is highly scale-sensitive and multivariate, and simple applications of known

theory about small-scale univariate relationships to large-scale areas produce contradictory

inferences. Just as the argument about sacrifice zones makes basic sense, the point that

increasing compaction produces more "bad" types of impervious areas is also true. From

a theoretical standpoint, one possible clarification is Randall Arendt's conception of

conservation subdivision design and New Urbanism as "two sides of the same coin." He

proposes their possible implementation in a wedges-and-corridors pattern with the New

Urban Transect implemented around each transit node in the corridors and conservation

subdivisions allowed in the green wedges (Arendt 1996 p. 8).

The regional development patterns corresponding to the conventional development,

conservation subdivision, and regional densification approaches are illustrated in Figure 3.

The purpose of this figure is to visualize the forms that emerge at the regional scale when

these varying principles for benchmarking lot, one-acre, and watershed scale density are

applied. Each cell in the figure shows the same, constant watershed scale density. However,

the patterns that emerge from varying lot and one-acre scale densities are distinct. The

diagrams shown in Figure 3 are simply conceptual and do not show the only possible

Conventional Development	Conservation Subdivision	Regional Densification
LOW lot-scale density	LOW lot-scale density	HIGH lot-scale density
LOW one-acre density	HIGH one-acre density	HIGH one-acre density
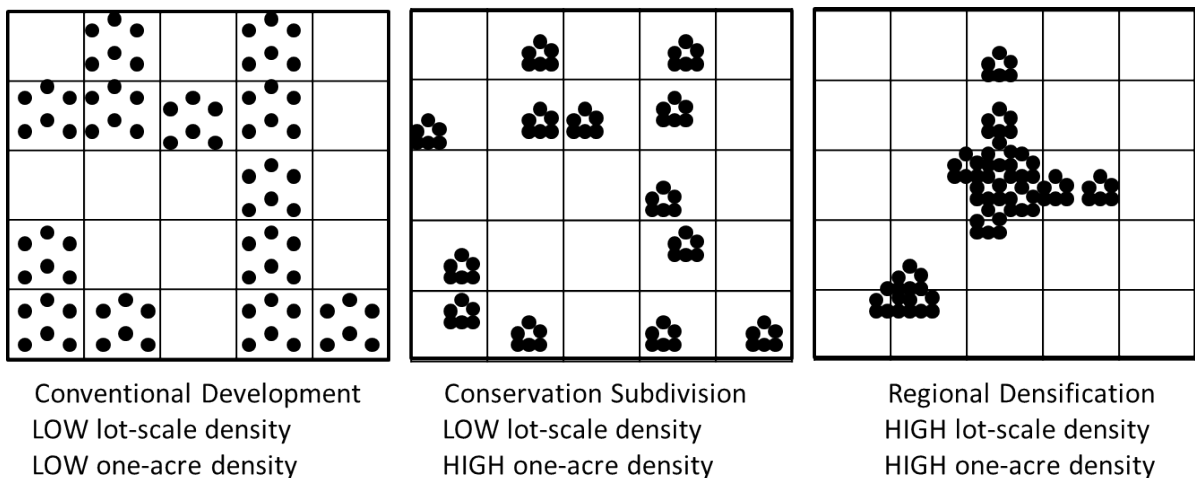
Figure 3: Density Concepts

representation of each density concept. These diagrams are abstract sketches. Real regional

urban form is the result of a long-term urbanization process and reflects many influences

other than density regulation.

Acknowledging this process, Figure 4 shows a theoretical framework for the

relationship between drivers of urban form (of which density regulation, e.g. zoning, is only

one) and environmental performance. Note that the model in Figure 4 includes feedback.
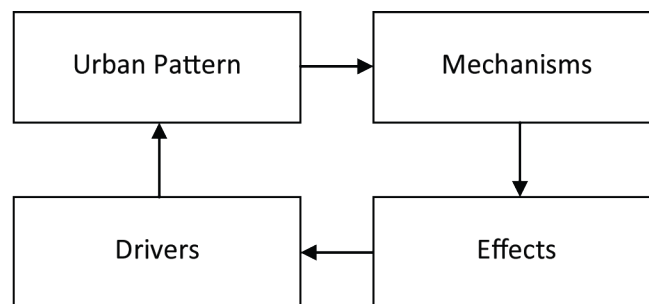
Figure 4: General Conceptual Model

The arrow connecting effects back to drivers illustrates the idea that when applying this

model for large time scales, gradually increasing effects will eventually provoke adaptive

responses in the drivers. However, when re-stating the Figure 4 model for water quality

(Figure 5), this feedback link is removed. This represents the current state of regional

planning, where water quality is rarely a consideration. There are two reasons for this

externalizing of water quality. The first is that the effect of urban growth on water quality

is doubly indirect, occurring only through the manifestation of an urban pattern and the

mechanism of stormwater runoff. This makes the effect difficult to trace beyond the site

level. The second reason is that even though there is increasing regulation of this issue,

in the past cities have coped with decreasing water quality not by establishing policy links

between effects and drivers, but by simply treating drinking water. It is only recently that

Urban Pattern:		Mechanisms:
Compactness/Edge & residential density		Combined sewer overflow
Polycentricity/Patch size & employment density		Point source pollution
Connectivity/Road density		Nonpoint pollution
Impervious surface ratios		Erosion and deforestation
Directly connected area		Culvertization
Land use intensity and type		

Drivers:		Effects:
Topography		Flooding
Stormwater management policy		Chemistry changes
Land use planning		Increased water temps.
Transportation planning		Channelization
Urban economics		Loss of habitat
Agricultural practices		Eutrophication
Population growth		Sedimentation
Housing preferences		Public health risks (bacteria,
Environmental attitudes		carcinogens)

Figure 5: Water Quality Conceptual Model

some large cities have been stymied in this strategy by the extremely high fixed costs of

water treatment, as well as limits to which contaminants and how much of them can be

removed through such a process. In addition, Phase II implementation of the Clean Water

Act greatly expanded the number of cities subject to the performance measures known as

Total Maximum Daily Loads (TMDLs). The best-known American example of attempting to

link effects and drivers is the City of New York, where planners and decision makers have

made a combined effort to understand this conceptual model and create strategies for

action based on it (Mehaffey et. al. 2005). However, such efforts are highly experimental

given how little empirical evidence elucidating this model is available.

    With regards to the available evidence, the review of the literature in Chapter 2

identified two key knowledge gaps within Figure 4. First, the process connecting the drivers

in Figure 5 to urban pattern is typically not modeled in studies relating urban form to water

quality. Replacing this connection with assumptions produces findings that are of very limited utility to planners. Second, in previous research the design of scenarios representing alternative values for the drivers in Figure 5 suffers from varying pitfalls: selecting drivers that planners do not actually have tools to substantially manipulate, such as population growth; missing data forcing researchers to replace drivers with assumptions; and the selection of artificially extreme values for drivers that do not represent plausible scenarios.

The research design and methods applied in this project directly address both of these gaps. Figure 6 restates the conceptual model of Figure 5, narrowing the frame to the specific mechanism considered in this research, nonpoint source pollution, and one proxy effect - stormwater volume. This figure shows the key variables considered in this project. Two computer simulations, applied in sequence, trace the conceptual model established in Figure 5 from drivers to effects. First, all drivers are initialized with rich data. To explore the scenario space, alternative plausible values are generated for key drivers that represent

Urban Pattern:

Compactness/Residential density
Polycentricity/Employment density
Connectivity/Road density
Impervious surface ratios
Directly connected area

Mechanisms:

Nonpoint pollution

Drivers:

Topography
Land use planning
Transportation planning
Urban economics
Population growth
Housing preferences

Effects:

Stormwater volume
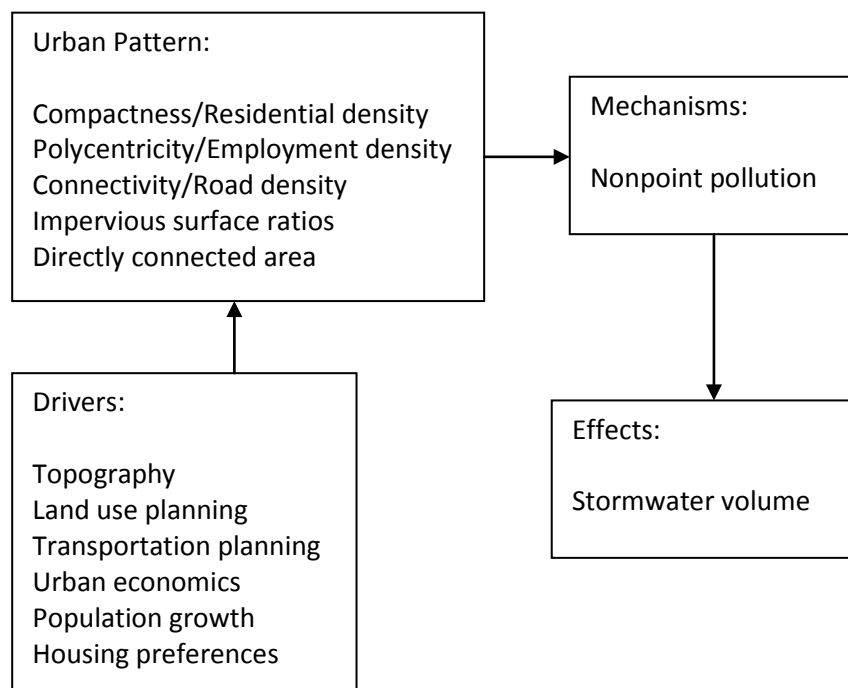
Figure 6: Key Variables

areas of opportunity for intervention such as land use planning (zoning) and transportation

planning (location and capacity of transportation infrastructure). These drivers are then

connected to urban patterns via the first simulation, an integrated land use-transportation

model. Focusing in on the mechanism of nonpoint source pollution, the urban patterns are

connected to effects via the second simulation, a stormwater hydrology/hydraulics model.

The final output, stormwater volume, is a proxy for the effects.

CHAPTER 4

RESEARCH DESIGN AND METHODS

<u>Research Design</u>

This project uses a scenario planning approach to test the hypothesized relationship between regional urban form and water quality. I combine an advanced, data-rich, policy-driven land use change simulation with a well-calibrated hydrological model to produce estimates of stormwater peak and total volumes (Figure 7). Multiple models are applied in sequence. This chapter describes in detail the development of each model. The linear chaining of these models, in which the output of one model is the input to another model, means that intermediate results of the research are reported as part of the description of the project's methods in this chapter. Only the final stormwater volume results that directly speak to the research question are reported in Chapter 5 (Results).
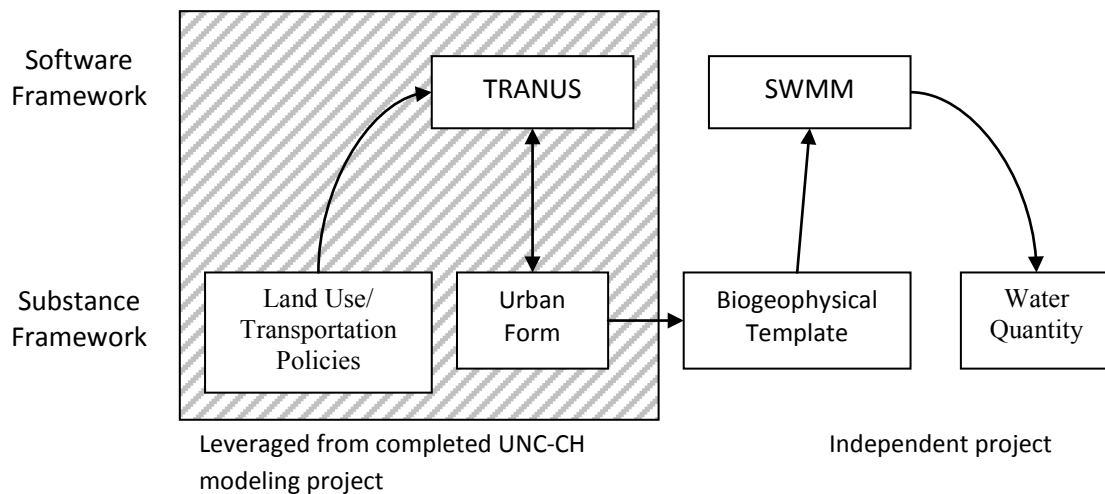

Figure 7: Model Framework

The project uses a quasi-experimental design. At time T = 0, the baseline TRANUS model of Mecklenburg County, and corresponding SWMM implementation, represent the initial state of the system. At time T = 1, each scenario represents a possible intervention. Note that there is no control group per se. Rather, a "surprise-free" scenario represents one possible intervention choice: maintaining the status quo. This quasi-experimental design is made possible through the use of computer simulation.

Combining a scenario planning process with computer simulation brings a number of potent advantages. The scenario planning approach provides a mechanism for dealing with the uncertainty that is inherent in exploring the future. By examining plausible alternatives, rather than a single possibility, the modeling results will yield output that can be used to explore tradeoffs and comparative advantages with a sense of their direction and magnitude, rather than a single set of numbers that lack a hard estimate of the confidence we might have in them. Creating scenarios also allows the design to encompass large numbers of variables over a large spatial area, which is necessary in order to meet the spatial scale implied by the research question. Similarly, computer simulation typically demands large numbers of variables. The application of a simulation enables the exploration of long time horizons and large systems in the present, without the cost and obstacles associated with waiting for or attempting to create a natural experiment, conditional upon the incorporation of observed data for model validation.

Marrying scenario analysis with computer simulation embodies a shift from a forecasting mode to a policy analysis mode, a shift that mimics the application of integrated models in the research literature. At the same time that they aid in policy analysis, scenarios

can support public participation and engagement. Performing a simulation can raise awareness of expected and unanticipated consequences of policy scenarios. While this quasi-experimental case study design provides limited external validity, the internal validity is strong. In other words, my goal is to compare the scenarios to each other, not to forecast a speculative future. However, the outputs are only as good as the model itself. Selecting the correct model to perform the simulation is vital.

This research design applies two computer simulation models in sequence to trace the steps from drivers to effects in the conceptual model of Figure 5. The process connecting drivers with urban form is simulated through the integrated land use and transportation model TRANUS. Of the potential models reviewed in Chapter 2, TRANUS was selected because it includes both land use and transportation, both of which are critical drivers in Figure 5. Applying an integrated model enhances the possibility of detecting the land development effects of transportation policies and vice versa. Of the integrated models, TRANUS is among the most widely validated, and this project was able to leverage a TRANUS implementation developed for Mecklenburg County by another research project at the University of North Carolina at Chapel Hill (UNC-CH) (Morton et. al. 2007).

The process connecting urban pattern to nonpoint source pollution is simulated in this project by the Environmental Protection Agency's Storm Water Management Model (SWMM). Of the models reviewed in Chapter 2, SWMM excels in application to urbanized areas because of its ability to simulate hydrology and hydraulics, which is necessary in Mecklenburg County. The model's treatment of imperviousness, in which the model builder may distinguish directly connected impervious area, is essential to correctly representing

the dynamics outlined in Figure 2. In addition, the option of incorporating user-defined

land uses to the model's representation of urban form allows for numerous future research

applications, which helps justify the cost of building the simulation.

The framework of Figure 7 is restated as an operational model in Figure 8. This

figure elaborates the methodology of the project by illustrating the data inputs that form

each construct in the overall modeling framework. There are five major subsections to this

research design. First, the pattern or mosaic that is composed of the units of analysis for

the model must be defined and measured. Second, the urban simulation model requires

a number of inputs that calibrate the model to the study area. Third, the future scenarios

must be envisioned and parameterized for the simulation model. Fourth, a calibrated

baseline hydrology model provides the basis for two future scenario models quantifying the

stormwater impacts of the scenarios. Fifth and finally, the outputs of the urban simulation

must be translated into inputs for the hydrological simulation in order to build the future
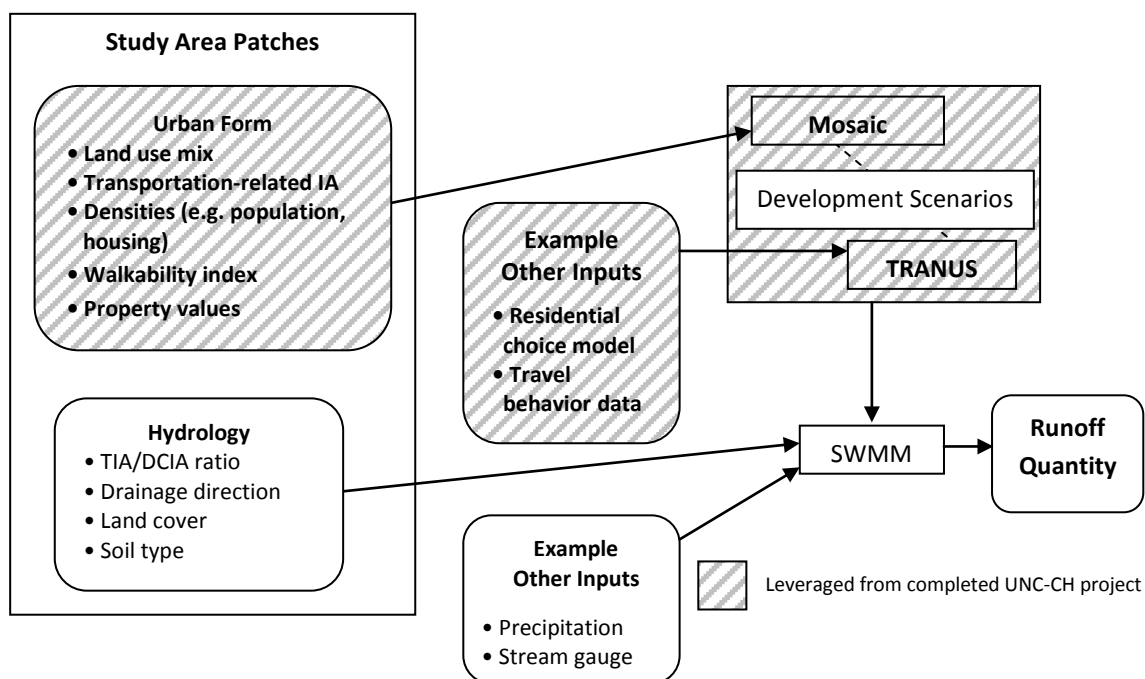

Figure 8: Operation

scenario hydrology models. The first two components are leveraged from the completed

UNC-CH project. The subsequent four sections of this paper will describe the data,

assumptions, and methods used to implement this design.

<u>Representing Pattern</u>

In order to be feasible, the model must use some reasonably small number of

characteristics to define urban form in the study area. Typically, this means reducing the

complexities of urban form down to broad, imprecise categories such as "residential,"

"commercial," "undeveloped," and so forth. While such categories may be generally

accurate, they do not necessarily emphasize the most significant underlying factors that

make one land use, or one area with a dominant land use, different from the next. The UNC-

CH project used factor analysis to identify from a large number of basic variables a smaller

number of underlying structural factors that determine urban form variation, and imputed

scores for each factor for each zone. Then, they used cluster analysis of the factor scores to

classify an urban form typology of eight neighborhood types, henceforth "ntypes." In the

end, eight neighborhood types were identified.

<u>Modeling Land Use and Transportation</u>

The TRANUS modeling framework is separated into two main components that

interact with each other: land use and transport. The land use component is based on

the aggregation of space in the study area into zones, which form the unit of analysis. For

Mecklenburg County, the model uses the 373 Census block groups as zones, as a wealth of

data is available at this resolution for specifying the local model. The land use component is

concerned with the locations of activities and interactions between them, as determined by

an input-output framework. The term "activities" refers to both employment, categorized by sector, and households, categorized by type. The land use component maintains an inventory of the supply of land in each zone, and models a market for real estate. The land use component uses the input-output matrix both to calculate the endogenous production implied by the matrix and to calculate the demand for travel based on the relationships between activities once locations have been chosen. Figure 9 illustrates the data inputs required by the land use component.

In this project's implementation of TRANUS, the transport component is based on an abstract network that represents the transportation infrastructure connecting the zones. Travel within zones is considered negligible. The network is composed of links of various types joined by nodes. The transport component is concerned with converting the demand for travel into actual trips, specifying the mode and the route. In addition to maintaining the inventory of physical supply in the form of the link network, the transport component tracks the operative supply, representing the different travel services available (e.g. cars, buses, light-rail transit, park-and-ride lots, etc). Three types of agents exist in the transport component and are tracked by it: users, who demand transport, operators, who charge users, and administrators, who charge operators and pay maintenance costs. By applying an accounting system to these three groups of agents, the transport component clears the market for travel, establishing equilibrium. The transport component returns to the land use component the accessibility of each zone, and the transport costs for each activity. In this way the model integrates land use and transportation, though the integration is lagged, not dynamic. Figure 10 illustrates the data inputs required by the transport component.
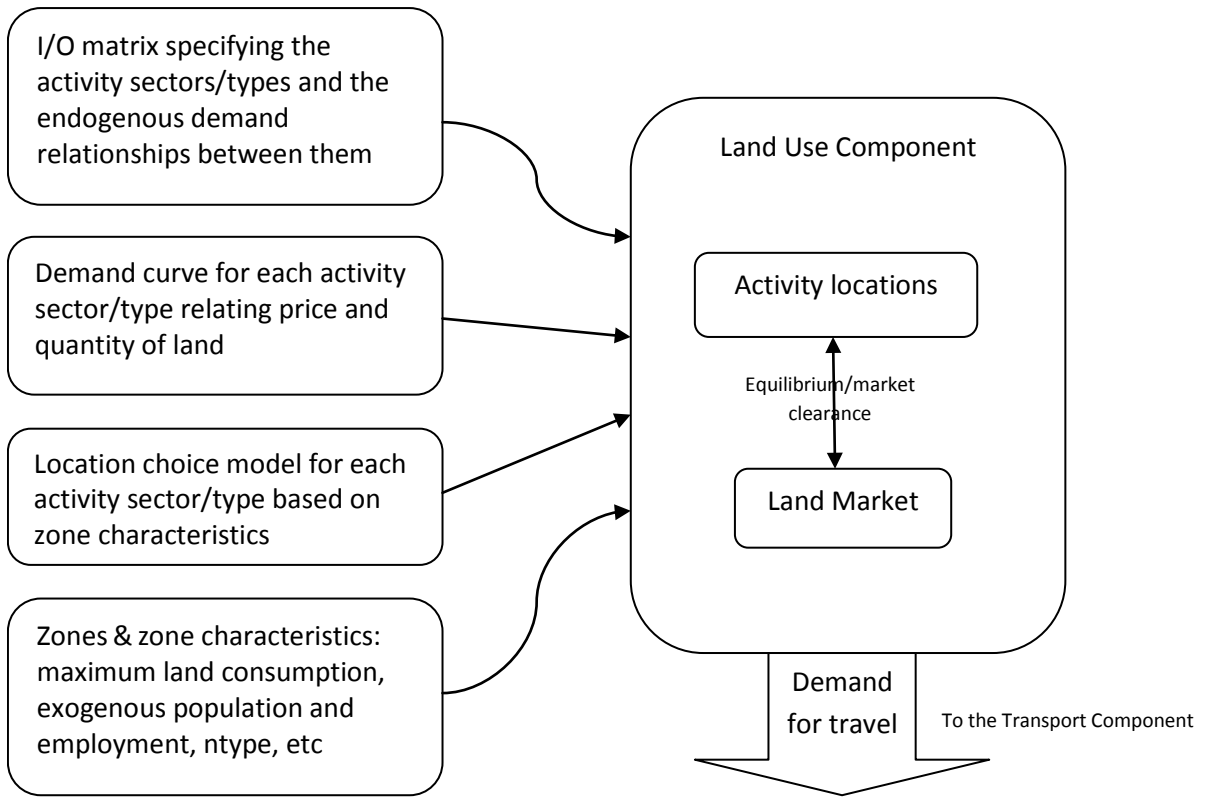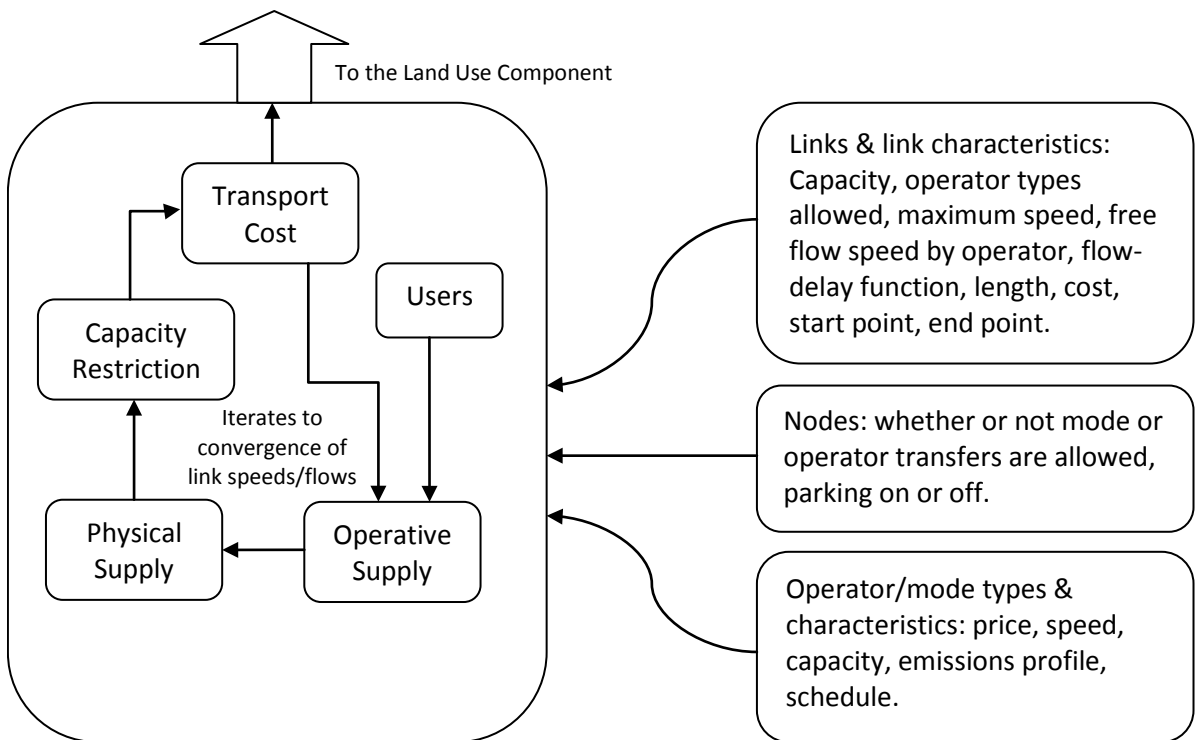
Figure 9: TRANUS Land Use

Figure 10:TRANUS Transport

An economic sector's demand for labor and a population sector's demand for commodities other than transport and land were derived from a year-2000 input-output model of Mecklenburg County prepared by the Minnesota IMPLAN Group. Demands for land (i.e., quantity regardless of location) were estimated statistically, sector by sector. A sector's locational choice (i.e., zone) was captured with disaggregate, conditional logit models.

The activity model was divided into 15 sectors: 12 employment sectors and 3 household sectors (Table 3). The baseline composition of the study area with regards to these 15 sectors is shown in Table 3. The included economic sectors account for nearly all employment, and the included population sectors account for the entire resident population at the baseline year. The excluded economic sectors are agriculture and the extractive industries. The economic sectors encompass dozens of sub-sectors, which are grouped into conventional aggregates. At the most fundamental level, this economic sectorization carries maintained hypotheses about each sector's aggregate demands for labor and for land. The

Table 3: TRANUS Sectors		
Number	Name	Baseline
1	Construction	38,935
2	Manufacturing	53,363
3	Wholesale Trade	25,614
4	Retail Trade	50,153
5	Transportation & Warehousing	38,828
6	Information	17,705
7	Finance, Insurance, Real Estate, & Rental/Leasing	66,180
8	Professional, Scientific, Management, Admin., & Waste Management	53,241
9	Educational, Health, & Social Services	66,846
10	Arts, Entertainment, Recreation, Accommodation, & Food Services	31,791
11	Other Services	19,913
12	Public Administration	10,352
21	High Income Households (>= $75,000)	63,165
22	Medium Income Households ($30,000 $\leq$ X < $75,000)	110,115
23	Low Income Households (< $30,000)	62,250

population sectors are also conventional; the grouping of households reflects maintained

hypotheses about households' aggregate demands for retail goods and for services, notably

transport.

Scenario Development

The literature review in Chapter 2 identified some key questions that must be

answered when initiating a scenario planning process. Regarding the representation model,

Chapter 2 established a physical-spatial framework as most appropriate to the research

question, leaving only the basic drivers that characterize the representation model to be

identified. The conceptual framework of Chapter 3 laid out several theories of regional

urban form that suggest values for two key drivers: land use and transportation planning.

The influence of the theories of regional urban form that were distilled conceptually

in Figure 3 are clearly evident in extant planning efforts within the Mecklenburg County

study area. The *Centers, Corridors and Wedges Growth Framework* (Charlotte-Mecklenburg

Planning Department 2010) first introduced in Charlotte in 1994 and then updated and

reaffirmed by the Charlotte City Council in 2010 incorporates an approach to regulating

density that shares much in common with Arendt's conservation subdivision-New Urbanism

coinage. The framework identifies five corridors within the city's "sphere of influence"

and articulates an activity center concept that prioritizes development in the center city,

the growth corridors, and key mixed-use areas. This regional densification concept is an

excellent starting place for a scenario that is vivid, but plausibly unexpected.

Basing a scenario on an existing plan for the region also meets the goodness

criteria that the scenario be cognitively ergonomic. Continuing in that vein, the regional

transportation planning organization, the Mecklenburg-Union Metropolitan Planning

Organization (MUMPO) has a long-range transportation plan for the region, including

Mecklenburg County. This plan represents a surprise-free scenario in that planning

professionals serving the study area consider this plan to represent the most likely future for

the area, and are operating on that basis.

Two scenarios fits within the range of the optimal number of scenarios suggested

by the literature. These scenarios target those parts of the scenario space that have

the greatest relevance for contemporary growth management in the region, while also

speaking to the critical conceptual issues raised in Chapter 3. Therefore, I created one

scenario based on the 2030 long-range transportation plan created by the Mecklenburg-

Union Metropolitan Planning Organization (hereafter, MU), and an alternative Wedges and

Corridors scenario (hereafter, WC).

The process of converting a narrative vision into some estimate of how much of what

types of growth will happen in the future, and then into a set of parameters acceptable to

TRANUS, was a series of challenges and compromises. The fundamental issue underlying

these challenges and compromises was the level of uncertainty created by the very distant

planning horizon of the project (50 years). However, the interaction between land use

and transportation that drives urbanization happens on the scale of decades, so this leap

into the far unknown is a requirement of the undertaking. Therefore, the first step in the

scenario development process was creating population and employment growth targets.

Both scenarios have the same amount of growth sector by sector, and, with respect to the

socioeconomic parameters, vary only in the geographic location of that growth.

i. Population totals

I based the 2050 population projection control totals on the 2007 Woods & Poole Economics Database, which uses a regional projection model to calculate estimates of a variety of variables to 2030. The Woods & Poole method uses a historical database of county-level demographic and economic data. The export-base projection method links counties, so that growth in one county affects the growth or decline of other counties. Further detail on the Woods & Poole methodology is available (W&P 2009). In order to take these projections from 2030 to 2050, I used a combination of extrapolation methods. For population, I created three extrapolations of the 2030 population. The first used the rate of change from 2029 – 2030, compounded annually. The second calculated the annual rate of change for each year from 1991 – 2030. Then, I calculated the rate of change between each of these rates of change (i.e. the second derivative). I then averaged these figures and used that rate to extrapolate the 2030 population to 2050, one year at a time. The third extrapolation is a conceptual combination of the previous two approaches – in essence, I took the rate-of-rate-of-change as it was at 2030 and compounded it annually to 2050. The final household population control total, 756,465 households (more than 3 times the current population of the county), was the average of the results of these three extrapolations. I held the distribution of households between income brackets constant from the baseline for lack of a better hypothesis about how they might change.

ii. Employment totals

I took a different approach to derive an employment control total. The inherent nature of the TRANUS input-output model relating sectors is that there is a structural relationship between population and employment. In our TRANUS model, population is

entirely endogenous. Exogenously specified increments to employment produce additional

population growth, though some economic sectors have an endogenous component. In

order to achieve a given population control total, therefore, the employment increments are

actually implied by the model. However, there is more than one set of possible employment

increments by sector that would produce the desired population control total. I could

have held the distribution of jobs between sectors constant from the baseline and found a

unique solution that way. The Woods & Poole employment projections, however, included

significant structural changes in the economy driven by growth in the service sectors. In

order to incorporate this information, I retained the sectoral distribution of employment

from the Woods & Poole projections, and calculated the implied increments to employment

from that. I also made some changes to the matrix specifying the demand for labor from

each employment sector to reflect structural changes to the economy within each economic

sector. This effort provided control totals for the exogenous employment sectors, but these

still needed to be distributed somehow among the zones.

iii. Land supply and demand for land

One other key piece of information was needed for each zone in order to specify the

scenarios. TRANUS does not have a land supply model, so land supply is a user- provided

input. This presented an ideal opportunity to differently specify the two scenarios for key

drivers. Both increments (or decrements) to land supply and exogenous (basic) employment

could have different spatial allocations between the two scenarios. Rephrased from model

terms to conceptual terms, the two scenarios represent different plausible possibilities for a

key driver, land use planning, in the form of model parameters analogous to zoning.

I used the neighborhood types described in the previous section to facilitate construction of two scenarios. For the WC scenario, the over arching vision of the scenario involves the creation of activity centers located on transit corridors at station nodes. Therefore the general principle for creating land increments was that future growth should be allocated to zones with desired urban form features. In addition, future zones should be "upgraded" to different neighborhood types based on the desired outcomes of alternatives.

For the WC scenario, I classified each zone into one of four types, based on a transit-oriented development (TOD) approach: High TOD, Low TOD, Transition, and Wedge (Figure 11). These designations were based on the proposed right-of-ways and station locations in the county's proposed future transit planning for a system of up to five fixed-guideway transit lines, also shown in Figure 11. The TOD zones were selected by proximity to planned stations. Of the selected zones, ones of neighborhood types 1 – 4 in the baseline were designated "High TOD" based on the assumption that the existing urban form of these zones is best suited for future incorporation of transit and retrofit through TOD design techniques. TOD zones of neighborhood types 5 – 8 were designated as "Low TOD" based on similar reasoning. Though population is allocated endogenously in TRANUS, I first allocated the population control totals to the zones to serve as an input to the allocation of land supply increments (which are entirely exogenous) and employment increments, which, depending on the sector, are partially exogenous. A very small amount (≤ 5%) of growth in land supply was allowed for the Wedge zones. The household population was allocated in thirds to the High TOD, Low TOD, and Transition zones. For the TOD zones, an estimate of the amount of developable land was calculated with an arbitrary 15% of developed land also included as 'redevelopable.' The population was then allocated to maximize residential density over
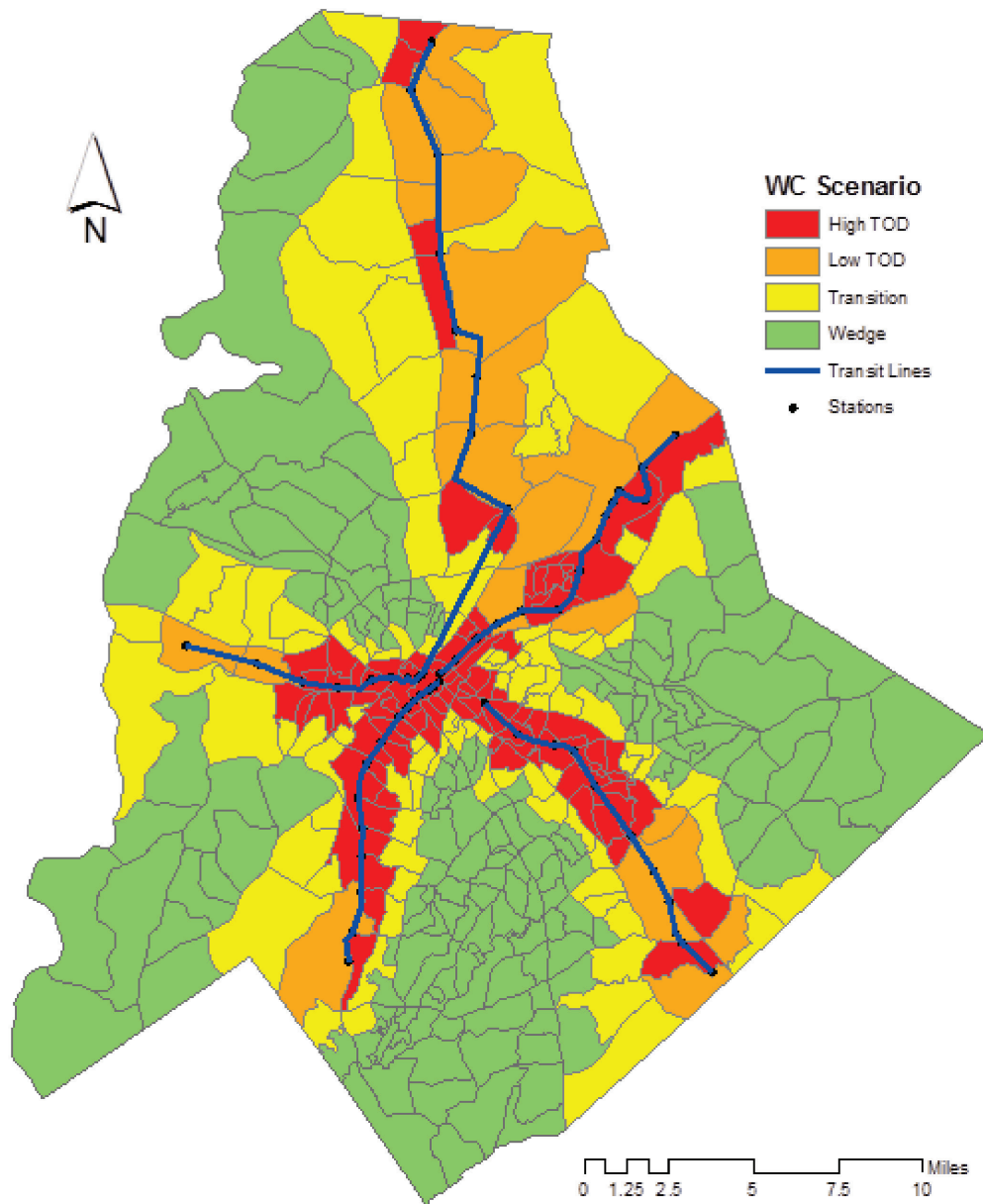
Figure 11: Zoning Concept for WC Scenario

the developable acreage of the TOD zones. This density benchmark approach produced

allocated densities in the High TOD zones that were about twice the Low TOD zones, for

each sector. For the transition zones, the allocation was done using a gravity surface created

from the baseline population, so that dense residential areas got denser. These allocations

of population only guide my initial calculation of each zone's increments for residential land,

which are inputs to TRANUS and seed the land use module's search for the market-clearing equilibrium.

Exogenous employment for the WC scenario was allocated similarly. Sectors 4, 6, 7, 8, 10, and 11 were allocated in the same way as population. The only difference was that for the transition zone allocation, sector 8 was allocated using a gravity surface of the baseline zonal distribution of sector 8, rather than the baseline household population. Sectors 1, 2, 3, 5, 9, and 12 were confined to the transition zones, and were allocated using gravity surfaces of their respective baselines.

Land in the TRANUS model is divided into three sectors: Sector 31 (Commercial Land consumed by sectors 4 and 6 - 12), Sector 32 (Other Business Land consumed by sectors 1, 2, 3, and 5), and Sector 33 (Residential Land). The UNC-CH project team calculated baseline levels of supply and demand using a parcel-level database obtained from the county's tax assessor and the county's business license database. Those data allowed them to calculate actual land consumption by individual enterprises and households. Future supply was determined by a combination of estimating future demand (via the population allocation) and incorporating scenario-specific ideas about land supply policy (e.g. zoning). In the WC scenario, minimal development is allowed in the wedge zones, so these zones received a correspondingly small (≤ 5% of baseline) increment in supply for each land sector. For the other zones, I calculated the baseline densities for each land sector. Then I calculated the implied demand of the residential and employment allocations assuming that unit demand remained constant. In the case of zones where the baseline density was zero but a future allocation was planned, I used the minimum nonzero baseline density. I had previously

estimated the quantity of developable land for each zone as part of the population

allocation. If the total estimated new demand was less than or equal to the developable

land, then the land increment for that zone was the estimated new demand (e.g. new

development occurred at the same density as in the baseline). If the estimated new demand

was greater than the available land, then the land increment for that zone was calculated

using the benchmarks in Table 4.

Table 4: Density Benchmarks for Land Consumption			
	Sector 31	Sector 32	Sector 33
High TOD	50 jobs/acre	n/a	8.41 households/acre
Low TOD	14 jobs/acre	n/a	8.41 households/acre
Transition	26 jobs/acre	40 jobs/acre	8 households/acre
MU zones	28 jobs/acre	40 jobs/acre	5 households/acre

For the MU scenario, the employment sector and land supply zonal increments were

calculated using similar techniques, but guided by different strategic principles. Once again

a population allocation was created even though population is ultimately endogenously

allocated in TRANUS, in order to serve as an input to the process of incrementing

employment and land supply. The Mecklenburg-Union MPO's long range transportation

plan included an estimate of population growth in 2030 that is available by transportation

analysis zone (TAZ). I aggregated this TAZ data to the block group unit of analysis in GIS. I

then calculated the average annual change in households from 2000 to 2030 from this data,

and compounded this rate on the MPO 2030 household totals for each zone until I reached

the control total. I reached the control total in 2046, which is reasonably close to 2050.

Employment by sector was allocated in the same manner as for the transition zones in the

WC scenario. The land increments were calculated by the same method as the WC scenario,

but using the benchmarks shown in Table 4 for MU zones.

These land supply increments were merely seed estimates. In order for TRANUS to converge, future land supply must be sufficient to accommodate base scenario exogenous employment (which does not relocate), base scenario population (which may relocate), growth in exogenous employment, and growth in endogenous employment and population. Net decreases in employment and population for a given zone are possible as firms and households relocate, but which cannot be anticipated prior to running the land use module of TRANUS to observe the emergent outcomes of the interacting choice models and supply increments. In order to find a satisfactory set of land supply inputs, including both increments and decrements, I repeatedly interacted with TRANUS's land use module, the results of which revealed where the land markets were in disequilibrium and thus where land supply needed positive or negative adjustment.

In constructing the scenarios, the UNC-CH team also made changes to the transport sector (another key driver). For the WC scenario, they added additional links representing the five lines of the fixed-guideway transit system. New transit modes were added to the list of operator types with the required mode characteristics. For the MU scenario, they also included three transit lines: the existing south line (LYNX), the Northeast light rail line, and the North commuter rail line. They chose to include these lines in the MU scenario because they are the top fixed-guideway transit priorities for the region, and the most likely to obtain funding and be implemented (the North line because it runs on existing track, and the Northeast line as an extension of the existing LYNX line). For both scenarios, they also modified the capacity of existing links and increased the frequency of existing (2000) bus routes. Similarly to the land use module, they needed to iteratively interact with the

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transport module of TRANUS in order to identify the capacity improvements that would allow trip assignment to converge, meaning that transport supply accommodates all trips.

Modeling Stormwater Runoff Volume

The SWMM conceptual model is composed of four interacting components: atmosphere, land surface, groundwater, and transport. The atmosphere component introduces precipitation and pollutants on to the land surface component. Land surface is composed of a mosaic of hydrological response units called subcatchments. The land surface component sends flows to the groundwater and transport components. The quantity and quality of the flow is mediated by a number of subcatchment attributes, including imperviousness, internal routing, and internal hydraulics. The groundwater component also sends flows to the transport component. This final component is represented by a network of channels, pipes, storage units, and regulators such as pumps and weirs that ultimately send flows to outfalls. This network is modeled through a set of links and nodes.

The purpose of applying SWMM in this case is to evaluate changes in the pattern of stormwater runoff in alternative future scenarios. Since the focus is event-based (i.e. what happens when it rains), the groundwater component was not included in the model. The atmosphere component was represented by a network of 61 rain gauges throughout the study area, shown in Figure 12. Realtime precipitation data, recorded in fifteen minute increments, was obtained from the CRONOS database of the State Climate Office of North Carolina, which archives data from stations maintained by the National Oceanic and Atmospheric Administration, the Federal Aviation Administration, the United States Geological Survey, and other local agencies (State Climate Office of NC 2011). The transport
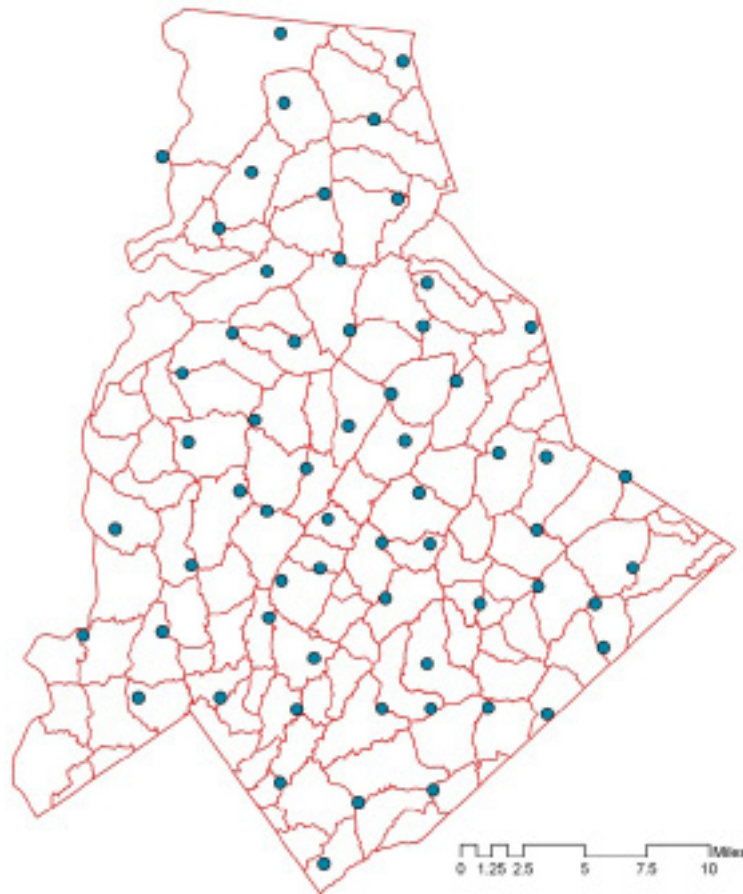
Figure 12: Precipitation Gauges of the SWMM Atmosphere Component

component was modeled as a network of 93 conduits representing a mix of stormwater

pipes, drainage channels, and natural streams connected by 122 nodes and outfalls. Data for

parameterizing the size, shape, and surface roughness of the conduits were obtained from

the GIS asset inventory of the Charlotte-Mecklenburg Storm Water Services utility (C-MSWS

2011). This inventory only covers the area of the city of Charlotte, so parameters for natural

channels outside this area were seeded with initial values (subject to calibration) using

visual estimates from orthophotography of the study area (Reid 2001).

The parameters required by the land surface component, along with their data

sources, are listed in Table 5. Each subcatchment (the polygons shown in Figure 12) must

Table 5: Land Surface Component Required Parameters		
Name	Description	Data Source
Physical Parameters		
Rain Gauge	A single rain gauge that inputs precipitation to the subcatchment	Each subcatchment was assigned to a rain gauge using a nearest-neighbor analysis based on the rain gauge coordinates and the subcatchment centroids
Outlet	Each subcatchment must drain to a single outlet, which is an identified node in the transport component	
Area	In acres	
Slope (%)	The average slope of the subcatchment	USGS Digital Elevation Model
Key Construct Parameters		
Impervious (%)	The percentage of the area of the subcatchment that is impervious	Polygon data of commercial and residential building footprints were obtained from Mecklenburg County.
Subarea Routing	How runoff is routed internally in the subcatchment prior to reaching the outlet node: - IMPERV (from pervious to impervious) - PERVIOUS (from impervious to pervious) - OUTLET (both areas straight to outlet)	All subcatchments were assigned to PERVIOUS, as the impervious surface polygons obtained from Mecklenburg County were not 100% DCIA.
Percent Routed*	The percentage of runoff from the subcatchment that is subjected to the subarea routing	All subcatchments were seeded with an initial value of 25.
Hydraulics Parameters		
Characteristic width	The characteristic width is a mathematical construct within the flow equations of the model. It can be roughly conceptualized as the average maximum length of overland flow within a subcatchment. It is a single parameter representing two physical attributes: the actual surface width of a subcatchment and the drainage network within the subcatchment (channelized flow that is not modeled in the transport component).	Seed values for this parameter were generated by creating several estimates for the maximum overland sheet flow length for each subcatchment, calculating an average, and then dividing by the area of the subcatchment, a method recommended by James (2011).
N Imperv	The Manning's N for overland flow in the impervious area of the subcatchment	All subcatchments were assigned with a default value of 0.011
N Perv*	The Manning's N for overland flow in the pervious area of the subcatchment	All subcatchments were seeded with a default value of 0.1
Dstore Imperv	The depth of depression storage in inches for the impervious area of the subcatchment	All subcatchments were assigned a default value of 0.05
Dstore Perv	The depth of depression storage in inches for the pervious area of the subcatchment	All subcatchments were assigned a default value of 0.05
Zero Imperv (%)	The percentage of impervious area in the subcatchment that does not have depression storage (i.e. slanted roofs, etc)	All subcatchments were assigned a default value of 25
Soil Drainage Parameters		
Suction Head	A soil characteristic in the Green-Ampt Method	USGS SSURGO
Conductivity*	A soil characteristic in the Green-Ampt Method	USGS SSURGO
Initial Deficit	A soil characteristic in the Green-Ampt Method	USGS SSURGO

* Sensitive parameters adjusted during calibration

be characterized by these parameters. Of particular note are % Impervious, a measure to total impervious area within the subcatchment, and Subarea Routing/% Routed, a set of parameters that allow the model to distinguish directly connected impervious area.

The soil parameters enumerated in Table 5 require additional explanation. There are three possible infiltration schemes in SWMM that regulate how flow moves between the pervious areas of the land surface component and the transport component (and the groundwater component, if implemented): Horton's Equation, the Green-Ampt Method, and the Curve Number Method. Horton's Equation and the Green-Ampt Method are both attractive in that they are based on real physical hypotheses about the relationship between soil parameters and infiltration behavior. However, the Green-Ampt Method requires fewer parameters.

I obtained a polygon data set of soils for the study area from the US Department of Agriculture Natural Resource Conservation Service's Soil Survey Geographic Database (SSURGO). This dataset contained 42 distinct soil types for the county. I reclassified these into 12 more general soil texture classes (Table 6). Typical values for the Green-Ampt parameters for these texture classes are given by Rawls (1982). I then calculated area-weighted average parameters for each subcatchment using the Geospatial Modelling Environment's isectpolypoly command. I further assumed that soils classified as "Urban" in SSURGO implied highly impervious soils similar to clay. The scale of the subcatchments relative to the spatial grain of the SSURGO dataset is much less fine. Thus, the soil parameters I created for SWMM are very crude generalizations of the real physical attributes, and strong candidates for calibration.

Table 6: Simplified Soil Types	
SSURGO Soil Type	Reclassification
Appling sandy loam, 2 to 8 percent slopes	Sandy Loam
Appling sandy loam, 8 to 15 percent slopes	Sandy Loam
Cecil sandy clay loam, 2 to 8 percent slopes, eroded	Sandy Clay Loam
Cecil sandy clay loam, 8 to 15 percent slopes, eroded	Sandy Clay Loam
Cecil-Urban land complex, 2 to 8 percent slopes	Urban
Cecil-Urban land complex, 8 to 15 percent slopes	Urban
Davidson sandy clay loam, 2 to 8 percent slopes	Sandy Clay Loam
Davidson sandy clay loam, 8 to 15 percent slopes	Sandy Clay Loam
Davidson sandy clay loam, 15 to 25 percent slopes	Sandy Clay Loam
Dam	Other
Enon sandy loam, 2 to 8 percent slopes	Sandy Loam
Enon sandy loam, 8 to 15 percent slopes	Sandy Loam
Georgeville silty clay loam, 2 to 8 percent slopes, eroded	Silty Clay Loam
Georgeville silty clay loam, 8 to 15 percent slopes, eroded	Silty Clay Loam
Goldston slaty silt loam, 2 to 8 percent slopes	Silt Loam
Goldston slaty silt loam, 8 to 15 percent slopes	Silt Loam
Helena sandy loam, 2 to 8 percent slopes	Sandy Loam
Helena-Urban land complex, 2 to 8 percent slopes	Urban
Iredell fine sandy loam, 0 to 1 percent slopes	Sandy Loam
Iredell fine sandy loam, 1 to 8 percent slopes	Sandy Loam
Iredell-Urban land complex, 0 to 8 percent slopes	Urban
Lignum gravelly silt loam, 2 to 8 percent slopes	Silt Loam
Mecklenburg fine sandy loam, 2 to 8 percent slopes	Sandy Loam
Mecklenburg fine sandy loam, 8 to 15 percent slopes	Sandy Loam
Mecklenburg-Urban land complex, 2 to 8 percent slopes	Urban
Monacan loam	Loam
Monacan and Arents soils	Other
Pacolet sandy loam, 15 to 25 percent slopes	Sandy Loam
Pacolet sandy loam, 25 to 45 percent slopes	Sandy Loam
Pacolet-Udorthents complex, gullied	Other
Pits	Other
Udorthents, loamy	Other
Udorthents, sanitary landfill	Other
Urban land	Urban
Vance sandy loam, 2 to 8 percent slopes	Sandy Loam
Vance sandy loam, 8 to 15 percent slopes	Sandy Loam
Water	Other
Wilkes loam, 4 to 8 percent slopes	Loam
Wilkes loam, 8 to 15 percent slopes	Loam
Wilkes loam, 15 to 25 percent slopes	Loam
Wilkes loam, 25 to 45 percent slopes	Loam
Wilkes-Urban land complex, 8 to 15 percent slopes	Urban

Within Mecklenburg County, land surface drains into two separate river basins, the Yadkin/Pee Dee River Basin in the eastern part of the county, and the Catawba River in the west. These two basins are divided into 46 major basins, which are used for stream monitoring and the calculation of the county's Stream Use-Support Index (SUSI) scores. The SUSI scores are used for benchmarking in the county's semiannual State of the Environment Report, published by the Land Use and Environmental Services Agency. The 46 major basins are further sub-divided into 122 sub-basins of approximately six square miles each. These sub-basins are used to monitor water quality for the purpose of complying with state and federal Total Maximum Daily Load (TMDL) standards for various water quality constituents. These sub-basins represent the finest grain at which watershed monitoring and planning are conducted within the county. I further bisected nine of these sub-basins so that monitoring sites located within the sub-basin would be located at a sub-basin outlet point, to maximize the usefulness of the model for future water quality evaluation. Thus, the baseline SWMM model as implemented has 131 subcatchments.

The model was calibrated with precipitation and streamflow data from 2005, which is the first year where rainfall data was collected in 15-minute increments in Mecklenburg County. This means that there is a discontinuity built in to the model, since the impervious surface data layer dates to closer to the year 2000, which is also the TRANUS base year. However, there is no alternative to this five-year gap, as fine-timestep precipitation data is logically absolutely critical to accurately modeling a stormwater response. Streamflow data was obtained from CRONOS for six stream gauges in the study area. Figure 13 shows the subcatchments that are upstream of the observed data points. For subcatchments and conduits where observed downstream data was not available, I calibrated the parameters

in synchronicity with the closest neighboring section for which data was available. For example, if increasing the Manning's N of the conduits upstream of conduit C81 by 20% in Figure 13 improved the fit of the model, then I also increased by 20% the Manning's n of the conduits for the un-gauged subcatchments north of that section.

I performed a sensitivity analysis on every parameter that I had some level of uncertainty about, either because the parameter had been seeded with an arbitrary default
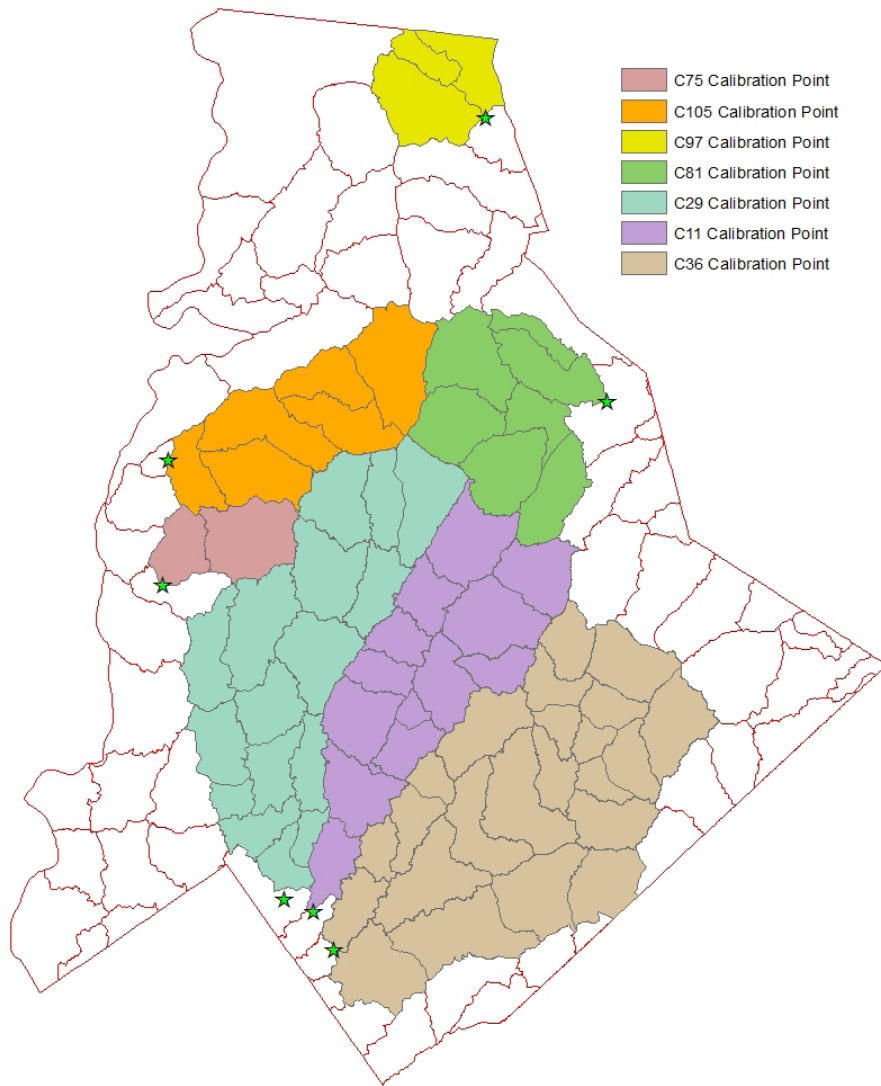
Figure 13: Calibration Locations

value or because the model parameter was an average generalized from data observed at another spatial scale. The model was most sensitive to the characteristic width, Percent Impervious, N Perv, % Routed, and hydraulic conductivity parameters in the land surface component and the Manning's n parameter in the transport component. I was able to calibrate the model making only adjustments to N Perv, % Routed, Hydraulic conductivity, and Manning's N. With the exception of hydraulic conductivity and Manning's N for conduits in the Charlotte portion of the study area, these were the sensitive parameters for which I had no observed data, and thus total uncertainty about the true values of the parameters. In addition, hydraulic conductivity was a strong candidate for calibration for reasons given

Figure 14: Conduit 29 Observed Versus Predicted Flow

previously. Traditionally in SWMM modeling, characteristic width, slope, and % Impervious are all considered good candidates for calibration. However, in the case of this model they were not the most uncertain parameters.

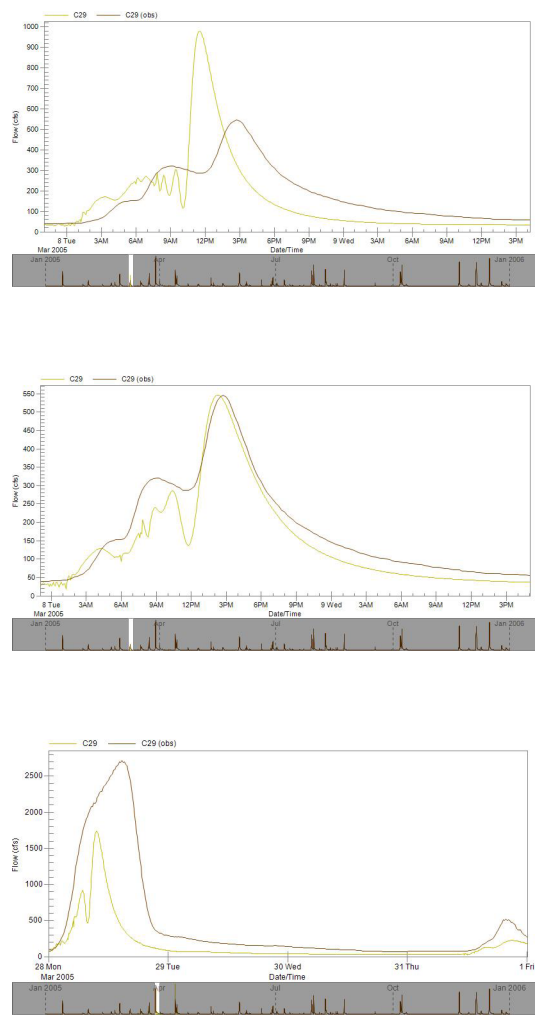The model was calibrated using a 1-year storm (roughly 1 inch of rain over six hours, by Mecklenburg County's standards[2]) that occurred on March 9, 2005. Figure 14 shows the uncalibrated model graphed against the observed data, followed by the calibrated model against the observed data, for Conduit 29, part of Sugar Creek near Pineville, NC south of Charlotte. Table 7 gives the Nash-Sutcliffe model efficiency coefficient for the calibration period at each calibration location. This statistic ranges from negative infinity to 1, with an efficiency of 1 indicating perfect fit, an efficiency of zero indicating that the model predictions are as accurate as the average of the observations, and a negative efficiency indicating that the residual variance is larger than the data variance.

Table 7: Model Calibration and Validation Statistics			
Conduit	Nash-Sutcliffe R^2 Before	Nash-Sutcliffe R^2 After	Nash-Sutcliffe R^2 Validation
29	-0.42	0.89	0.31
11	0.64	0.83	0.53
36	-0.17	0.81	0.69
81	0.31	0.95	0.69
97	-4.27	0.77	0.49
105	-0.07	0.94	0.51

Generally speaking, the results of the baseline model were surprisingly good prior to calibration, and are excellent post-calibration. The first graph in Figure 14 shows the performance of the model prior to calibration. The model, shown in pale green, incorrectly predicts peak flow by a factor of 2. This corresponds to the very poor Nash-Sutcliffe R^2 of -0.42. However, the overall shape of the curve is a plausible hydrograph and simply highlights the importance of calibrating a stormwater model to observed data. The second

graph in Figure 14 shows the model after calibration. The peakiness of the initial model has been addressed through adjustment to parameters within the model that were uncertain to begin with, and the Nash-Sutcliffe R^2 is an impressive 0.89. However, this very strong fit is arguably the result of over-calibration to a specific storm event. In order to be valid, we must evaluate the performance of the model for other, non-calibrated storm events. The third graph in Figure 14 shows this validation. For the large storm event on March 28, the model errs in both the shape and height of the hydrograph, and the model also underestimates the more modest storm event on March 31. This performance is quantified in the lukewarm Nash-Sutcliffe R^2 of 0.31. However, this model performance is still better than average (a Nash-Sutcliffe R^2 of zero). In addition, as Table 7 shows, these are the weakest model results – at all the other calibration locations, the model did better.

The storms that I selected to validate the model occurred on March 28, 2005 and the evening of March 31, 2005, with two dry days in between. The first of these storms was much larger than the calibration storm, while the second was comparable in size. The Nash-Sutcliffe R^2 for the model over this four-day period at these same locations for the uncalibrated storms are also given in Table 7, and the corresponding graph shown in Figure 14. At all six calibration locations, the model performs better than average, but not as particularly well as for the calibration storm. This is largely attributable to the fact that the March 28 storm was very intense, dropping well over three inches of rain in less than six hours. This suggests that the model is valid for 1-year storms, but is not conclusive for larger storm events. This is consistent with Mecklenburg County's design standards for BMPs related to water quality and channel protection (as opposed to flood protection)[2]. Since the

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[2] http://charmeck.org/stormwater/regulations/Pages/BMPStandardsManual.aspx

purpose of this model is, in a sense, to evaluate regional land use management as a water quality BMP, the model is valid for the purpose of testing this project's hypotheses.

From TRANUS to SWMM

The actual TRANUS outputs are the future locations of households and jobs – in other words, residential density and job density. In addition, each TRANUS scenario comes with some transportation network data (which can be expressed as lane miles of road) and each TRANUS zone (representing an area) has a baseline and a future neighborhood type ("ntype"). To further complicate matters, TRANUS has 373 zones corresponding to the block groups in Mecklenburg County, while SWMM has 131 subcatchments. Figure 15 shows the SWMM subcatchments overlayed on top of the TRANUS zones.
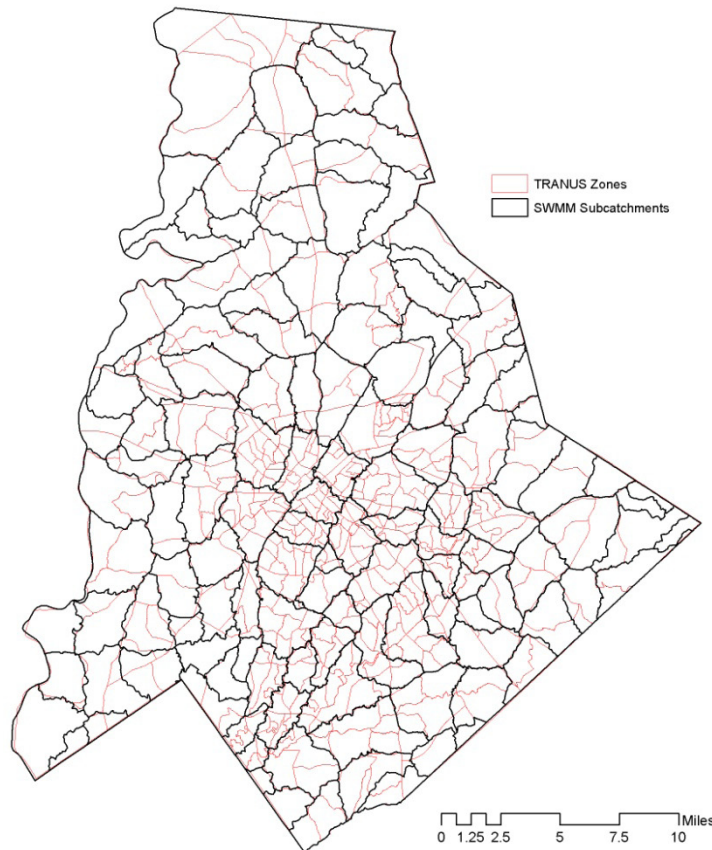

Figure 15: Simulation Model Response Units for TRANUS and SWMM

Impervious surface is the key variable linking the land development outputs of

the TRANUS model with the land surface component of SWMM. I tested the potential

of residential density, job density, lane-mile density, and neighborhood type to predict

imperviousness using an OLS regression with the TRANUS zone as the unit of analysis. This

initial test yielded a model (Model 1) with an adjusted R^2 of 0.54, indicating a potential

predictive relationship between these variables. The full results are presented in Table

8. However, the use of the neighborhood types in the model was problematic for several

reasons. First, the neighborhood type is a categorical variable with eight possible values, and

must be converted into seven dummy variables in order to be used in an OLS regression.

Not surprisingly with such a large number of dummy variables, none of the coefficients

were statistically significant. Second, the model should have included a spatial variable

Table 8: Model 1 OLS Results								
Variable	Coeff.	Std. Err.	t-Statistic	P		Robust SE	Robust t-Statistic	Robust P	VIF[1]
Intercept	6.89	7.18	0.96	0.34		5.21	1.32	0.19	--------
RESDENS	1.06	0.24	4.45	0.00 *	0.39	2.72	0.01 *	1.19
JOBDENS	0.30	0.05	5.49	0.00 *	0.13	2.31	0.02 *	1.47
NTYPE2	6.22	6.85	0.91	0.36		4.75	1.31	0.19	77.88
NTYPE3	8.19	7.00	1.17	0.24		4.99	1.64	0.10	86.16
NTYPE4	5.31	7.07	0.75	0.45		5.15	1.03	0.30	94.49
NTYPE5	3.09	7.23	0.43	0.67		5.13	0.60	0.55	23.11
NTYPE6	1.41	7.19	0.20	0.85		5.19	0.27	0.79	34.98
NTYPE7	-5.01	7.39	-0.68	0.50		5.17	-0.97	0.33	14.29
NTYPE8	5.96	7.19	0.83	0.41		5.38	1.11	0.27	20.57
LMDENS	0.03	0.00	6.59	0.00 *	0.01	5.53	0.00 *	2.73
Number of Observations:			373	Akaike's Information Criterion (AICc):				2455.61
Multiple R-Squared:			0.55	Adjusted R-Squared:				0.54
Joint F-Statistic:			44.76	Prob(>F), (10,362) deg. of freedom:				0.00 *
Joint Wald Statistic:			20666.01	Prob(chi-squared), (10) deg. of freedom:				0.00 *
Koenker (BP) Statistic:			41.52	Prob(chi-squared), (10) deg. of freedom:				0.00 *
Jarque-Bera Statistic:			49.46	Prob(chi-squared), (2) deg. of freedom:				0.00 *

* Statistically significant at the p < 0.05 level

to control for spatial autocorrelation. However, both median distance to the CBD and a CBD dummy variable were part of the factor analysis that generated the neighborhood types, so including such a variable would have introduced multicolinearity to the model. In fact, residential density, employment density, and road density were all also included in the factor analysis that generated the neighborhood types, which also introduces multicolinearity to the model, a third reason why including the neighborhood types in this model was undesirable. Finally, since the neighborhood types are categorical, in order to use them the unit of analysis must be the TRANUS zone. However, the purpose of fitting this model is to create SWMM parameters, which must be by subcatchment.

Assuming that population and employment were uniformly distributed within each zone, I generated household and employment densities for each SWMM subcatchment using an area-weighted sum. I directly calculated road density in ArcView using the roadway links from the TRANUS network, and discarding conceptual links such as the centroid connectors. I then re-fitted the OLS regression, after I replaced the neighborhood types with a continuous centroid-distance-to-CBD variable to account for spatial autocorrelation. This new model (Model 2) had an adjusted R^2 of 0.70. The results of this regression are shown in Table 9, along with some diagnostic statistics. The coefficients were all of the expected sign, and all were statistically significant at the $p < 0.05$ level, except for employment density. The variance inflation factors for all variables were well within the acceptable range. Both a visual inspection of the scatterplot and the statistically significant Jarque-Bera test suggested that the model was highly heteroskedastic, indicating bias in the standard errors. However, this does not affect the estimates of the relationship between the predictor variables and the outcome variable.

Table 9 : Model 2 OLS Results									
Variable	Coeff.	Std. Err.	t-Statistic	P		Robust SE	Robust t-Statistic	Robust P		VIF[1]
Intercept	9.57	2.40	3.98	0.00	*	3.04	3.15	0.00	*	--------
RESDENS	0.05	0.01	5.62	0.00	*	0.01	5.20	0.00	*	1.98
JOBDENS	0.00	0.00	0.01	0.99		0.00	0.01	0.99		3.99
LMDENS	0.08	0.02	3.55	0.00	*	0.02	3.14	0.00	*	5.83
DIST2CBD	0.00	0.00	-2.44	0.02	*	0.00	-2.11	0.04	*	2.57
Number of Observations:			131	Akaike's Information Criterion (AICc):						787.63
Multiple R-Squared:			0.71	Adjusted R-Squared:						0.70
Joint F-Statistic:			78.62	Prob(>F), (10,362) deg. of freedom:						0.00 *
Joint Wald Statistic:			527.23	Prob(chi-squared), (10) deg. of freedom:						0.00 *
Koenker (BP) Statistic:			9.01	Prob(chi-squared), (10) deg. of freedom:						0.06
Jarque-Bera Statistic:			56.74	Prob(chi-squared), (2) deg. of freedom:						0.00 *

* Statistically significant at the p < 0.05 level

One potential source of bias in Model 2, however, is the assumption that the relationship between the independent variables and the outcome variable is linear. A visual inspection of the scatterplots shows mixed results for each variable. Figure 16, plotting subcatchments by impervious ratio (Y axis) and residential density (X axis), suggests a linear relationship, though there are also a few outliers. Figure 17, with impervious ratio on the Y axis and employment density on the X axis, is more open to interpretation. The spatial distribution of employment, namely the highly centralized employment in the central business district, means that the relationship between imperviousness and employment density is either nonlinear, or the relationship has different linear characteristics in different places. This may also explain why employment density was not statistically significant in Model 2. In Figure 18, road density and the impervious ratio once again show a clear linear relationship.
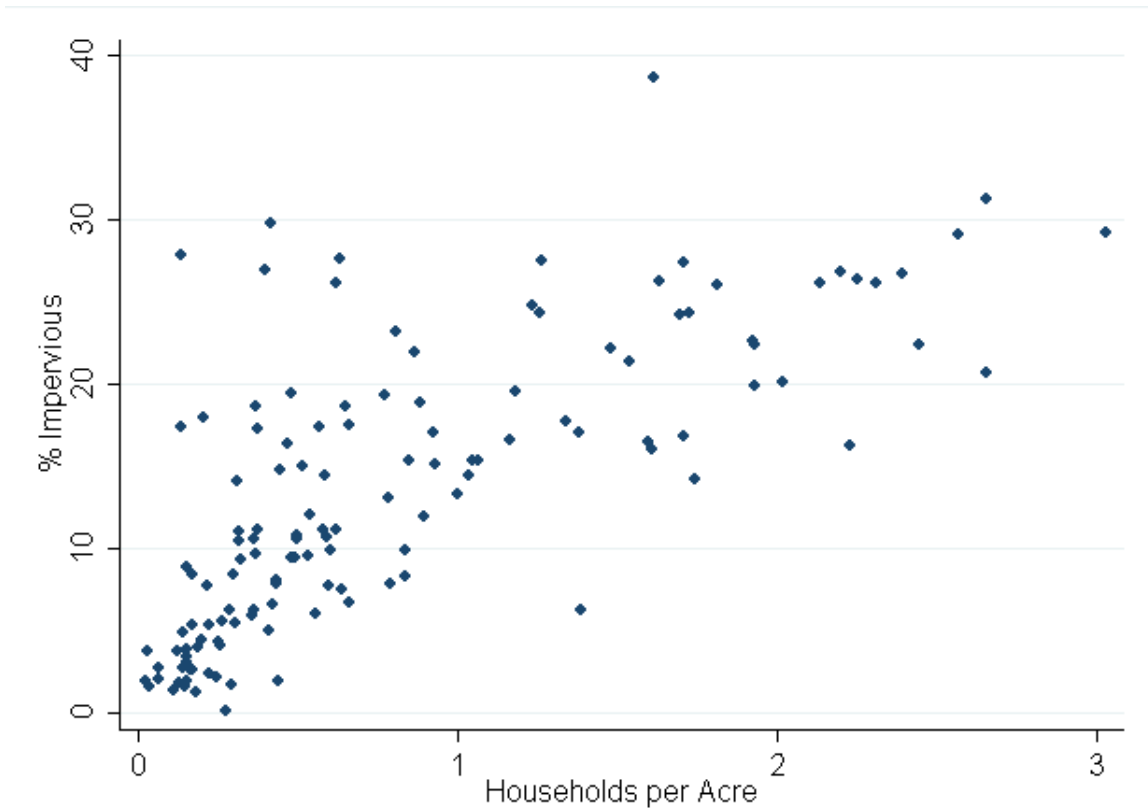
Figure 16: Scatterplot of Impervious Ratio and Residential Density by Subcatchment
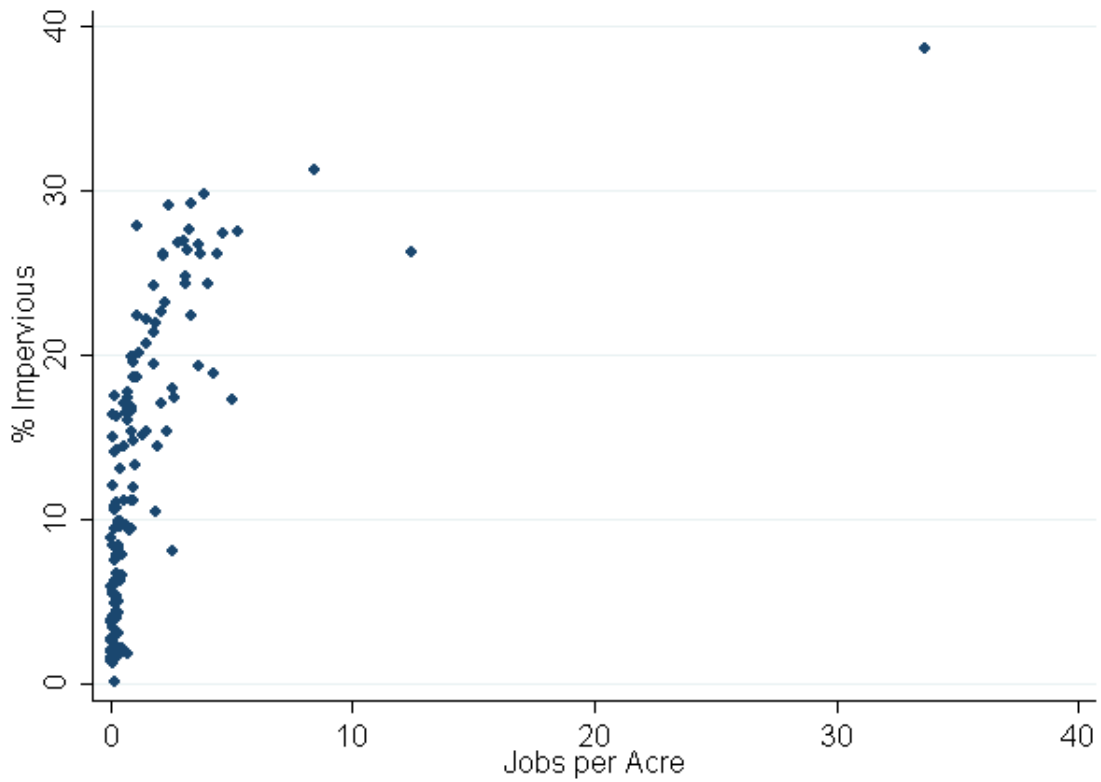

Figure 17: Scatterplot of Impervious Ratio and Employment Density by Subcatchment
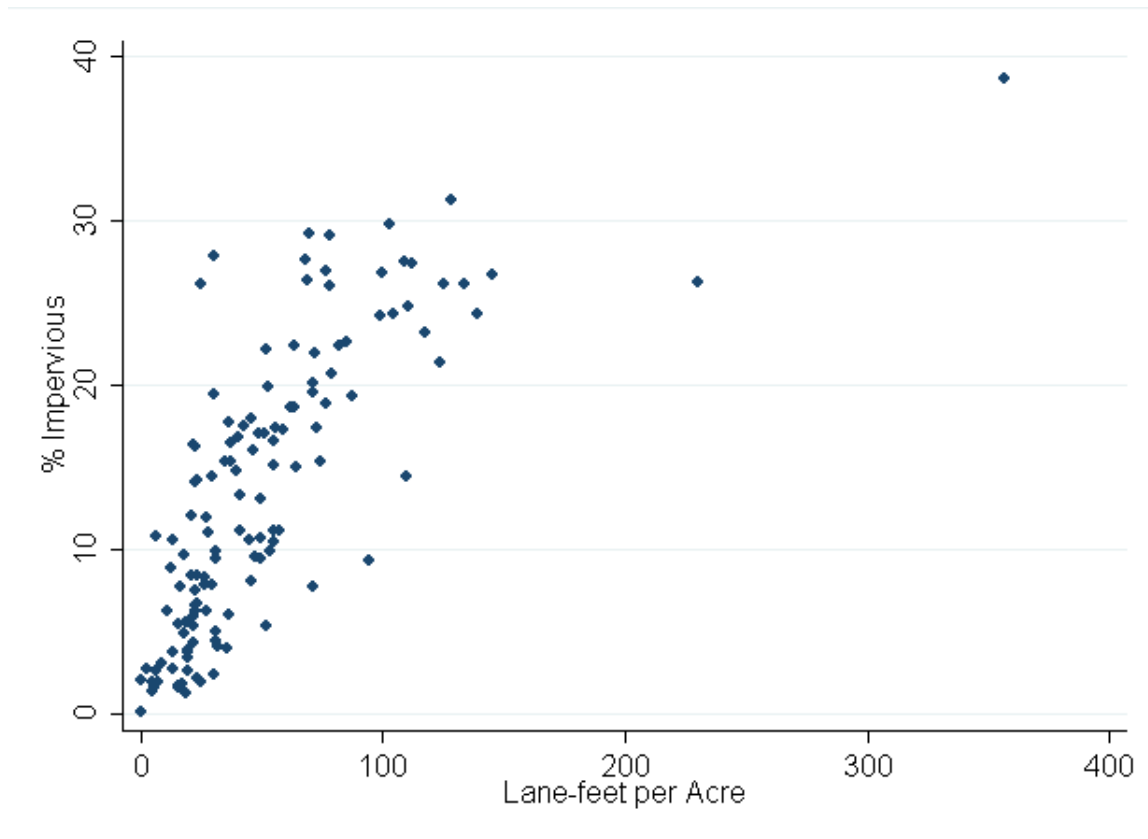
Figure 18: Scatterplot of Impervious Ratio and Road Density by Subcatchment

To investigate the possibility that the relationship between employment density and imperviousness is simply nonlinear, I re-fitted Model 2 with the addition of a quadratic power transformation for employment density. The results are presented in Table 10. As in Model 2, the coefficients are of the expected sign. The adjusted R^2 of Model 3 is 0.74, a slight improvement over Model 2. The lower value for Akaike's Information Criterion also suggests that Model 3 is a better fit for the data than Model 2. In Model 3, both employment density and its quadratic term are significant, while the spatial variable measuring distance to the central business district is now insignificant. This change from Model 2 suggests that the addition of the quadratic term is not expressing a nonlinear relationship between employment density and imperviousness, but rather controlling for the different relationship between the two variables in different spatial locations. Not

Table 10: Model 3 OLS Results									
Variable	Coeff.	Std. Err.	t-Statistic	P		Robust SE	Robust t-Statistic	Robust P	VIF[1]
Intercept	7.401	2.30	3.21	0.00	*	3.10	2.39	0.02 *	--------
RESDENS	0.04	0.01	5.54	0.00	*	0.01	5.07	0.00 *	2.00
JOBDENS	0.02	0.00	3.86	0.00	*	0.01	2.73	0.01 *	17.99
LMDENS	0.05	0.02	2.29	0.02	*	0.02	2.09	0.04 *	6.43
DIST2CBD	0.00	0.00	-1.43	0.16		0.00	-1.16	0.25	2.74
JOBD2	0.00	0.00	-4.37	0.00	*	0.00	-2.90	0.00 *	9.61
Number of Observations:			131	Akaike's Information Criterion (AICc):					771.23
Multiple R-Squared:			0.75	Adjusted R-Squared:					0.74
Joint F-Statistic:			75.76	Prob(>F), (5,125) deg. of freedom:					0.00 *
Joint Wald Statistic:			505.12	Prob(chi-squared), (5) deg. of freedom:					0.00 *
Koenker (BP) Statistic:			22.43	Prob(chi-squared), (5) deg. of freedom:					0.00 *
Jarque-Bera Statistic:			49.37	Prob(chi-squared), (2) deg. of freedom:					0.00 *

* Statistically significant at the $p < 0.05$ level

surprisingly, the quadratic term also introduces multicolinearity to the model, as shown by the high variance inflation factors for the two terms.

In both Models 2 and 3, the Koenker test, an OLS diagnostic statistic that tests for non-stationary relationships between the dependent variable and the independent variables, was significant at the $p < 0.1$ level. This suggests that the model's results could have been improved by moving to a geographically weighted regression (GWR). A GWR fits a unique regression equation for each observation in the dataset. Each of these equations has an intercept, the explanatory variables, and an error term. However, when fitting the equation, a GWR uses only the dependent and explanatory variables within a certain bandwidth of the current observation. This approach allows for the explanatory variables to have varying impacts on the dependent variable depending on where they are in space. For example, I might hypothesize that employment density is a really strong predictor of imperviousness in downtown Charlotte, because much of the commercial development in

that area took place at a particular time when road, building, and parking standards were a certain way. However, we might expect employment density to have a different coefficient in downtown Mint Hill, where more recent commercial development has occurred since the county or municipality modernized design standards. It is particularly important to control for spatial autocorrelation in such a model, because it is vulnerable to extreme local multicolinearity.

Diagnostics of a GWR of imperviousness with residential density, employment density, road density, and distance to the CBD as the explanatory variables are presented in Table 11. This is Model 2 fitted as a GWR. The regression was run using the ESRI ArcToolbox

Table 11: Geographically Weighted Regression	
Neighbors	53
ResidualSquares	1506.85
EffectiveNumber	27.27
Sigma	3.81
AICc	745.62
R2	0.85
R2Adjusted	0.81

with an adaptive kernel that optimized the bandwidth based on Akaike's Information Criterion. The improved AICc from Models 2 and 3 indicates that the GWR is a better fit. As an additional regression diagnostic, I calculated Moran's I for the residuals. The Moran's I of 0.05 had a z-score of 0.94 and a p-value of 0.35, consistent with the null hypothesis that the spatial pattern of the residuals was not statistically significant from random. A spatial pattern in the residuals would have been a sign that the model was mis-specified.

I used the unique regression equations generated by the GWR to calculate out-of-sample predictions of imperviousness for the two future scenarios. The average difference in predicted imperviousness by subcatchment was only 0.1%, indicating that the two

scenarios are similar. This is not surprising given that the two scenarios accommodate

the same amount of future growth and have similar transport networks. However, the

standard deviation of difference in predicted imperviousness was 7.17, and the minimum

and maximum differences were -20% and 22%, respectively. Clearly there are some

subcatchments that differ between the two scenarios. Figure 19 shows the predicted

imperviousness of each scenario with the major planning basins outlined. While some

basins are identical under the two scenarios, others are clearly different.

I created a SWMM model for each scenario with parameters identical to the baseline

SWMM model, except for the % Impervious parameter in the land surface component, for

which I substituted the predicted values. In both scenarios, about 20% of the total land
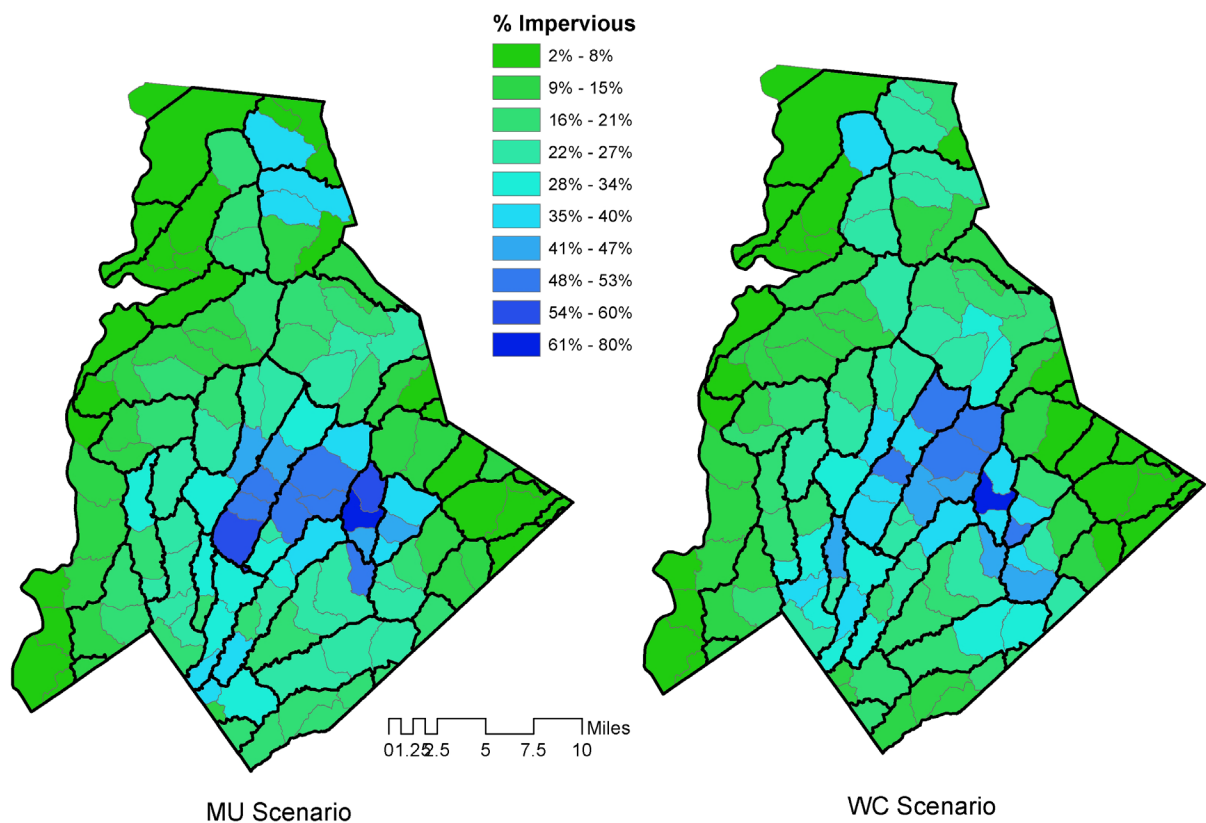

Figure 19: Impervious Ratio Predictions by Scenario

surface within the study area is impervious – only the spatial distribution of imperviousness differs. This is not surprising, because both scenarios accommodate the same total amount of residential and commercial growth, and these were two of the predictive variables in the GWR to estimate future imperviousness. This method of predicting future imperviousness has a significant limitation in that it inherently assumes that the relationship between density and imperviousness in the future will be the same as it was at the baseline time. However, there is little basis to assert in what way this relationship might change in the future.

Some of this similarity between scenarios is an expected outcome of the research design. Placing emphasis on the plausibility of the scenarios means exploring a relatively confined portion of the scenario space. While there is great uncertainty about what will happen in the future, it is inevitable that it will be somewhat like the past, given the legacy of existing population and infrastructure. Sharing the same, known, past introduces some level of similarity between all plausible future scenarios. It is a validation of the research design and the contribution of this research that the integrated land use-transportation model, in concert with the method for forecasting imperviousness, were able to create distinct scenarios within the fairly narrow portion of the scenario space that can be safely considered plausible. Some of these similarity is not expected, however, and will be discussed in Chapter 5.

CHAPTER 5

RESULTS

Intermediate results of the modeling effort to convert TRANUS output into SWMM input are reported in Chapter 4. These consist of the geographically weighted ordinary least squares regression used to relate baseline residential density, employment density, and road density to imperviousness and the resulting out-of-sample predictions for the two future scenarios. While these impervious surface predictions are results, they are also part of the method used to build the SWMM models representing the two scenarios. Thus, only the SWMM model output results are presented in this chapter.

The spatial pattern of changes in runoff volumes is shown in Figure 20. These changes are also reported in tabular format in Table 12. These results are reported only at the major basin level for two reasons – accessibility and congruency with local planning practice. Regarding accessibility, a table reporting results of for all subcatchments would have 131 rows, analogous to trying to look at a blizzard by viewing individual snowflakes. Summarizing results at the major basin scale eases access to the numbers. Additionally, the major basins are the unit of analysis used for planning purposes in the county, with the sub-basins/subcatchments used for data collection and modeling purposes. This analysis mirrors that approach.

Overall, both scenarios result in a 42% increase in total runoff volumes. However, the spatial pattern of the runoff increases does substantially differ between the two scenarios.
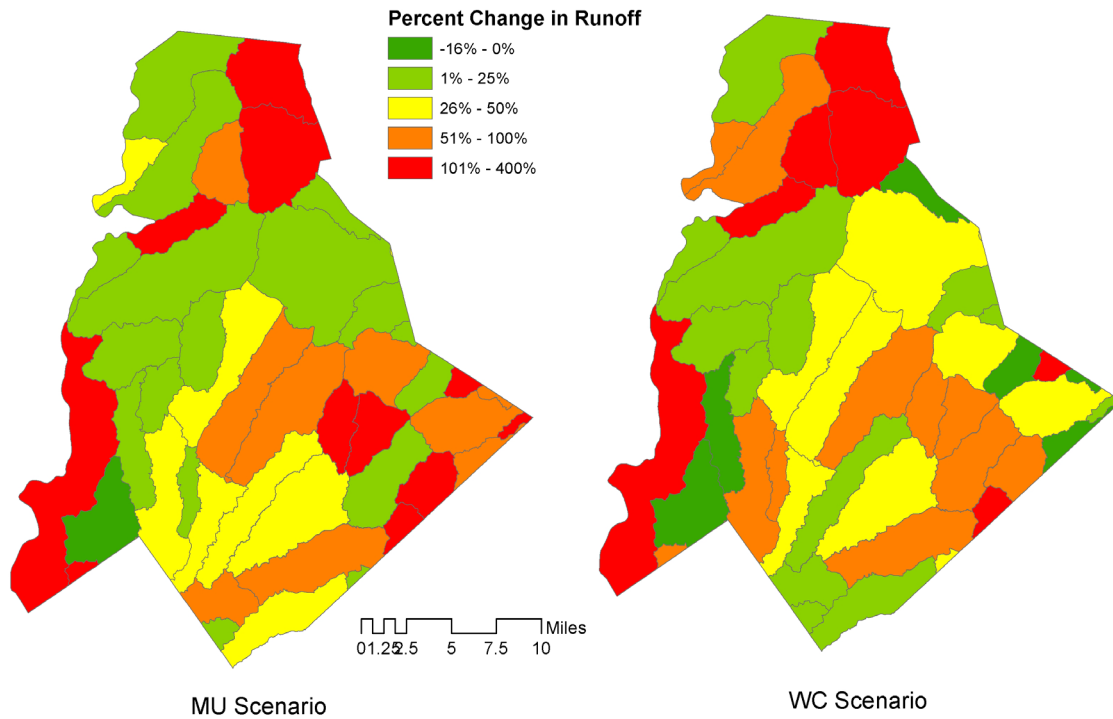
Figure 20: Percent Change in Runoff by Major Basin for Two Scenarios

Out of 46 major basins, the difference in runoff change between the two scenarios was less than 5% for nine basins. For these basins, the tradeoff between scenarios is neutral. Of the remaining basins, however, 25 experienced more runoff under the MU scenario as opposed to 12 under the WC scenario. This is because the WC scenario concentrates the increase in stormwater runoff in three basins in particular: Minor Basin 7, Rocky River West Branch, and Gar Creek. In effect, the WC scenario treats these basins as sacrifice zones, while the MU scenario spreads smaller increases in stormwater runoff around more basins.

This study found equivalent per-capita runoff between the two alternative scenarios, with only the spatial pattern of stormwater runoff varying. This finding departs from previous research including Richards (2002), Greenberg et. al.(2003), and Jacob and Lopez (2009), all of which were based on models that assumed that high-density scenarios

Table 12: Changes in Runoff Volume by Basin						
	MU	WC			MU	WC
Minor Basin 1	5.4%	-0.8%	UPPER IRWIN CREEK		36.9%	35.4%
Minor Basin 2	26.1%	32.4%	COFFEY CREEK		8.5%	-3.3%
Minor Basin 3	21.2%	5.2%	STEELE CREEK		-10.2%	-16.5%
CALDWELL	356.5%	172.4%	SUGAR CREEK		32.2%	64.3%
Minor Basin 4	92.2%	-0.7%	KINGS BRANCH		14.3%	62.1%
Minor Basin 5	130.8%	9.6%	UPPER LITTLE SUGAR CREEK		60.4%	45.5%
Minor Basin 6	96.1%	-0.7%	LOWER LITTLE SUGAR CREEK		33.0%	37.0%
Minor Basin 7	136.1%	243.6%	BRIAR CREEK		97.0%	99.1%
Minor Basin 8	125.7%	92.4%	CAMPBELL CREEK		135.3%	86.4%
Minor Basin 9	4.4%	26.2%	UPPER MC ALPINE CREEK		132.1%	83.9%
Minor Basin 10	21.8%	5.3%	MID MC ALPINE CREEK		46.7%	26.2%
MCMULLEN	42.9%	23.8%	FOUR MILE CREEK		52.8%	69.1%
LAKE NORMAN	23.6%	11.6%	SIX MILE CREEK		29.5%	6.9%
ROCKY RIVER WEST BRANCH	209.2%	257.1%	IRVINS CREEK		17.1%	69.2%
CLARKE CREEK	210.5%	157.2%	LOWER MC ALPINE CREEK		53.9%	1.8%
MALLARD CREEK	21.4%	39.7%	TAGGART CREEK		7.1%	3.6%
BACK CREEK	15.8%	17.9%	MC DOWELL		4.7%	63.5%
REEDY CREEK	73.5%	42.8%	GAR CREEK		182.3%	372.0%
MC KEE CREEK	21.3%	-1.0%	LONG CREEK		17.0%	20.4%
CLEAR CREEK	83.7%	27.8%	PAW CREEK		5.6%	7.1%
STEVENS CREEK	113.2%	66.4%	UPPER MTN ISLAND LAKE		48.3%	52.2%
TORRENCE CREEK	52.8%	127.0%	LOWER MTN ISLAND / UPPER WYLIE		20.9%	5.8%
STEWART CREEK	12.7%	8.2%	LAKE WYLIE		156.2%	137.9%

reduced per-capita imperviousness, and thus per-capita runoff. This new and divergent finding is the result of increased model sophistication. This study departs from previous research in that imperviousness was modeled as a function constructed with observed data, rather than given (set by the modeler based on assumptions). In addition, all three previous studies considered only residential density, while this study applies a multivariate model including residential density, employment density, and road density, and accounts for regional location.

One important caveat to note is that the model predicts reductions (i.e. negative changes) in stormwater volume in six basins under the WC scenario and one basin under

the MU scenario. This is a result of the fact that future imperviousness is based on current

land consumption (e.g. density) rather than historical maximums of land consumption. Thus,

if a zone in 2050 has a lower residential or employment density due to the relocation of

households or firms, then the model will likely predict a lower imperviousness for that zone.

In reality, impervious surface once created does not simply disappear. Therefore, the model

is underestimating the real total imperviousness to some extent.

In stormwater management, planners are interested not just in volumes but in

peak flows. This is because increased peak flow volumes and velocities degrade stream

channel structure, causing erosion, sedimentation, and destroying riparian habitat. Table 13

reports descriptive statistics for the percent change in peak flow from the baseline for each

scenario by subcatchment. The MU scenario's median increase in peak flow is 10% higher

than the WC scenario, suggesting that while the MU scenario spreads around the increased

stormwater runoff volume, it does not do so enough to prevent substantial increases in peak

flow.

The spatial distribution of changes in peak flow is shown in Figure 21. This map

visualizes the tradeoffs between the two scenarios. In the WC scenario, the extension

of transit to the northern part of the county and the promotion of transit-oriented

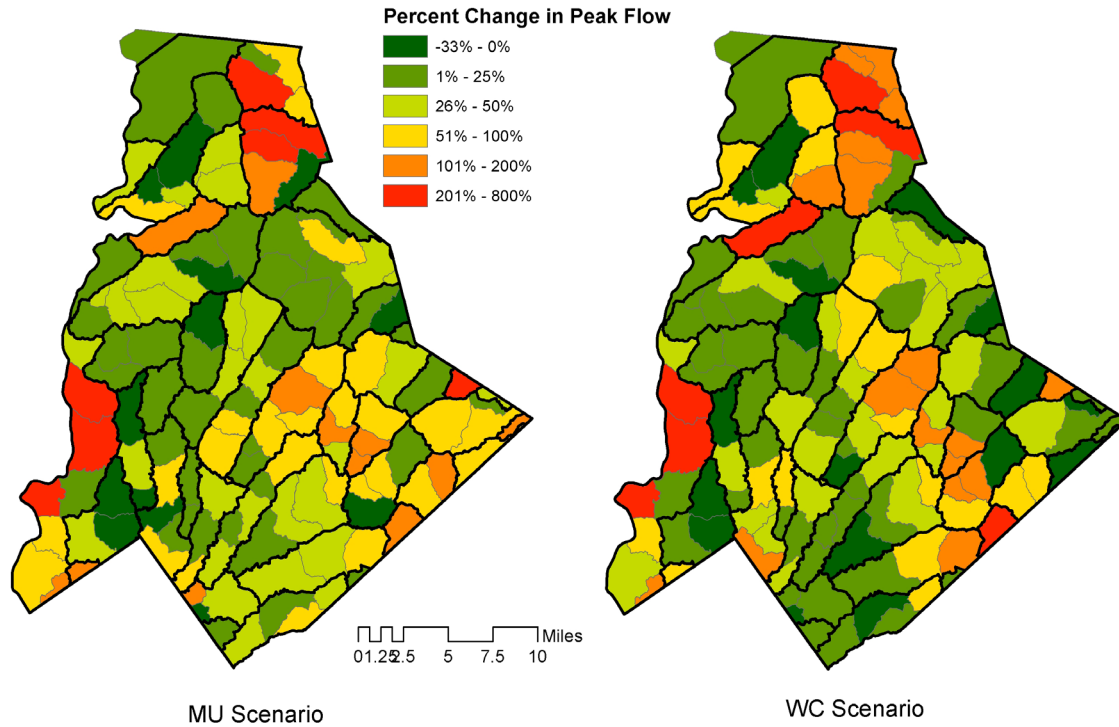| Table 13: Descriptive Statistics of Subcatchment Peak Flow Changes from Baseline		
	MU	WC
Count	131	131
Average	62%	56%
Minimum	-33%	-29%
Maximum	798%	562%
Median	37%	27%
Std. Dev.	105%	90%

Figure 21: Percent Change in Peak Flow by Subcatchment for Two Scenarios

development along the corridor intensified development in the area, resulting in peak

flow increases of more than 50% in many subcatchments. The MU scenario, on the other

hand, anticipates continued growth in the southern part of the county on the border

with adjacent and rapidly urbanizing Union County. Visualizing these tradeoffs makes the

stormwater management impacts of the two scenarios spatially explicit. This information

could potentially be used in a variety of ways: to refine the scenarios, to plan mitigation, or

to select an alternative.

Table 13 summarizes peak flow by scenario, while Figure 21 shows peak flow results

at their finest resolution, the subcatchment level. Table 14 combined with Figure 22 present

peak flow results through another spatial lens in order to further explore the spatial pattern

of peak flow changes. While Table 13 showed that the overall median increase in peak flow
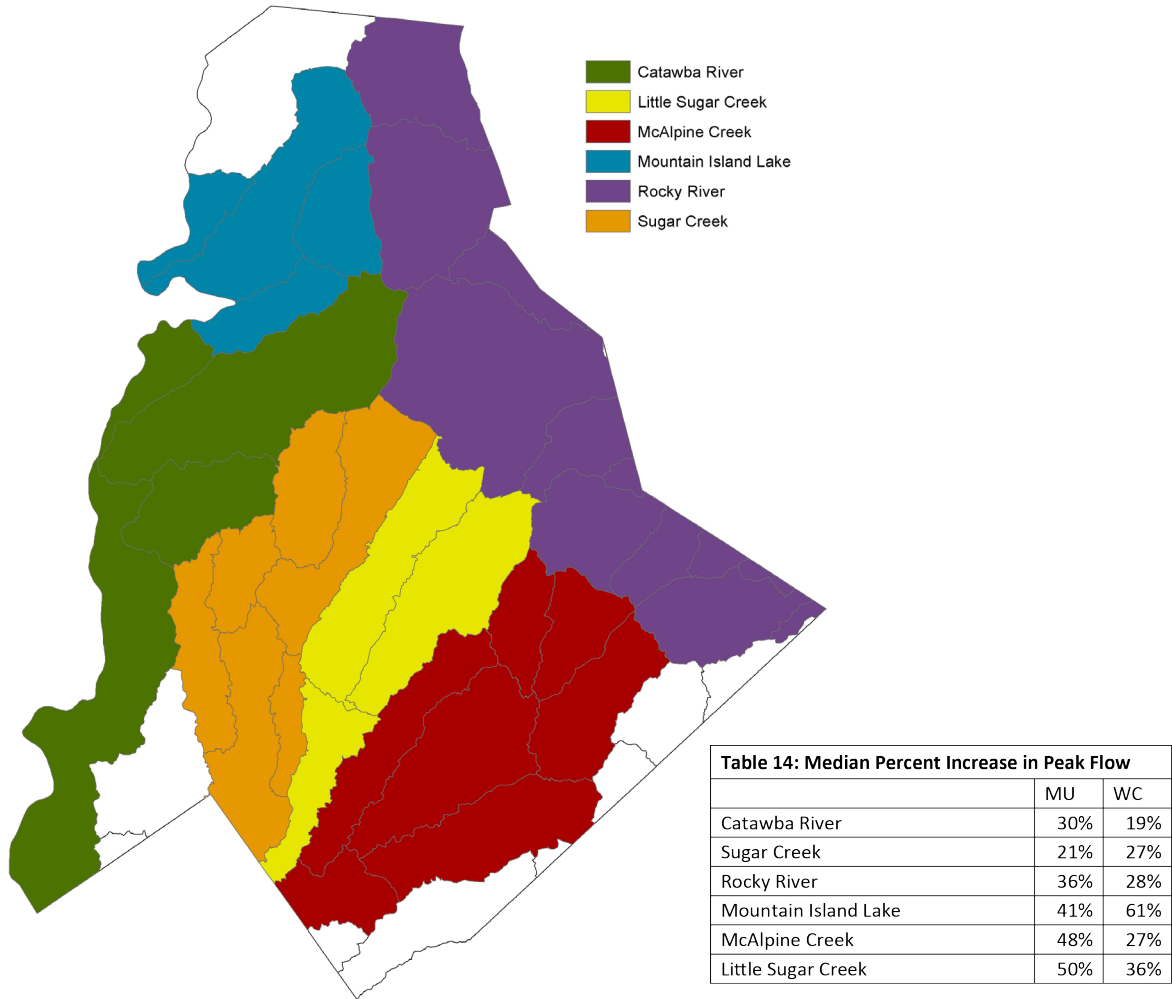
97

Table 14: Median Percent Increase in Peak Flow

	MU	WC
Catawba River	30%	19%
Sugar Creek	21%	27%
Rocky River	36%	28%
Mountain Island Lake	41%	61%
McAlpine Creek	48%	27%
Little Sugar Creek	50%	36%

Figure 22:   Major Catchments of Mecklenburg County

for the MC scenario was 10% higher than for the WC scenario, at the catchment level shown

in Figure 22 the results are more complex. One scenario is not simply superior to another.

Rather, there are comparative advantages to each alternative. The results also indicate that

there are areas that the simulation suggests will be seriously negatively impacted by both

alternatives, most notably the catchment area north of Mountain Island Lake, the drinking

water reservoir of Charlotte. Strategically speaking, if multiple plausible development

alternatives point to impairment within a particular area, this finding supports the case for

intervention in that area irregardless of other possible choices.

These results suggest that if stormwater management considerations were a part of regional transportation planning processes, it would be possible to achieve some watershed protection goals, such as greater protection for particular streams, through integrated land use and transportation planning. However, greater protection for particular streams would come at the expense of other streams, by displacing development to other nearby locations. These results are consistent with the conceptual framework advocated by Niesenson (2005).

The concentration of runoff increases within three major basins in the WC scenario confirms the principle that increased density in some areas will allow the preservation of other areas. However, these results are not sufficient to determine if the watershed benefit derived from protecting these basins is greater than the watershed harm done to the basins in which runoff volumes are drastically increased. In order for watershed-scale densification to be effective as a BMP, a connection between effects and drivers in the conceptual model of planning and development shown in Figure 5 would need to exist. In other words, watershed health must be considered as a variable when land use planning decisions like zoning and transportation planning decisions like long-range infrastructure investments are made. Depending on the goals of the region, different basins may be of differing priority in order to protect, and at different levels of protection.

For example, Charlotte-Mecklenburg Storm Water Services (SWS) identified the McDowell Creek basin as a major priority for protection, because this basin flows directly into the primary reservoir that provides drinking water to the region. This basin is within the jurisdictions of Huntersville and Cornelius, though the city of Charlotte depends on it as well. In 2006, SWS created a watershed management plan[3] for this basin in collaboration

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[3] http://charmeck.org/stormwater/Projects/Pages/McDowellCreek.aspx

with the two municipalities, the county parks department, and a variety of state partners

with interests in land, resources, and transportation. This is a basin that would be desirable

to protect in a scenario that sheltered some areas from development while intensifying

development in others using watershed-scale densification. However, as Table 12 shows,

the McDowell Creek basin experiences a 63.5% increase in runoff under the WC scenario,

and only a 4.7% increase in runoff under the MU scenario. Therefore, while the WC scenario

protected more basins, it did not protect the most important basins.

Limitations

The findings of this research have several key limitations. First, the method used

to connect TRANUS output to SWMM inputs has several methodological limitations. By

posing imperviousness as a function of several densities, the model underestimates future

imperviousness. A more accurate model would render imperviousness as a function of

historical maximum densities. In addition, the use of baseline data to parameterize the

model and make out-of-sample predictions for the outcome variable based on 'future'

values for the independent variables means that the relationship between the independent

and dependent variables is held constant through time. This limits the alternatives that can

be explored through this methodology.

The complexity of the computer simulations applied in this project is matched

by the gross simplifications of reality that are inherent in building a model. While the

general principle is that the model should represent in detail the key signals and abstract

away only the noise, in practice the demands of the models required compromises. These

compromises were undertaken with deliberation and rigor, but nonetheless they limit the

significance that should be ascribed to the model output. The simulation results are not

accompanied by an estimate of confidence in their precision. Therefore, the results are most

useful and appropriate for relating one scenario alternative to another, not as predictions of

the outcome of one scenario.

The SWMM implementation can be described as 'basic' in many ways. Groundwater

dynamics are not modeled, nor are BMPs (though many jurisdictions within the study area

do have ordinances mandating BMPs for new construction). The current model is valid only

for 1-year storms.

CHAPTER 6

CONCLUSION

Water is essential to life. In many parts of the United States, drinking water comes from surface water bodies such as rivers and lakes. Water is part of a cycle, continuously exchanging between the surface, atmosphere, and underground through natural hydrological processes. For example, water moves from the air to the ground through precipitation. When it rains, stormwater falls on the surface and takes one of two paths: infiltration into groundwater, or runoff into surface waters. As the human population has urbanized over time, changing land use patterns have disrupted this natural process. Increasing impervious surfaces increase the amount of stormwater that is mobilized as runoff, and accumulated pollutants on those surfaces are transported into the surface water system, potentially contaminating drinking water stocks.

In the United States today, the Environmental Protection Agency has identified nonpoint source pollution from stormwater runoff as the top threat to water quality nationwide. Engineered substitutes for the natural hydrological processes that manage stormwater and make water potable are expensive. Growing awareness of these costs has increased interest in understanding the relationship between urban development and water quality. For example, one recent study found that a 30% improvement in water quality over a 30 year period in the Neuse River basin in North Carolina would save between $2.7 million and $16.6 million in water treatment costs (Elsin et. al. 2010). Understanding these natural

hydrological processes as ecosystem services has drawn the attention of planners and communities concerned about water security and environmental quality.

The goal of this research was to test the hypothesis that alternative regional urban forms can significantly influence water quality outcomes. Previous research exploring the relationship between urban form and water quality has established impervious surface area as a key measure of urban form. Research exploring the drivers of impervious surface has focused on residential density. Several studies have gone so far as to apply computer simulations of hydrology to simple alternative development scenarios. This project built on this previous research by combining plan-based scenarios with an integrated land use-transportation model and hydrological simulation to trace a complete conceptual model relating drivers of urban pattern to water quality.

This research exploited data and advanced models to address several key conceptual and methodological gaps in the literature: plan-based scenarios that illustrate plausible policy alternatives; a multi-faceted approach to density through multiple measures and scales; leveraging a sophisticated land use-transportation model to explicitly simulate the connection between policy drivers and measured urban form; and distinguishing between total impervious area and directly connected impervious area in an innovative application of a hydrology/hydraulics stormwater model.

This results of this project offer quantitative evidence that regional growth management strategies can play a role in watershed protection by influencing the spatial pattern of stormwater runoff over time. The model did not show any difference between scenarios in terms of overall stormwater runoff volumes. However, a scenario inspired by a

"wedges and corridors"-style regional densification strategy did concentrate runoff volume increases in a smaller number of subcatchments, while a scenario representing a "surprise-free" development trend produced smaller increases on average in a greater number of subcatchments. There was a clear difference between the two scenarios with regards to peak flow volumes. Median peak flow by subcatchment was 10% higher in the MU scenario. However, the MU scenario did protect a key basin that was a priority from a watershed management perspective.

Implications for Planners

The WC scenario intensified development in Huntersville and Cornelius because this scenario included a commuter rail extension from the city of Charlotte to the northern part of the county, where these two municipalities and the McDowell Creek basin are located. Zones within this basin were designated as "High TOD" and land supply for employment and housing were both greatly increased under a regional densification strategy. This occurred because regional watershed goals were not a part of the WC scenario development process. Generally speaking, the regional agencies that are responsible for watershed management and transportation planning, Charlotte-Mecklenburg SWS and the Union-Mecklenburg MPO, do not share staff. While Huntersville and Cornelius are voting members of the MPO, it is not necessarily the same people who represent the municipalities in both contexts, and there is no requirement that one agency coordinate with another's planning efforts.

This paradoxical outcome of the WC scenario is typical of parallel and competing planning processes. In the context of this region, municipalities and planners have multiple goals at different scales which are sometimes in conflict. No model, no matter

how sophisticated, will ever be able to fully quantify the tradeoff between promoting the co-location of employment and housing in secondary regional centers like Huntersville, which would reduce stress on the transportation network, and protecting the McDowell Creek basin from development. Achieving full transparency about these tradeoffs is particularly fraught because the costs and benefits inherent in these competing goals are not experienced at the same spatial scale, or by the same localities or classes of people. To point, it is interesting to note that the MU scenario produced a good outcome for the McDowell Creek basin. This scenario was based on the MPO's long-range transportation plan, which covers the entire study area region, while the WC scenario was inspired by a plan focused on the City of Charlotte.

Regions can achieve consensus about key goals and attempt to minimize conflict between goals. The WC scenario could be adjusted to achieve a better balance between development and preservation in the McDowell Creek basin. Alternatively, the importance of site design and incorporating BMPs as part of land development is emphasized by this finding. If the preferred scenario indicates that major development will be facilitated through policy in this basin, then these policies should at a minimum be accompanied by state-of-the-art design standards that mandate the use of low impact design strategies. In addition, with new development comes new tax revenue, and there are a number of taxing possibilities that could be used to generate dedicated revenue to SWS to implement the infrastructure improvements called for in the basin's watershed management plan. What is gained through a simulation effort like this project is the quantification and spatial distribution of the expected impact of a development scenario on this basin, which is a tool for affected municipalities and the utility to identify and explain rational policy changes.

Beyond McDowell Creek, the substantial variation in the spatial pattern of stormwater runoff between the two scenarios suggests that there is significant value in evaluating regional planning proposals using such a simulation. This evaluation process could help refine particular scenarios, or serve as a decision support tool when choosing between alternatives. Within one scenario, knowing the spatial pattern of potential runoff increases can identify target areas for increased mitigation and other policy interventions. The simulation provides an evidence-based platform to bring together citizens, municipalities, utilities, and planners in the search for better outcomes for a developing watershed.

While water advocates are wise to call for increased regional planning, the findings of this study suggest that particular regional growth management strategies are not inherently BMPs in and of themselves. However, these results indicate that a regional growth management strategy can contribute to watershed protection. The existing regulatory environment provides opportunities to exploit this potential. Through the framework of the Clean Water Act (both the National Pollutant Discharge Elimination System and section 303(d) regarding surface waters), as well as many state environmental laws, localities already engage in a variety of planning efforts tied to performance measures that are designed to improve the environmental outcomes of urbanization. For example, Phase II of the Clean Water Act requires urbanized areas to implement minimum control measures for stormwater management. These required measures include establishing local ordinances to regulate post-construction stormwater runoff - in other words, mandating the implementation of BMPs for new development.

These ordinances address stormwater management at the site level, but they do not apply to all construction and there is no regional component. Thus, urbanization scenarios that do not consider watershed management goals, like those explored in this research, are still possible. Undertaking stormwater impact analysis of long-range transportation plans, similar to the air quality impact assessments required of metropolitan planning organizations in the regulatory framework of the Clean Air Act, is the key to integrating regional growth management and watershed protection. This planning effort is the key to connecting the effects and drivers of the conceptual model stated in Figure 5.

Implications for Research

This study is a relatively novel application of the SWMM model, which is more typically exploited in storm sewer design and system management due to SWMM's unique ability to model hydraulics. While traditionally considered a "design" model, SWMM has great potential as a "planning" model. This is especially true for urbanizing watersheds. The SWMM model developed for this project included an absolute minimum of explicit representation of the storm sewer network. The SWMM model's characteristic width and Manning's N parameters approximate hydraulic behavior within subwatersheds and allow the use of SWMM for scenario planning at large spatial scales.

This study did not take advantage of SWMM's user-defined land use capabilities. Future research using this SWMM model could simulate the accumulation of different water quality constituent contaminants under the alternative scenarios. This is an alternative avenue for incorporating the neighborhood typology developed for TRANUS into the stormwater model. This would increase the sophistication of the results available to

decision-makers weighing the impacts of each scenario, providing more axes on which to measure the tradeoffs between alternatives. For each scenario, such information would be useful in understanding which BMPs could be most effective in which basin.

The model could also be used to explore additional sub-scenarios, such as the impact of BMP implementation at the watershed level, or within specific catchments. For example, the model could quantify the impacts of partial versus full implementation (or no implementation) of a long-term control plan for a particular surface water feature. However, the exploration of other scenarios representing alternative values for the drivers in the conceptual model would require additional parallel application of the integrated land use-transportation model.

This study did not find any reduction in per-capita stormwater runoff, which might have been expected because some imperviousness, such as a building rooftop, is shared by more people at higher densities. Under the current development pattern, this study's results indicate that this benefit is largely neutralized by additional development from other land sectors that are linked by market forces to higher residential densities, including commercial development and transportation-related imperviousness. This contradicts the assumptions of Jacob and Lopez (2009), and merits further investigation. Does this relationship have different dynamics at varying spatial scales? Are there interactions between residential density and employment density? If so, what form do these interactions take?

The relationship between employment density and imperviousness in particular requires additional exploration. Do different economic sectors have different relationships to imperviousness? Are the spatial dynamics in the relationship different in other metropolitan

areas beyond Mecklenburg County, or similar? The policy implications of these questions are potentially far-reaching, touching on a number of subdisciplines within planning practice and economics.

Broadly speaking, this study demonstrates that the way we conceptualize density is critical to how we form hypotheses about urbanization and test them. Beyond exploring the relationship between density and imperviousness, exploring innovative methods for measuring and modeling density is a major avenue for planning research and practicing modelers. There is tremendous potential for creative approaches to defining density to improve both models and policy.

REFERENCES

1.   Agarwal C., Green G.M., Grove J.M., Evans T.P. & Schweik C.M. (2002) A review and assessment of land-use change models: Dynamics of space, time, and human choice. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. Gen. Tech. Rep. NE-297.

2.   Alberti M. & Marzluff J. M. (2004) Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. Urban Ecosystems 7: 241 - 265.

3.   Alberti M. & Waddell P. (2000) An integrated urban development and ecological simulation model. Integrated Assessment 1: 215 - 227.

4.   Arendt R. G. (1996) Conservation design for subdivisions: A practical guide to creating open space networks. Island Press, Washington, DC.

5.   Arendt R. G. (2006) Conservation development. In: Planning and urban design standards (ed. E. Sendich) pp. 453 - 455. John Wiley and Sons, Hoboken, NJ.

6.   Arnold Jr. C. L. & Gibbons J. C. (1996) Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association 62: 243 - 259.

7.   Arnold J. G., Srinivasan R., Muttiah R. S. & Williams J. R. (1998) Large area hydrologic modeling and assessment Part I: Model development. Journal of the American Water Resources Association 34: 73 - 89.

8.   Arnold J. G. & Fohrer N. (2005) SWAT2000: Current capabilities and research opportunities in applied watershed modeling. Hydrological Processes 19: 563 - 572.

9.   Athayde, D.A. (1983) Results of the Nationwide Urban Runoff Program: Volume 1 - Final Report. Accession Number: PB84-185552.

10.   Avin U. P. & Dembner J. L. (2001) Getting scenario-building right. Planning 67: 22 - 27.

11.   Bartholomew K. (2005) Integrating land use issues into transportation planning: scenario planning. Summary Report of Federal Highway Administration Cooperative Agreement No. DTFH61-03-H-00134. URL: http://faculty.arch.utah.edu/bartholomew/SP_SummaryRpt_Web.pdf. Accessed 9/23/2009.

12.   Bartholomew K. (2006) Land use-transportation scenario planning: promise and reality. Transportation 34: 397 – 412.

13.   Batty M. (2005) Agents, cells, and cities: new representational models for simulating multiscale urban dynamics. Environment and Planning A 37: 1373 – 1394.

14.   Batty, M. & Torrens, P.M. (2005). Modeling and prediction in a complex world.

Futures 37(7): 745-766.

15.   Batty M. (2008) The size, scale, and shape of cities. Science 319: 769 – 771.

16.   Becker H. S. (1983) Scenarios: A tool of growing importance to policy analysts in government and industry. Technological Forecasting and Social Change 23: 95 - 120.

17.   Berke P. R., MacDonald J., White N., Holmes M., Line D., Oury K. & Ryznar R. (2003) Greening development to protect watersheds. Journal of the American Planning Association 69: 397 - 414.

18.   Berling-Wolff S. & Wu J. (2004) Modeling urban landscape dynamics: A review. Ecological Research 19: 119 - 129.

19.   Bhaduri B., Minner M., Tatalovich S. & Harbor J. (2001) Long-term hydrologic impact of urbanization: A tale of two models. Journal of Water Resources Planning and Management 127: 13 - 19.

20.   Bicknell B. R., Imhoff J. C., Kittle J. L., Donigan A. S. & Johanson R. C. (2001) Hydrologic Simulation Program - Fortran, User's Manual. Athens, GA: National Exposure Research Laboratory, US Environmental Protection Agency.

21.   Brabec E., Schulte S. & Richards P. L. (2002) Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. Journal of Planning Literature 16: 499 - 512.

22.   Brun S. E. & Band L. E. (2000) Simulating runoff behavior in an urbanizing watershed. Computers, Environment, and Urban Systems 24: 5 - 22.

23.   Charlotte-Mecklenburg Planning Department. (2010) Centers, Corridors and Wedges Growth Framework. Date accessed: 11/14/2012. URL: http://charmeck.org/city/charlotte/planning/AreaPlanning/CentersCorridorsWedges/Pages/Home.aspx.

24.   Charlotte-Mecklenburg Storm Water Services. (2010) Storm Water Inventory. Date accessed: 4/21/2010. URL: http://charmeck.org/stormwater/data/Pages/Storm%20Water%20Inventory%20Program%20Description.aspx.

25.   CHI (2008) Introduction to PCSWMM.NET. Guelph, ON: Computational Hydraulics International. Date accessed: 7/20/08. URL: http://www.computationalhydraulics.com/Software/PCSWMM.NET/index.html.

26.   Choi K.-s. & Ball J. E. (2002) Parameter estimation for urban runoff modeling. Urban Water 4: 31 - 41.

27.   City of Olympia. (1994) Impervious surface reduction study: technical and policy analysis – final report. Public Works Department, Olympia, Washington.

28.   Claytor R. (2006) Stormwater treatment. In: Planning and urban design standards (ed. E. Sendich) pp. 340 - 342. John Wiley and Sons, Hoboken, NJ.

29.   Coates J. F. (2000) From my perspective: Scenario planning. Technological Forecasting and Social Change 65: 115 - 123.

30.   Congress for the New Urbanism. (2000) Charter of the new urbanism. Bulletin of Science, Technology, and Society 20: 339 - 341.

31.   Cooperative Research Centre for Catchment Hydrology. (2005) Model for Urban Stormwater Improvement Conceptualization (MUSIC). URL: http://www.toolkit.net. au/music. Accessed 12/06/05.

32.   Costanza R., Voinov A., Boumans R., Maxwell T., Villa F., Wainger L. & Voinov H. (2002) Integrated ecological economic modeling of the Patuxent River watershed, Maryland. Ecological Monographs 72: 203 - 231.

33.   Deal B. (2001) Ecological urban dynamics: the convergence of spatial modeling and sustainability. Building Research and Information 29: 381 – 393.

34.   De la Barra, T. (1989) Integrated land use and transport modelling. Cambridge University Press, New York.

35.   Donigan A. S. & Huber W. C. (1991) Modeling of nonpoint source water quality in urban and non-urban areas. Athens, GA: Environmental Research Laboratory, US Environmental Protection Agency. EPA/600/391/039.

36.   Duany A. (2002) Introduction to the special issue: The transect. Journal of Urban Design 7: 251 - 260.

37.   Dueker K. J. (2002) A critique of the urban transportation planning process: The performance of Portland's 2000 regional transportation plan. Transportation Quarterly 56: 15 - 21.

38.   Elsin Y.K., Kramer R.A. & W.A. Jenkins. (2010) Valuing drinking water provision as an ecosystem service in the Neuse River Basin. Journal of Water Resources Planning and Management 136(4): 474 - 482.

39.   EPA (1994) National Water Quality Inventory: 1994 Report to Congress. Environmental Protection Agency. EPA841-R-95-005.

40.   EPA (2000) Projecting land-use change: a summary of models for assessing the effects of community growth and change on land-use patterns. EPA/600/R-00/098. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

41.   Ewing R. & Cervero R. (2002) Travel and the built environment: A synthesis.

Transportation Research Record: 87 - 114.

42.   Forman R. T. T. & Collinge S. (1997) Nature conserved in changing landscapes with and without spatial planning. Landscape and Urban Planning 37: 129 - 135.

43.   Girling C. & Kellett R. (2002) Comparing stormwater impacts and costs on three neighborhood plan types. Landscape Journal 21: 118 - 128.

44.   Gordon P. & Richardson H. W. (1997) Are compact cities a desirable planning goal? Journal of the American Planning Association 63: 95 - 107.

45.   Grant J., Manuel P. & Joudrey D. (1996) A framework for planning sustainable residential landscapes. Journal of the American Planning Association 62: 331 - 344.

46.   Greenberg M., Mayer H., Miller K. T., Hordon R. & Knee D. (2003) Reestablishing public health and land use planning to protect water supplies. American Journal of Public Health 93: 1522 - 1526.

47.   Grimm N.B., Stanley H.F., Golubiewski N.E., Redman C.L., Wu J., Bai, X., & Briggs J.M. (2008) Global change and the ecology of cities. Science 319: 756 – 760.

48.   Guhathakurta S. (1999) Urban modeling and contemporary planning theory: is there a common ground? Journal of Planning Education and Research 18(4): 281 – 292.

49.   Harbor J. (1994) A practical method for estimating the impact of land use change on surface runoff, groundwater recharge, and wetland hydrology. Journal of the American Planning Association 60: 91 - 104.

50.   Herold M., Goldstein N.C. & Clarke K.C. (2003) The spatiotemporal form of urban growth: measurement, analysis, and modeling. Remote Sensing of Environment 86: 286 – 302.

51.   Hotchkiss R. H., Jorgensen S. F., Stone M. C. & Fontaine T. A. (2000) Regulated river modeling for climate change impact assessment: the Missouri River. Journal of the American Water Resources Association 36: 375 - 386.

52.   Houlahan J.E. & Findlay C.S. (2004) Estimating the 'critical' distance at which adjacent land-use degrades wetland water and sediment quality. Landscape Ecology 19: 677 – 690.

53.   Hulse D., Eilers J., Freemark K., Hummon C. & White D. (2000) Planning alternative future landscapes in Oregon: evaluating effects on water quality and biodiversity. Landscape Journal 19: 1 – 19.

54.   Hunt J.D., Kriger D.S., & Miller E.J. (2005) Current operational urban land use-transport modeling frameworks: a review. Transport Reviews 25: 329 – 376.

55. Huston M. A. (2005) The three phases of land-use change: Implications for biodiversity. Ecological Applications 15: 1864 - 1878.

56. Goonetilleke A., Thomas E., Ginn S. & Gilbert D. (2005) Understanding the role of land use in urban stormwater quality management. Journal of Environmental Management 74: 31 – 42.

57. Grimm N.B., Faeth S.H., Golubiewski N.E., Redman C.L., Wu J., Bai X. & Briggs J.M. (2008) Global change and the ecology of cities. Science 319: 756 – 760.

58. Im S., Brannan K. M. & Mostaghimi S. (2003) Simulating hydrologic and water quality impacts in an urbanizing watershed. Journal of the American Water Resources Association 39: 1465 - 1479.

59. Jacob J.S., & Lopez R. (2009) Is denser greener? An evaluation of higher density development as an urban stormwater-quality best management practice. Journal of the American Water Resources Association 45(3): 687 - 701.

60. Jantz C.A., Goetz S.J. & Shelley M.K. (2003) Using the SLEUTH urban growth model to simulate the impacts of future policy scenarios on urban land use in the Baltimore-Washington metropolitan area. Environment and Planning B: Planning and Design 30: 251 – 271.

61. Johnson B. & Hill K. eds. (2002) Ecology and design: Frameworks for learning. Island Press, Washington, DC.

62. de Jouvenel H. (2000) A brief methodological guide to scenario building. Technological Forecasting and Social Change 65: 37 - 48.

63. Kayhanian M., Singh A., Suverkropp C. & Borroum S. (2003) Impact of annual average daily traffic on highway runoff pollutant concentrations. Journal of Environmental Engineering 129: 975 - 990.

64. Khakee A. (1991) Scenario construction for urban planning. Omega: International Journal of Management Science 19: 459 - 469.

65. Landis J. D., Monzon J. P., Reilly M. & Cogan C. (1998) Development and pilot application of the California Urban and Biodiversity Analysis (CURBA) Model. Accessed 18 June 2008. URL: http://gis.esri.com/library/userconf/proc98/PROCEED/TO600/PAP571/P571.htm.

66. LeBlanc R. T., Brown R. D. & FitzGibbons J. E. (1997) Modeling the effects of land use change on the water temperature in unregulated urban streams. Journal of Environmental Management 49: 445 - 469.

67. Lee J. G. & Heaney J. P. (2003) Estimation of urban imperviousness and its impacts on storm water systems. Journal of Water Resources Planning and Management 129:

419 - 426.

68.   McColl C. & Aggett G. (2007) Land-use forecasting and hydrologic model integration for improved land-use decision support. Journal of Environmental Management 84: 494 – 512.

69.   Mehaffey M. H., Nash M. S., Wade T. D., Ebert D. W., Jones K. B. & Rager A. (2005) Linking land cover and water quality in New York City's water supply watersheds. Environmental Monitoring and Assessment 107: 29 - 44.

70.   Moglen G.E. & Kim S. (2007) Limiting imperviousness: Are threshold-based policies a good idea? Journal of the American Planning Association 73: 161 - 171.

71.   Morton B.J., Rodriguez D.A., Song Y. & Cho E.J. (2007) Using TRANUS to construct a land Use-transportation-emissions model of Charlotte, North Carolina. Proceedings of the 2007 Transportation Land Use, Planning, and Air Quality Conference, Orlando, Florida, July 9-11. American Society of Civil Engineers.

72.   Muleta M. K. & Nicklow J. W. (2005) Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model. Journal of Hydrology 306: 127 - 145.

73.   Mumford L. (1938) The culture of cities. Harcourt, Brace, and World, New York.

74.   Nassauer J.I., Allan J.D., Johengen T., Kosel S.E. & Infante D. (2004) Exurban residential subdivision development: effects on water quality and public perception. Urban Ecosystems 7: 267 – 281.

75.   Newburn D.A. & Berck P. (2006) Modeling suburban and rural-residential development beyond the urban fringe. Land Economics 82(4): 481 – 499.

76.   Newman P. & Hogan T. (1981) A review of urban density models: Toward a resolution of the conflict between populace and planner. Human Ecology 9: 269 - 303.

77.   Nisenson, L. (2005) Using Smart Growth techniques as stormwater best management practices. Washington, DC: Environmental Protection Agency. 231-B-05-002.

78.   Parker D.C., Manson S.M., Janssen M.A., Hoffmann M.J. & Deadman P. (2003) Multi-agent systems for the simulation of land-use and land-cover change: a review. Annals of the Association of American Geographers 93(2): 314 – 337.

79.   Rawls, W.J., Brakensiek D.L., & Miller N. (1983). Green-Ampt infiltration parameters from soils data. Journal of Hydrologic Engineering 109(1): 62 – 70.

80.   Reid, J. C. (2001) Digital Orthophoto Quarter-Quadrangle Images. Accessed 8/5/2010. URL: http://www.geology.enr.state.nc.us/doqq.html.

81.   Rhodes A. L., Newton R. M. & Pufall A. (2001) Influences of land use on water quality of a diverse New England watershed. Environmental Science and Technology 35: 3640 - 3645.

82.   Richards L., Anderson G. & Santore M. K. (2002) Protecting water resources with higher density developments. Washington, DC: Environmental Protection Agency.

83.   Rogers G. O. & DeFee II B. B. (2005) Long-term impact of development on a watershed: Early indicators of future problems. Landscape and Urban Planning 73: 215 - 233.

84.   Rosenberg N. J., Epstein D. L., Wang D., Vail L., Srinivasan R. & Arnold J. G. (1999) Possible impacts of global warming on the hydrology of the Ogallala Aquifer region. Climatic Change 42: 677 - 692.

85.   Rossman L. A. (2005) Storm Water Management Model User's Manual. Cincinnati, OH: National Risk Management Research Laboratory, US Environmental Protection Agency. EPA/600/R-05/040.

86.   Schueler T. (1995) Site planning for urban stream protection. Center for Watershed Protection.

87.   Shearer A. W. (2005) Approaching scenario-based studies: Three perceptions about the future and considerations for landscape planning. Environment and Planning B: Planning and Design 32: 67 - 87.

88.   Smith R. A., Alexander R. B. & Wolman G. M. (1987) Water-quality trends in the nation's rivers. Science 235: 1607 - 1615.

89.   Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for North Carolina. Available online at http://soildatamart.nrcs.usda.gov. Accessed 6/3/2010.

90.   Spirn A. W. (2002) The authority of nature: Conflct, confusion, and renewal in design, planning, and ecology. In: Ecology and design: Frameworks for learning (eds. B. Johnson & K. Hill). Island Press, Washington, DC.

91.   Srinivasan R., Ramanarayanan T. S., Arnold J. G. & Bednarz S. T. (1998) Large area hydrologic modeling and assessment part II: model application. Journal of the American Water Resources Association 34: 91 - 101.

92.   State Climate Office of North Carolina, NC State University. CRONOS [internet database] available at http://www.nc-climate.ncsu.edu/cronos/. Accessed Feb. 25, 2010.

93.   Steinitz C., Rojo H. M. A., Bassett S., Flaxman M., Goode T., Maddock III T., Mouat D., Peiser R. & Shearer A. (2003) Alternative futures for changing landscapes. Island

Press, Washington, DC.

94. Stonefelt M. D., Fontaine T. A. & Hotchkiss R. H. (2000) Impacts of climate change on water yield in the Upper Wind River basin. Journal of the American Water Resources Association 36: 321 - 336.

95. Tang Z., Engel B. A., Pijanowski B. C. & Lim K. J. (2005) Forecasting land use change and its environmental impact at a watershed scale. Journal of Environmental Management 76: 35 - 45.

96. Tarr J. (1996) The search for the ultimate sink: Urban pollution in historical perspective. The University of Akron Press, Akron, OH.

97. Tong S. T. Y. & Chen W. (2002) Modeling the relationship between land use and surface water quality. Journal of Environmental Management 66: 377 - 393.

98. Tsihrintzis V. A. & Hamid R. (1997) Modeling and management of urban stormwater runoff quality: A review. Water Resources Management 11: 137-164.

99. USDA-NRCS (1986) Urban hydrology for small watersheds. Natural Resources Conservation Service, US Department of Agriculture. Technical Release 55.

100. Van Der Waals J. F. M. (2000) The compact city and the environment: A review. Tijdschrift voor Economische en Sociale Geografie 91: 111 - 121.

101. Waddell P. (2002) Modeling urban development for land use, transportation, and environmental planning. Journal of the American Planning Association 68: 297 - 314.

102. Waddell P., Borning A., Noth M., Freier N., Becke M. & Ulfarsson G. (2003) Microsimulation of urban development and location choices: design and implementation of UrbanSim. Networks and Spatial Economics 3(1): 43 – 67.

103. Waddell P., Gudmundur F.U., Franklin J.P. & Lobb J. (2007) Incorporating land use in metropolitan transportation planning. Transportation Research Part A 41: 382 – 410.

104. Wang Y., Choi W. & Deal B.M. (2005) Long-term impacts of land-use change on non-point source pollutant loads for the St. Louis metropolitan area, USA. Environmental Management 35: 194 – 205.

105. Wegener M. (1994) Operational urban models: state of the art. Journal of the American Planning Association 60(1): 17 – 29.

106. Wong T., Coleman J., Duncan H., Fletcher T., Jenkins G., Siriwardena L., Taylor A. & Wootton R. (2005) MUSIC User Manual. CRC for Catchment Hydrology, Melbourne.

107. Woods & Poole Economics, Inc. (2009) Summary technical description of the Woods & Poole Economics, Inc. 2010 regional projections and database. URL: http://

woodsandpoole.com/pdfs/TECH10.pdf. Accessed: 9/23/2009.

108.   Xiang W. & Clarke K. C. (2003) The use of scenarios in land-use planning. Environment and Planning B: Planning and Design 30: 885 - 909.

109.   Zegras C., Sussman J. & Conklin C. (2004) Scenario planning for strategic regional transportation planning. Journal of Urban Planning and Development 130: 2 - 13.

110.   Zhou B. & Kockelman K.M. (2008) Neighborhood impacts on land use change: a multinomial logit model of spatial relationships. Annals of Regional Science 42(2): 321 – 340.