APPLYING FUTURE CONDITIONS FLOOD MODELS to HAZARD MITIGATION PLANNING

by

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May 2015

Masters project submitted in partial fulfillment of the requirements
for the Master of Environmental Management degree in the
Nicholas School of the Environment of Duke University

April 22, 2015

Executive Summary

The 100-Year floodplain is a central driver of both federal flood insurance requirements and local land development policy in the United States. Existing development in flood hazard areas is grandfathered into lower insurance rates, while new development inside of the 100-Year floodplain is required to carry flood insurance at higher rates. Local floodplain regulations control the types of uses and the standard of construction for development in the 100-Year floodplain. Accurate floodplain delineations ensure that there is no increase in uninsured or under-insured development in high-risk areas.

Yet maintaining accurate floodplain delineations is an ongoing challenge. The accuracy of adopted Flood Insurance Rate Maps is complicated by the influence of changing land cover and urban infrastructure. The process of urbanization tends to result in more frequent high-magnitude flood events, effectively expanding the 100-Year floodplain. As a result, the delineated 1% probability flood is often not representative of the actual probability of flood damage.

Land use planning has been cited as a key component of addressing the shortcomings of floodplain management policy because it governs the placement, use, density and standards for new development. However, land use planners do not have a ready supply of alternative delineations as authoritative as the 100-Year floodplain to use as the basis for development permitting. Additionally, there is little consensus on the best land use planning paradigm or development pattern to emulate for hazard mitigation purposes. Different urban development configurations have been found to result in different spatial distributions of peak discharge, but little is known about the degree to which the location and configuration of future development affects the future 100-Year floodplain and overall levels of flood risk.

This project demonstrates a process by which land use planners can evaluate the hazard mitigation potential of different land use configurations using future conditions hydrologic and hydraulic models coupled with a flood risk assessment. The proposed process incorporates feedbacks between urban development, hydrology, and flood risk using standard land use planning techniques and existing engineering models.

Two small watersheds in Mecklenburg County, North Carolina were selected to test this process. The future land use designations in these basins indicate the planned conversion of forestland and open space to approximately 4,068 dwelling units and 691 acres of commercial, industrial and institutional development. I reallocated this planned future development among roughly 200 sub-basins in the two watersheds to create two alternative future land use scenarios: (1) a Compact Growth scenario, in which new urban development is concentrated in sub-basins closest to the downtown hub, and (2) a Transit-Oriented Development (TOD) scenario in which new urban development is concentrated around public transit stations.

I used a standard flood insurance study workflow to determine the impacts of each scenario on peak flows and base flood elevation within the study area, and a risk assessment to determine the impacts of each scenario on exposure of existing development to the 100-Year flood. I calculated weighted curve numbers at the sub-basin level for each scenario to parameterize a basin model in HEC-HMS v. 4.0. I ran five simulations for each watershed: the 100-Year and 500-Year floods

based on existing land use conditions, and the 100-Year flood based on the three future land use configurations.

Water surface profiles for each scenario were estimated through one-dimensional steady state analyses in HEC-RAS v.4.1 using the discharge estimates from the hydrologic model. I mapped the floodplain extent for each existing and future land use scenario by differencing the water surface profiles with an elevation dataset in ArcGIS v. 10.1. I then estimated the exposure of existing structures in the two watersheds from each of the different future conditions floodplains.

The hydrologic and hydraulic analysis demonstrated that different future land use scenarios can influence the degree of expansion of the 100-Year floodplain. The response of individual watersheds to different land use scenarios varies depending on the degree to which development is intensified. The Compact Growth scenario resulted in the broadest floodplain in one of the watersheds, while the Planned Future scenario resulted in the broadest floodplain in the other.

The flood risk assessment allowed for direct comparison between the outcomes in each watershed. By summing the total exposure in each watershed for each scenario, it is evident that the TOD scenario results in the lowest overall exposure of existing structures to the 100-Year flood. All three future conditions scenarios result in an increase in exposure relative to the existing conditions 100-Year floodplain, reaffirming the importance of considering future flood conditions when regulating present-day development.

This project does not attempt to draw conclusions about whether one planning paradigm is a better hazard mitigation strategy than others. The outcomes are largely dependent on the individual watersheds included in the analysis and the level of existing development in those watersheds. Under any scenario involving an increase in urban development, some watersheds will fare better than others. Estimating the total amount of exposure on the basis of future flood conditions provides a salient indicator of citywide or regional risk - one that local decision-makers could include when considering the costs and benefits of different future land use configurations.

Contents

INTRODUCTION

National Flood Policy

Flooding is the single-most expensive and chronic hazard in the United States, accounting for 80 to 90% of disaster declarations (Knebl, Yang, Hutchison, & Maidment, 2005; Patterson & Doyle, 2009) and causing losses of $2 to 5 billion per year, on average (Ntelekos, Oppenheimer, Smith, & Miller, 2010; Pielke, Jr., Downton, & Barnard Miller, 2003; Pielke & Downton, 2000).[1] Despite the billions of dollars invested in flood damage prevention and disaster preparedness in the U.S., the frequency and cost of flood damage continues to grow. Losses have increased more than 50-fold since the 1960s (Highfield, Norman, & Brody, 2013).

Historically, the National Flood Insurance Program (NFIP) has been the primary driver of floodplain management and flood hazard mitigation activities in the U.S. The NFIP was established in 1968 under the same Act (PL 90-448) that directed the Department of Housing and Urban Development (HUD) to promulgate regulations for safe floodplain management. Local governments were required to adopt floodplain management regulations that met or exceeded the federal standard by 1972 in order to become eligible to join the NFIP (American Institutes for Research, Pacific Institute for Research and Education, & Deloitte & Touche LLP, 2002). In the same year, USGS and the Army Corps of Engineers initiated an effort to map flood hazard areas, defined by federal committee as those areas inundated by the 1% annual chance flood, more commonly known as the 100-Year floodplain. Property owners were eligible to purchase flood insurance through the NFIP after flood hazard areas had been identified for their community on Flood Insurance Rate Maps (FIRMs).

Today, FIRMs still form the basis of insurance purchases and floodplain management activities. Existing development in flood hazard areas (pre-FIRM) is grandfathered into lower premium rates, while new development inside of the 100-Year floodplain is required to carry flood insurance at higher rates.[2] Local floodplain regulations control the types of uses and standards of construction for development in the 100-Year floodway and floodplain.[3] Assuming that participating communities enforce their local floodplain regulations, the effectiveness of the program hinges on the amount of existing development in high-risk areas and the availability of accurate floodplain delineations. Accurate delineations ensure that there is no increase in uninsured or under-insured development in high-risk areas.

Unfortunately, creating and maintaining accurate floodplain delineations is an ongoing challenge. From its inception, the NFIP could not keep up with the demand for FIRMs due to the large number of eligible communities and the paucity of data needed to estimate floodplain extents. In 1974, 5% of eligible communities had FIRMs in place, and by 1978 coverage had only increased

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[1] Estimates vary based on the time period included in the analysis as well as definitions of flooding or flood damage (Pielke, Jr., Downton, & Barnard Miller, 2003). According to the National Flood Damage Data Set, between 1993 and 2003, flood damage averaged $5.2 billion annually (in 2003 dollars) (Pielke, Jr. et al., 2003).

[2] Only properties owned with a federally-backed mortgage or a loan from a federally-regulated financial institution are required to carry flood insurance. Property owned outright is exempt. Although the insurance premiums are higher for new development relative to pre-FIRM development, the rates remain highly subsidized.

[3] The floodway is defined as the boundary between the edge of the 100-Year floodplain and the stream bank, at which obstructions in the floodplain would cause an increase in the base flood elevation of 1-foot or more. Generally, all new development is prohibited in the floodway.

to 17% (American Institutes for Research et al., 2002). As of 2003, roughly 29% of all eligible rivers and coasts had been mapped (National Research Council, 2009). Even in communities with effective FIRMs, the accuracy of the maps is complicated by the influence of changing land cover and urban infrastructure (Villarini et al., 2009) and changing climate (Milly et al., 2008). Conversion of natural, vegetated land to impervious cover results in higher peak flows by reducing the amount of rainfall that infiltrates or evaporates before converting to runoff (Poff et al., 1997). Thus, the process of urbanization tends to result in more frequent high-magnitude flood events. Larger-scale feedbacks between urban heat islands and precipitation regimes may also increase the probability of large rainfall events, and consequently, the frequency of larger floods (Ntelekos et al., 2010).

Although changing conditions are known to influence flood recurrence intervals, these factors are not accounted for in FIRMs. Once a flood insurance rate map becomes effective, the 100-Year delineation is used to determine insurance obligations and development regulations without regard for changes in flood frequency over time. Over 60% of FIRMs are at least 10 years old, and an estimated 33% are more than 15 years old (Highfield et al., 2013). As a result, the delineated 1% probability flood is often not representative of the actual probability of flood damage. Property owners outside of the 100-Year floodplain file close to 25% of all flood insurance claims and receive 33% of Federal Disaster Assistance for flooding (FEMA, 2014). Though not the sole reason for the NFIP’s mounting debt, the inability of the program to identify and collect premiums from at-risk properties has contributed to its poor outcomes (Burby, 2001).

Map Maintenance

The Federal Emergency Management Agency (FEMA), which oversees the NFIP, is aware of the shortcomings of static FIRMs. In 1997, FEMA initiated the Map Modernization program, which focused on transitioning paper maps to digital (DFIRMs) and prioritizing communities for updated maps (Crowell, Hirsch, & Hayes, 2007). Communities were prioritized based on the age of existing maps, the rate of urbanization in a community, and the availability of updated topographic data (GAO, 2010). Between 2003 and 2008, FEMA spent $1.2 billion on prioritizing, updating and digitizing FIRMs (GAO, 2010). The Risk Mapping, Assessment, and Planning (Risk MAP) program superseded Map Modernization in 2009, and continues to target map maintenance resources to fast-growing communities and communities with maps that do not meet floodplain boundary standards (National Research Council, 2009).

Regardless of the success of these modernization efforts at the state and federal level, FIRMs are still established post hoc. By the time a local municipality is remapped, building permits have already been issued, subdivisions approved, and local comprehensive plans and zoning ordinances are already in place. Paradoxically, development tends to concentrate immediately outside the 100-Year floodplain demarcation (Patterson & Doyle, 2009), the area most affected by any increase in the 100-Year flood magnitude as a result of urbanization.

While the obvious solution to this issue would be to restrict development within some buffer distance of the 100-Year floodplain, land use planners do not have a ready supply of alternative delineations as authoritative as the 100-Year floodplain to use as the basis for development permitting. The 100-Year floodplain has the advantage of being both well-known and backed by federal regulation. The planning literature suggests several more conservative options, including the 500-Year floodplain or the 500-Year flood elevation (Burby, 2001; Burby, 2006). However, in some communities the 500-Year floodplain may represent a significant divergence from the 100-Year boundary and may not be a politically feasible option.

Future Conditions Flood Models

In 2001, FEMA issued guidance on an alternative floodplain delineation designed to maintain its validity over time. Future conditions floodplain maps use future land use plans or ultimate watershed urbanization rather than existing land cover data to model watershed hydrology and map the 100-Year floodplain extent. FEMA's guidance allows municipalities to include future-conditions flood hazard areas on FIRMs as a form of public information and risk awareness (FEMA, 2001).

The regulatory influence of the maps is relatively weak compared to traditional FIRMs. FEMA does not require development restrictions or insurance purchases within the future conditions 100-Year floodplain, due to "the uncertain nature of the future-conditions data and the relatively limited number of participating communities" (FEMA, 2001, p. 59168).[4] However, local governments may opt to use the future conditions floodplain maps to inform local land use policy and hazard mitigation activities.

Hazard mitigation is the activity of reducing long-term risks to life and property, where risk is a function of the probability that an event will occur, and the exposure of people and property to the hazard (Schwab, 2010). Future conditions floodplain mapping provides opportunities for flood hazard mitigation by identifying areas that may be subject to the 100-Year flood after additional urbanization. This information allows local governments to mitigate flood risk to *new* construction by restricting development within the future conditions 100-Year floodplain. It also enables local governments to mitigate the increased exposure of *existing* development to flood risk early on, through floodplain buyouts, elevation of critical infrastructure, and other measures. More widespread use of future conditions floodplain maps would improve the performance of the NFIP and help local governments reduce overall levels of flood risk (Burby, 2001).

Land Use Planning & Hazard Mitigation

Land use planning has also been cited as a key component of flood hazard mitigation because it governs the placement, use, density and development standards for development (Berke, 1998; Godschalk, 1999, 2003). As discussed above, where future conditions floodplain delineations are available, local governments could opt to restrict or prohibit new development within the future conditions 100-Year floodplain. In addition, because increases in urban development affect the extent of the 100-Year floodplain, there may be opportunities for land use plans to strategically allocate new development among watersheds in order to minimize increases in flood risk for existing structures.

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[4] There are at least eight communities that use future conditions floodplain maps: Fairfax County, Virginia; Tulsa, Oklahoma; Urban Drainage and Flood Control District, Colorado; Mecklenburg County, North Carolina; Alpharetta, Georgia; Fort Collins, Colorado; Roseville, California; Pierce County, Washington. This list is not necessarily comprehensive; only CRS Class 1-4 communities and No-Adverse Impact Best Practice communities (ASFPM, 2004) were contacted by the author for information on floodplain mapping procedures.

While it is clear that increased urban development can lead to a broader floodplain extent, little is known about the relative impacts different land use configurations may have on floodplain extent. If alternative land use configurations can reduce the overall impact of new urban development on the risk of existing development to flooding, then the cost and burden of mitigation can also be reduced. Despite the ongoing calls for increased participation of land use planners in hazard mitigation planning (Schwab, 2010; M. Stevens, 2010), there is little consensus on the best land use planning paradigm or development pattern to emulate for hazard mitigation purposes.

Some of the hazard mitigation literature directs practitioners to incorporate *smart growth* into plans in recognition of the overlapping environmental, social and fiscal problems associated with low-density urban expansion (Godschalk, 2003; National Research Council, 2006). Smart growth is an outcome-oriented planning concept that promotes mixed-use development in compact urban areas to conserve open space and facilitate alternative transportation options. Implementation of smart growth practices typically makes use of existing urban footprints, necessitating higher densities to accommodate new development within the same area. However, some smart growth strategies such as urban growth boundaries and urban service boundaries have been shown to increase development pressures on land in hazardous locations within the boundaries and service areas (R. J. Burby, Nelson, Parker, & Handmer, 2001). Indeed, the connection between impervious surface coverage, water quality, and stormwater management causes many communities to limit the density of development (Carle, Halpin, & Stow, 2005).

Other planning typologies like *clustered development* or *low-impact development* that claim to reduce the problem of environmental hot-spots may have the self-defeating effect of increasing urban expansion and sprawl. Clustered development and low-impact development models encourage developers to construct high-density improvements on a portion of a site in order to preserve floodplain areas and open space, and achieve a lower gross density and lower impervious cover ratio over the entire site (Beatley, 2009; Carle et al., 2005). Studies evaluating these practices found that the additional value attributed to open space increases the likelihood that nearby properties will be developed (Irwin & Bockstael, 2004) and that overall, more land is consumed in a more fragmented pattern (Lichtenberg & Hardie, 2007).

Low-density sprawl has been cited as a major culprit for the increase in natural hazard risks and damages during the 20th century (S. D. Brody, Gunn, Peacock, & Highfield, 2011; S. Brody, Kim, & Gunn, 2013; National Research Council, 2006). Certainly, the lower the density of urban development and sprawl, the more natural areas will be encroached upon and converted in order to accommodate a growing population. Furthermore, there is no evidence that cluster development projects avoid development in or adjacent to the 100-Year floodplain (M. R. Stevens, Song, & Berke, 2010).

While there is apparently no consensus on the most appropriate development pattern for mitigating flood risk, the literature does indicate that best practice land use planning concepts are not necessarily best practice hazard mitigation strategies, and that achieving hazard mitigation is not as simple as adopting a smart growth, clustered, or low-impact development pattern. Implementation of flood hazard mitigation through land use planning requires a more fine-grained approach that accounts for local hydrology and the specific location of hazard areas, and that allows planners to reconcile competing objectives (Berke, 1998).

This project aims to demonstrate a process that connects future conditions floodplain maps to the need for more context-specific land use plans and hazard mitigation interventions. The proposed process uses future conditions flood models to evaluate the impacts of different future land use configurations on the 100-Year floodplain extent and the exposure of existing development to the 100-Year flood.

Scenario Planning

This project makes use of a simplified form of scenario planning, which is already widely practiced by land use and transportation planners in the U.S. (Bartholomew, 2007; Schroeder & Lambert, 2011). Federal transportation regulations mandate alternatives analysis in transportation plans, so scenario planning often involves comparisons between different transportation investments and land use configurations that support those investments. Unlike scenario planning as-practiced in business management, the range of alternative scenarios are constrained by the factors that planners and regulators are able to control. The amount of future population and employment growth is fixed, while the distribution and characteristics of that growth are varied in each scenario (Lemp, Zhou, Kockelman, & Parmenter, 2008). The most common variables are location and density of growth, although some analyses include prices and other market factors (Bartholomew, 2007). The outcomes from each scenario (e.g. vehicle miles traveled, air quality, carbon emissions) are presented to the public and local decision-makers to help evaluate the trade-offs between different land use and transportation decisions.

Existing scenario planning efforts typically evaluate land use configurations and transportation options on the basis of multiple outcome measures that reflect multiple goals and objectives held by the community and local decision-makers (Lemp et al., 2008). In these real-world situations, it is impossible to optimize for all objectives. For example, Loh (2012) identified trade-offs between fostering transit-oriented development and maintaining water quality in Mecklenburg County, North Carolina. Lemp et al. (2008) identified trade-offs in Austin, Texas between reducing carbon emissions and minimizing development in aquifer recharge zones. Decision-makers and stakeholders are likely to weigh objectives differently (Ryffel, Rid, & Grêt-Regamey, 2014). Thus, the process of scenario planning provides information to support a more transparent, deliberative planning process rather than a single, optimal solution.

Despite the widespread availability of (1) hydrologic and hydraulic models that allow for estimating the impacts of land use change on flood conditions, and (2) urban growth models that allow for estimating the impacts of land use change on flood risk, these two analysis have not been systematically integrated in scenario planning efforts to evaluate the impacts of land use change on flood risk, given changes in flood conditions. A multitude of studies evaluate the impacts of urban growth and development scenarios on changes in hydrology (Brath, Montanari, & Moretti, 2006; De Roo, Schmuck, Perdigao, & Thielen, 2003; Lin, Verburg, Chang, Chen, & Chen, 2009; Naef, Scherrer, & Weiler, 2002; Niehoff, Fritsch, & Bronstert, 2002). Implicit in these analyses is the assumption that the scenarios leading to the greatest increases in peak discharge will be the same scenarios that lead to the greatest increase flood risk. However, risk depends not only on the hydrologic impacts but also the placement and exposure of development (Schwab, 2010) and the distribution of hydrologic impacts (Lin et al., 2009; Loh, 2012).

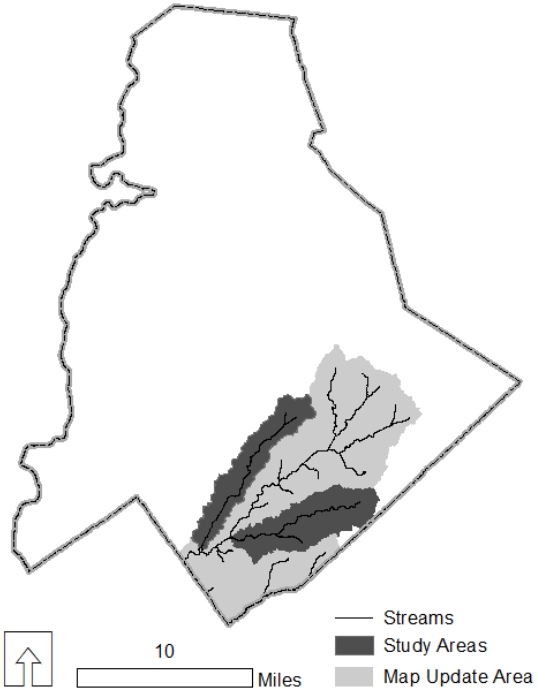
There is a call for modeling processes that can evaluate changes in flood risk given different urban growth and development scenarios and dynamic flood conditions (Barredo & Engelen, 2010). This project attempts to link future conditions flood models and land use planning to address this gap. The proposed process incorporates feedbacks between urban development, hydrology and flood risk at a very basic level – one that could potentially be applied by local-level planners working in concert with engineers or consultants preparing flood insurance studies. Future land use scenarios are used to parameterize existing hydrologic and hydraulic models to determine the impacts of development type and configuration on flood conditions. Future flood conditions for each scenario are then used to evaluate the change in exposure of existing development to the 100-Year flood event.

This project does not attempt to predict or evaluate other environmental impacts associated with each scenario, nor does it carry out the analysis at a citywide scale – the standard unit of analysis for land use planning. Rather, it demonstrates a process that could be employed to assess flood risk outcomes at a citywide scale in connection with other outcomes of local importance.

STUDY AREA

Two small watersheds in Mecklenburg County, North Carolina were selected to test this process: the McMullen Creek drainage basin and the Fourmile Creek drainage basin (Figure 1). Mecklenburg County's seat is the City of Charlotte, one of the fastest-growing cities in the U.S.

Figure 1. Location of Study Areas in Mecklenburg County



Charlotte-Mecklenburg Storm Water Services (CMSWS) is nationally recognized for its hazard mitigation initiatives, particularly for the use of future conditions floodplain delineations as a tool to communicate risk and identify prospective floodplain buyouts (ASFPM, 2004). The first set of future conditions floodplain maps were adopted in 2004 (Punchard, 2011).

The county's extensive stream gauge network and stream channel data support high-quality hydrologic and hydraulic studies. Though ideally, land use scenario planning should occur at a citywide or regional scale, this analysis was constrained to two watersheds due to the availability of engineering models with the same baseline date; the two watersheds in the study area are located within the same floodplain mapping update area, such that consistent model files are available for both watersheds.

The watersheds are similar in size, but have distinct land cover characteristics. McMullen Creek's drainage area is already quite urbanized, likely due to its vicinity to downtown Charlotte. Only 10% forest/brush cover and 5% open space remain in the drainage basin (Table 1). More than 50% of land area is covered by residential uses. Fourmile Creek is located southeast of McMullen Creek, traversing portions of the Town of Matthews and the City of Charlotte. It has double the forest cover and open space of the McMullen Creek drainage basin and is generally characterized by lower-intensity uses.

Table 1. Existing Conditions in Study Areas

	McMullen Creek		**Fourmile Creek**	
	Acres	% of Total	Acres	% of Total
Woods/Brush	990	10.1%	2,475	20.2%
>2 Acre Residential & Open Space	436	4.5%	1,250	10.2%
0.5 to 2 Acre Residential	1,521	15.6%	2,258	18.5%
0.25 to 0.5 Acre Residential	3,358	34.4%	3,107	25.4%
<0.25 Acre Residential	185	1.9%	287	2.3%
Institutional	389	4.0%	329	2.7%
Industrial – Light	46	0.5%	28	0.2%
Industrial – Heavy	943	9.7%	349	2.9%
Commercial – Light	298	3.1%	182	1.5%
Commercial – Heavy	321	3.3%	279	2.3%
Water Bodies	21	0.2%	104	0.8%
Transportation	1,259	12.9%	1,582	12.9%
TOTAL	**9,767**	**100.0%**	**12,230**	**100.0%**

Source: Calculated from existing land use layer; methods described below.

The location and distinct land cover characteristics of the two basins provide the opportunity to examine how different future land use scenarios impact the future conditions 100-Year floodplain extent and overall measures of flood risk.

METHODS

The hydrologic and hydraulic modeling approaches for this analysis were selected based on national and local floodplain mapping standards. CMSWS directs its contractors to use the latest versions of HEC-HMS and HEC-RAS for all hydrologic and hydraulic modeling, so these computer models were used for the hydrologic and hydraulic impact analyses in this project (Baker & Dewberry, 2012).

The Hydrological Modeling System (HEC-HMS), developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center, is one of 16 different hydrologic computer models approved for use in NFIP flood insurance studies and floodplain mapping (FEMA, 2015; Hydrologic Engineering Center, 2013b). HMS includes a variety of mathematical models to determine baseflow, volume and rate of infiltration and evapotranspiration, transformation of excess precipitation into runoff, and routing of runoff through a watershed.

The River Analysis System (HEC-RAS) is the most widely-used hydraulic computer model for NFIP studies, and FEMA has issued guidance encouraging its use (Buckley, 2001; Hydrologic Engineering Center, 2010) . RAS and its geospatial compliment HEC-GeoRAS (Hydrologic Engineering Center, 2013a) determine water surface profiles and base flood elevations at cross sectional points in the watershed based on peak discharge, stream channel morphology, and the physical characteristics of stream network.

The flood risk assessment was conducted in ArcGIS v. 10.1 (ESRI, 2012) using the HEC-GeoRAS and 3D Analyst toolbar extensions. Risk assessment methods were based on approaches identified in the literature (Barredo & Engelen, 2010; FEMA, 2013; Merz, Thieken, & Kreibich, 2011; Patterson & Doyle, 2009) that were compatible with data availability. The risk assessment consists of an exposure analysis of existing buildings and structures in the study area.

Data Procurement and Preparation

HMS and RAS model files for the two watersheds were obtained from CMSWS. CMSWS also provided complimentary spatial data, including sub-basin delineations, existing land use, future land use, and soil features with hydrologic soil group attributes. CMSWS developed the existing land use data from aerial imagery and development plans, reclassifying cover values into 12 categories (Table 2). CMSWS regularly updates its future land use data based on zoning districts and land use plans. The most recent flood mapping update for McMullen and Fourmile Creeks reclassified the agency’s 90 future land use categories into the 12 land use codes consistent with current conditions.

Additional geospatial data for transportation features, buildings, existing floodplain extents, and parcels were obtained from the Mecklenburg County Open Mapping website (Mecklenburg County, 2013) and clipped to the study area extent. All geospatial data were referenced to the NAD 1983 State Plane (North Carolina) coordinate system.

Land Use Scenario Development

Creating realistic land use scenarios requires determining demand for different types of land uses, developing location rules for each land use category, and adjusting land use designations to accommodate needs (Berke & Godschalk, 2006). Demand is determined based on population and employment growth forecasts, and is satisfied by both redevelopment and development in new growth areas. Although future land use planning is typically based on citywide growth forecasts, the same basic principles can be used to develop future land use scenarios for the two study areas.

Table 2. Land Use/Land Cover Classes

Land Use Code	Land Use Category	Representative Land Cover Types
1	Woods/Brush	Woods, vegetated fields, etc.
2	>2 Acre Residential & Open Space	Farms, golf courses, fields, etc.
3	0.5 to 2 Acre Residential	Primarily large-lot single family residential
4	0.25 to 0.5 Acre Residential	Primarily medium-lot single family residential
5	<0.25 Acre Residential	Primarily small-lot single family residential, condos, apartments
6	Institutional	Schools, hospitals, government offices, etc.
7	Industrial – Light	Warehouses, etc.
8	Industrial – Heavy	Terminal transfer facilities, etc.
9	Commercial – Light	Office parks, hotels, multi-family >6 dwelling units/acre, apartments, etc.
10	Commercial – Heavy	Car parks, malls, etc.
11	Water Bodies	Usually ponds > 2 acres in size
12	Transportation	Right-of-ways for major thoroughfare/interstates.

Source: Baker and Dewberry (2012). Per the source, Right-of-Ways for smaller streets are integrated with the dominant adjacent land use.

Future demand was estimated based on the total change in land area within each land use class between the existing and future land use designations provided by CMSWS. Land use layers were prepared in ArcGIS v.10.1 (ESRI, 2012). The existing and future land use layers were clipped to match the extent of the McMullen Creek and Fourmile Creek drainage areas. The acreage attributes were updated to reflect the size of clipped features. The summary statistics tool was used to calculate the total number of acres in each land use class for both existing and future land use layers. Statistics for McMullen Creek and Fourmile Creek were summed in Excel v. 2007 (Microsoft, 2006). Change in land use was calculated by taking the difference of future acres and existing acres in each class. The increase in land area dedicated to institutional, industrial, and commercial uses was taken as a given level of future demand, meaning the location of these land uses could change but the total increase in acres was fixed (Table 3).

Table 3. Assumed Future Demand for Non-Residential Urban Land Uses

Land Use Category	Future Demand (Acres)
Institutional	297
Industrial – Light	79
Industrial – Heavy	115
Commercial – Light	160
Commercial – Heavy	40

The change in land area in residential uses was used to generate an estimate of the total number of dwelling units planned for both watersheds. The net increase in land area in land use classes 4, 5 and 6 were divided by the average of their respective density ranges to yield 4,068 units (Table 4). The purpose of determining the future demand for residential uses in terms of dwelling units rather than acres is to allow flexibility between different residential land use densities. Assuming the future demand for housing is fixed, the same number of dwelling units can be accommodated over large, low-density areas as can be accommodated in smaller, high-density areas.

Table 4. Estimated Future Demand for Dwelling Units

Land Use Category	Change in Acres	Average Density	Future Demand (Dwelling Units)
0.5 to 2 Acre Residential	308	1.25 ac/du	246
0.25 to 0.5 Acre Residential	1,404	0.38 ac/du	3,744
<0.25 Acre Residential	10	0.13 ac/du	77
Total	**1,721**	**-**	**4,068**

Other sources of flexibility in developing alternative future land use scenarios are natural areas. The adopted future land uses result in a net decrease in both forested/brush land cover (2,270 acres) and open space (142 acres). This project assumes these values are not representative of demand; only that undeveloped sites provide a ready source of land for future urban development. Thus, future urban development scenarios that require less acreage to meet demand may result in smaller magnitude changes in undeveloped land use types.

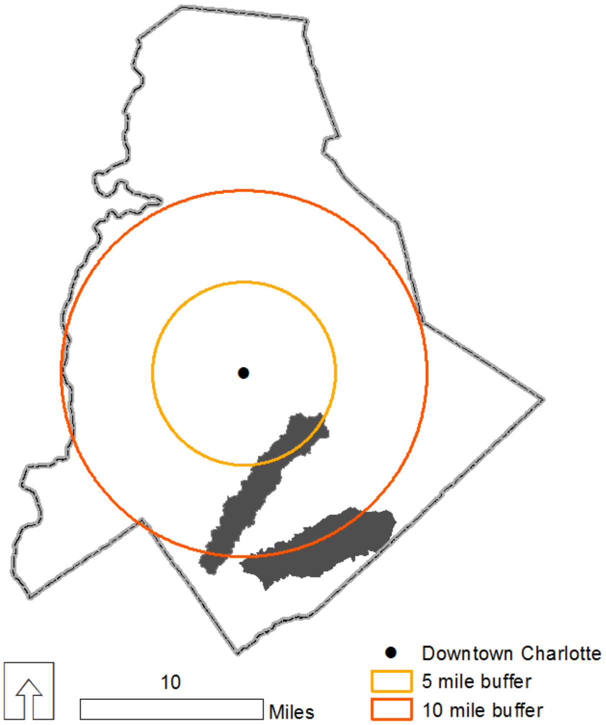
Location rules were developed for several of the land use categories to guide the placement of new uses (Berke & Godschalk, 2006). First, no land use conversion may occur in the designated floodplain areas. This reflects the expectation that existing local floodplain management ordinances will be enforced. Second, developed uses cannot revert to undeveloped uses, but can change to other developed uses (for example, industrial land may be converted to high-density housing). Although it is possible for developed land to revert to open space, this is rarely the result of a future land use designation. Third, the change in land area per land use category does not need to remain consistent within a single drainage basin so long as the total change across both basins is constant. This rule reflects the assumption that as long as the total growth forecast can be accommodated within the study area, growth can be accommodated in either watershed. In reality, local jurisdictions may compete for growth, particularly desirable commercial and industrial development. However, for this project, there was insufficient information about the relative population and employment forecasts in the constituent local jurisdictions to develop stricter location rules for new development.

Compact Growth Scenario

The Compact Growth scenario is based on a monocentric growth management concept, in which urban growth and development radiate outward from a central downtown hub (O'Flaherty, 2005). Buffers were generated for 5- and 10-mile radii from downtown Charlotte (Figure 2). Sub-basins falling within the 5-mile radius of Charlotte received the most new development and the highest intensity uses. Sub-basins falling within the 10-mile radius of downtown Charlotte received the remaining development, and sub-basins located more than 10 miles from downtown Charlotte did not receive new development. Land use classes were updated manually in ArcGIS starting from the sub-basins closest to downtown Charlotte and working outward. After six iterations, the total acreage in each developed use class was within 10 acres of the target demand, and the total number of dwelling units was within 99% of the target demand.[5]

Because sub-basins in the McMullen Creek watershed are located closer to downtown Charlotte than those in the Fourmile Creek watershed, the former received the vast majority of the development allocation. Under the Compact Growth scenario, most forest cover and open space are preserved in the Fourmile Creek watershed, while the McMullen Creek watershed loses nearly 40% of its forest cover and 80% of its open space.

Figure 2. Compact Growth Scenario Concept



Transit-Oriented Development Scenario

The Transit-Oriented Development (TOD) scenario concentrates new, higher-intensity uses in sub-basins closest to transit. Half-mile and one-mile buffers were generated around existing transit centers, existing light rail stations, and a bus rapid transit planning area (Figure 3).[6] Sub-basins that intersected with the half-mile buffers received the most new development and highest intensity uses, while sub-basins intersecting the 1-mile buffers received the remaining new

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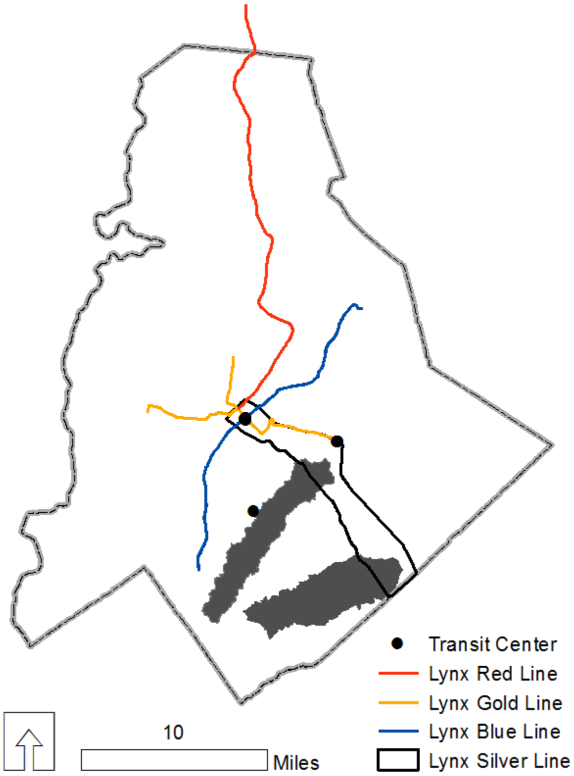
[5] See *Appendix* for land use tables.

[6] Station locations were not available for planned lines.

development. Land use classes were updated manually in ArcGIS starting from the sub-basins closest to transit. After seven iterations, the total acreage in each developed use class was within 12 acres of the target demand, and the total number of dwelling units was within 99% of the target demand.[7]

Figure 3. TOD Scenario Concept



The TOD scenario results in a more even distribution of high-intensity development between the two watersheds, compared to the Compact Growth scenario. Both watersheds lose approximately 20% of forest/brush cover due to the growth allocation. The Fourmile Creek watershed loses a greater share of its open space under the TOD scenario (44%) relative to the McMullen Creek watershed (21%) (Figure 4).

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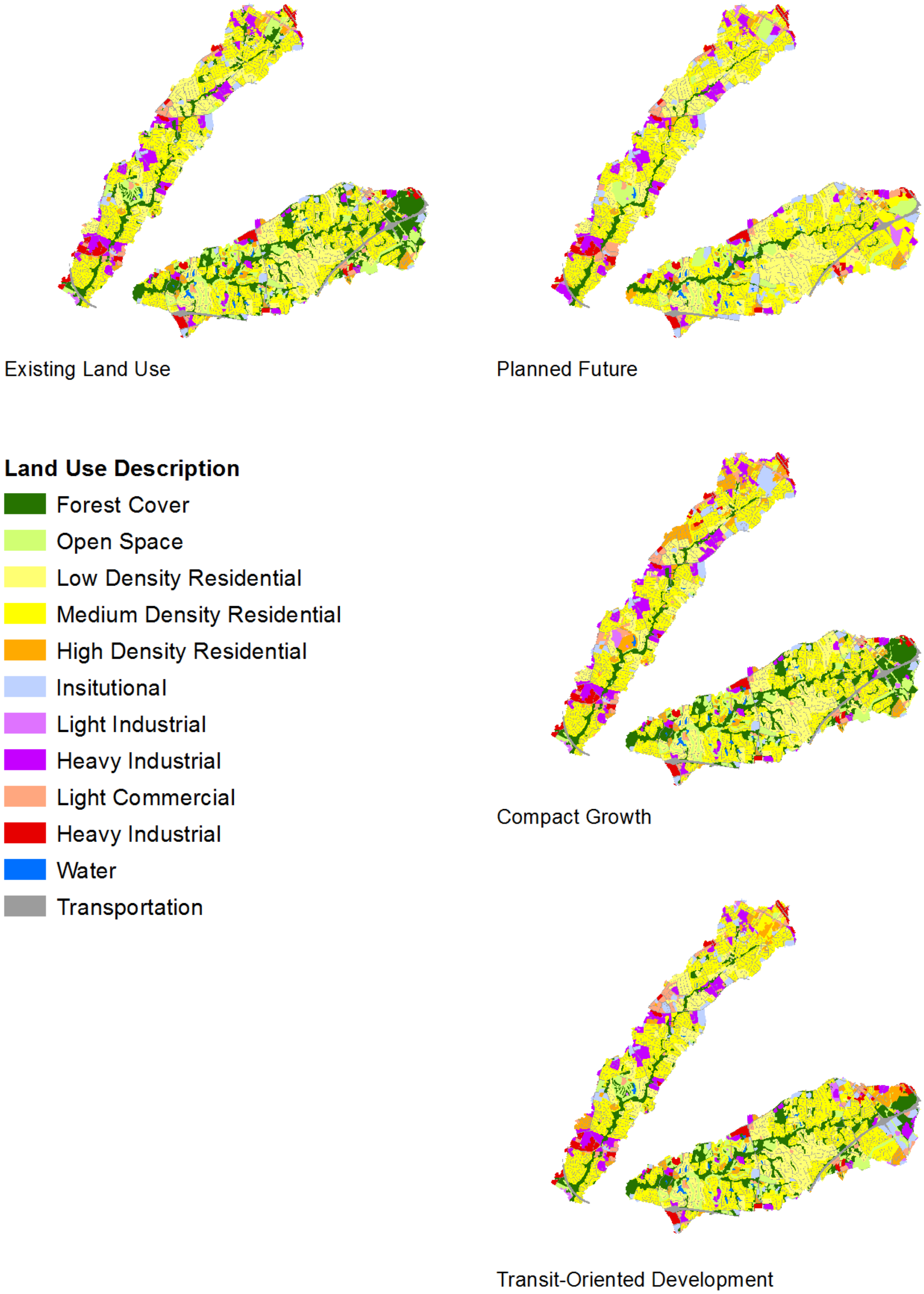
[7] See *Appendix* for land use tables.

Figure 4. Existing and Future Land Use Scenarios for the McMullen and Fourmile Creek Drainage Basins


Existing Land Use

Planned Future

Compact Growth

Transit-Oriented Development

Hydrologic Model

Calibrated HEC-HMS models for the study areas were obtained from CMSWS. Each HMS model contained multiple basin and meteorological models prepared to model the existing conditions and future conditions 100-Year floodplain, and the existing conditions 500-Year floodplain. The basin models were copied and adjusted to reflect basin characteristics under the two alternative future land use scenarios.

Curve Number Estimation

The HMS models obtained from CMSWS used the SCS runoff curve number approach to determine the proportion of runoff generated from rainfall over a given area. The SCS runoff equation is,

$$Q = \frac{P - I_a^2}{(P - I_a) + S} \qquad \text{[eq-1]}$$

where Q is the volume of runoff, P is rainfall, I_a is the loss to infiltration, evaporation, transpiration and shallow detention before runoff begins, and S is the potential maximum retention after runoff begins (units are inches) [eq-1]. Although I_a is a highly variable, SCS curve numbers are based on the empirically-derived relationship,

$$I_a = 0.2 \times \mathrm{S} \qquad \text{[eq-2]}$$

Curve numbers represent different solutions to the runoff equation for different values of S [eq-3], based on land cover type, soil group, and condition. In practice, curve numbers range from 30 to 98, with higher values indicating higher runoff potential (NRCS, 1986).

$$CN = \frac{1000}{S + 10} \qquad \text{[eq-3]}$$

The curve numbers for the McMullen Creek and Fourmile Creek drainage basins were derived from Table 2-2 in TR-55, which gives average curve number values for different combinations of land cover, cover condition and soil group (AECOM, 2011; NRCS, 1986). The final calibrated model for Fourmile Creek obtained from CMSWS included curve numbers adjusted by a factor of 0.92 and an I_a value of 0.2375*S (AECOM, 2011). Initial abstraction values for McMullen Creek were finalized at 0.275*S (AECOM, 2011).

The same methods used to generate the calibrated models by AECOM (2011) were followed to generate curve numbers for the Compact Growth and TOD scenarios. All data preparation and calculations were done in ArcGIS v.10.1 and Excel v.2007 (Microsoft, 2006). The soil feature layer was clipped to the drainage basin extent and a union function was used to combine soil features and land use features into a new feature layer. Hydrologic soil group attributes were coded numerically and added to land use attribute values to create a unique code for each combination. A lookup table was joined to the code field to associate each combination of soils and land use class with the appropriate curve number (Table 5).

The union tool was used to intersect the curve number feature layers with the sub-basin feature layers. The area of the new features was calculated and multiplied by the curve number of each feature. The layer was dissolved on the sub-basin field with summary statistics for the total area and sum of the curve number*area values. Finally, the total curve number*area values were divided by total area to produce a weighted curve number for each sub-basin (Figure 5). Fourmile Creek sub-basin curve numbers were further adjusted by a factor of 0.92. An adjusted I_a value was calculated from the final curve number values for each sub-basin. The curve numbers and I_a values for each alternative future land use scenario were copied into the loss parameter table for each basin model in HMS.

Table 5. Curve Number Lookup Table

Land Use Code	Soil Group						
	A	B	C	C/D	D	U	W
1	33	57	71	75	78	57	98
2	44	65	77	80	82	65	98
3	53	70	80	82	84	70	98
4	59	74	82	84	86	74	98
5	64	77	84	86	88	77	98
6	69	80	86	88	89	80	98
7	74	83	88	90	91	83	98
8	81	88	91	92	93	88	98
9	83	89	92	93	94	89	98
10	92	94	95	96	96	84	98
11	98	98	98	98	98	98	98
12	86	91	93	94	94	91	98

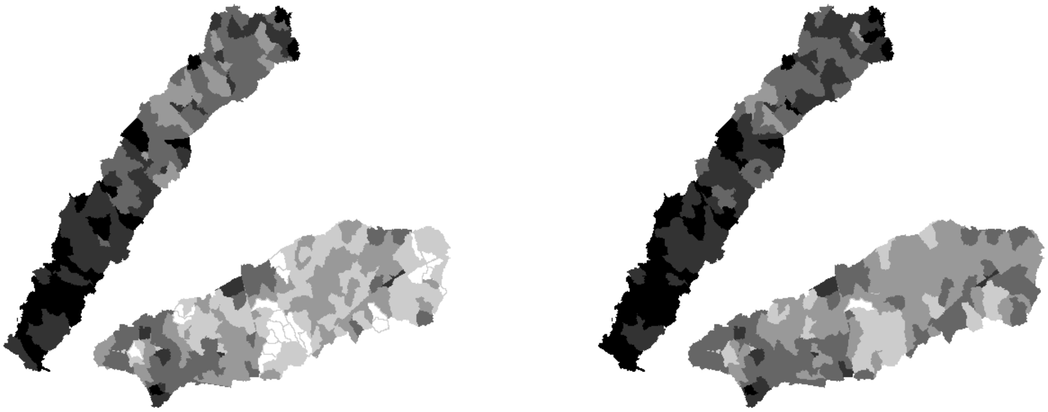
Source: AECOM (2011).

Time of Concentration and Lag Time

Time of concentration is the time required for rainfall runoff to travel from the furthest point in a watershed to its outfall, and is the sum of the travel time as sheet flow, shallow concentrated flow and channel flow (NRCS, 1986). Sheet flow travel time is affected by surface roughness, distance, rainfall depth and slope. Shallow concentrated flow is determined by velocity (in turn affected by surface roughness) and slope. Finally, channel flow is a function of the channel shape, slope and surface roughness.

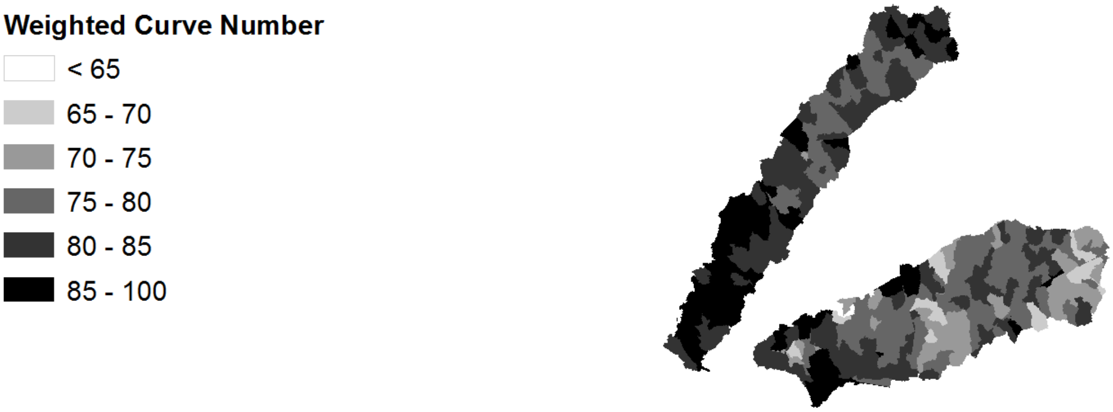
The alternative future land use basin models used the same lag times for each basin as those provided in the HMS models from CMSWS. Although time of concentration is affected by land cover (surface roughness) which changes in each scenario, a lack of data on other major determinants (such as culvert and pipe locations, and channel shape) prevented calculation of this parameter based on alternative future land use. In addition, close inspection of the lag times for each sub-basin in the existing and future conditions basin models provided by CMSWS confirmed that the parameter was kept constant for the effective future conditions study because it was used as a calibration parameter for the existing conditions model (AECOM, 2011).

Figure 5. Weighted Curve Numbers by Sub-basin for Existing and Future Land Use Scenarios

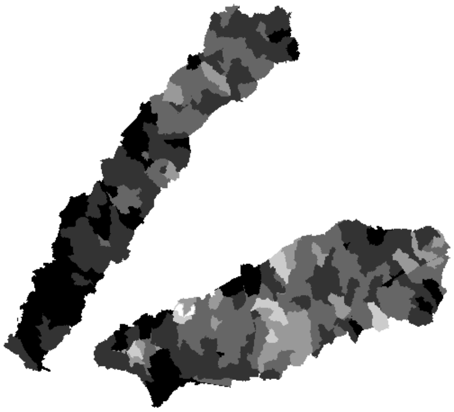


Existing Land Use

Planned Future



Compact Growth



Transit-Oriented Development

Channel Routing

A Modified Puls routing method was used. The Modified Puls routing method is based on the continuity equation, and assumes no lateral inflows during a single time-step (Hydrologic Engineering Center, 2000). Storage-outflow values were derived from field measurements of channel cross-sections (AECOM, 2011). The storage-outflow relationships developed by the mapping contractor were maintained for the purposes of this analysis.

Meteorologic Models

An SCS 24-hour Type II rainfall distribution was used for all simulation runs. The Type II distribution represents the most intense short-duration storm, and is appropriate for Mecklenburg County and other portions of western North Carolina (NRCS, 1986). Rainfall depths for the 1%, and 0.2% annual chance storm events were obtained from CMSWS guidelines (Baker & Dewberry, 2012).[8] Although the 1% chance rainfall event does not necessarily lead to the 1% annual chance flood, the models obtained from CMSWS were calibrated under this assumption.

Simulation Runs

Five simulation runs were conducted in HMS for each drainage basin (Table 6), all with an 84-hour control period and a 1-minute time step. The results from runs 1-3 were compared to results from the consultant's hydrology study for validation.

Table 6. Simulation Runs

No.	Basin Model	Meteorologic Model
1	Existing Conditions	1% annual chance
2	Existing Conditions	0.2% annual chance
3	Future Conditions	1% annual chance
4	Compact Growth Scenario	1% annual chance
5	TOD Scenario	1% annual chance

Hydraulic Model

Water surface profiles for each scenario were estimated through one-dimensional steady state analyses in HEC-RAS v.4.1 (Hydrologic Engineering Center, 2010). Four calibrated HEC-RAS models were obtained from CMSWS including models for Fourmile Creek, Rocky Branch Tributary, McMullen Creek and the McMullen Creek Tributary. Each RAS model contains a geometry file and a flow file. The geometry files for each RAS model were not altered. Though future urban development may change stream cross section characteristics (e.g. through construction of new stream crossings or culverts) the assumption that stream geometry will remain the same allows for the isolation of changes in flood elevation resulting solely from land use change.

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[8] Rainfall depth guidelines are within 0.1 inches of Atlas 14 estimates for Charlotte, North Carolina (NOAA, 2014).

The flow file for each model was updated with peak discharge values from the hydrologic analysis in HEC-HMS. Discharge values in the existing RAS flow files were used to cross-check the accuracy of the HMS model output for runs 1-3. Steady state analyses were performed for five flow profiles in each of the four RAS models, using a sub-critical flow regime, for a total of 20 water surface profiles. The results were exported as tables, and to a GIS-compatible file for inundation mapping.

Inundation Mapping

Inundation maps were created for each flood profile using ArcGIS v.10.1. A terrain model was generated from 2-foot contour lines and referenced to the North American Vertical Datum of 1988 (NAVD 88). Water surface elevations were imported to ArcGIS and interpolated in TIN format using the HEC-GeoRAS toolbar (Hydrologic Engineering Center, 2013a). The terrain model was subtracted from the water surface TIN using the surface difference tool. The output consisted of a raster of flood depths, with a 2-foot cell size, and a polygon representing the floodplain extent for each of the 20 profiles.

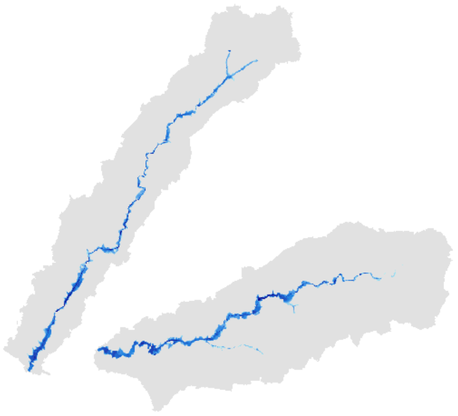
Isolated areas of inundation were removed; while these areas may be lower in elevation than the water surface profile, they cannot be inundated without a surface connection. The floodplain extent polygons for the McMullen Creek Tributary and Rocky Branch were merged with McMullen Creek and Fourmile Creek respectively. The merged files were then dissolved into a single floodplain polygon. The flood depth rasters for McMullen Creek Tributary and Rocky Branch were mosaiced with flood depth rasters for McMullen Creek and Fourmile Creek respectively. The depth raster of the parent stream was applied to areas that overlapped, in order to better represent backflow at the confluence with each tributary. Raster calculator was used to extract only values greater than zero, meaning all areas with positive flood depth. Finally, isolated areas of inundation were removed by extracting the rasters by a mask defined by the floodplain extent polygons (Figure 6).

Flood Risk Assessment

A flood risk assessment was conducted to determine the relative impact of each future land use scenario on potential flood losses. Although losses are a function of both exposure to flooding and vulnerability to damage, this analysis used only exposure to estimate potential losses, comparable to other desktop analyses examining changes in flood risk (Patterson & Doyle, 2009). Exposure analysis assesses the number, type and value of buildings at risk under each scenario (Merz et al., 2011).

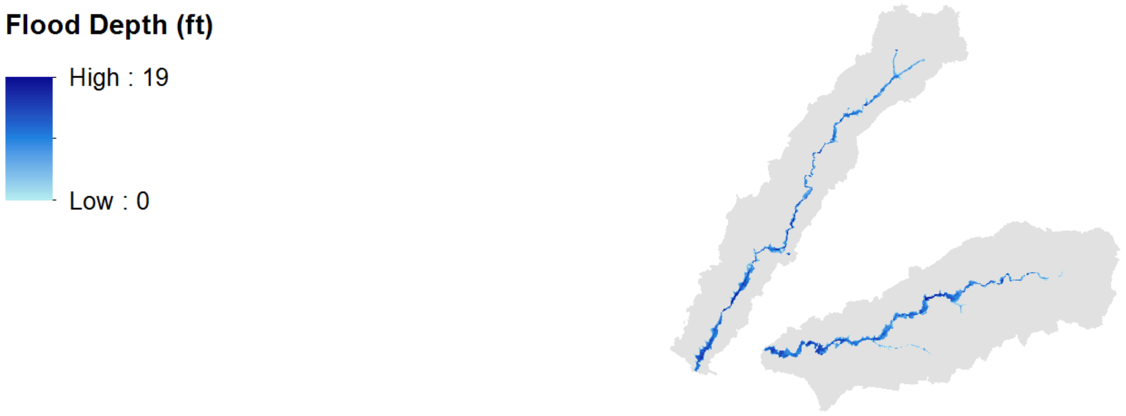
Parcel-level tax assessment data (Mecklenburg County GIS, 2011) were joined to a shapefile of all buildings in Mecklenburg County (Mecklenburg County GIS, n.d.) in ArcGIS v.10.1. For each scenario, buildings intersecting the floodplain were selected by location and summary statistics calculated on number of buildings, number of buildings larger than 1,200 square feet, and net building value. A separate intersect function was performed to calculate the total square footage of structures of structures falling within each of the 100-Year floodplain extents. Zonal statistics were calculated for each building using the flood depth raster, to determine the maximum flood depth per structure. Average maximum flood depths were calculated for each land use scenario. Because elevation data was unavailable for individual existing buildings in the two watersheds, the analysis assumed that all buildings have a first floor level at-grade.

Figure 6. 100-Year Floodplain and Flood Depth for Existing and Future Land Use Scenarios

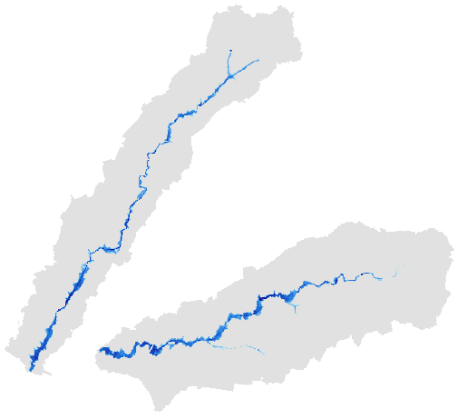


Existing Land Use

Planned Future



Compact Growth



Transit-Oriented Development

RESULTS

Hydrologic and Hydraulic Impacts

The hydrologic models estimated the peak discharges and time of peak for each hydrologic element and each storm event (Table 7). All of the future land use scenarios increase peak discharge relative to existing conditions. However, because the Compact Growth scenario concentrates new development and higher intensity uses in McMullen Creek watershed, it leads to the highest increase in peak discharge in McMullen Creek watershed and the lowest increase in peak discharge on Fourmile Creek, relative to existing conditions. The Transit-Oriented Development scenario results in peak discharges that are comparable to the Planned Future scenario in McMullen Creek watershed, while in Fourmile Creek watershed, the TOD scenario results in lower peak discharges than the Planned Future conditions scenario.

Table 7. Summary of Peak Discharges (reported upstream to downstream)

		Peak Discharge (cfs)				% Change from Existing		
Basin	Area (mi2)	Existing 100-Year	Planned Future	Compact Growth	TOD	Planned Future	Compact Growth	TOD
Fourmile Creek								
BAS787C	1.118	575	741	578	665	28.9%	0.5%	15.7%
BAS846C	3.139	1,801	2,155	1,840	2,096	19.6%	2.1%	16.4%
BA1104C	4.116	2,451	2,796	2,506	2,760	14.1%	2.2%	12.6%
BAS862C	5.046	3,076	3,497	3,143	3,383	13.7%	2.2%	10.0%
BAS875C	6.329	3,544	3,994	3,654	3,921	12.7%	3.1%	10.7%
BAS893C	8.074	3,812	4,295	3,944	4,180	12.7%	3.5%	9.7%
BAS905C	10.480	4,370	4,879	4,528	4,739	11.6%	3.6%	8.4%
BAS930C	18.173	5,005	5,525	5,170	5,338	10.4%	3.3%	6.6%
Rocky Branch Tributary								
BAS777C	0.978	756	818	780	780	8.3%	3.2%	3.2%
BAS806C	1.460	1,164	1,265	1,193	1,193	8.7%	2.5%	2.5%
BAS831C	2.121	1,337	1,461	1,380	1,380	9.2%	3.2%	3.2%
McMullen Creek								
BAS816C	1.688	1,958	2,102	2,152	2,101	7.3%	9.9%	7.3%
BAS828C	1.999	2,051	2,198	2,253	2,198	7.1%	9.8%	7.2%
BAS861C	4.752	3,964	4,215	4,320	4,209	6.3%	9.0%	6.2%
BAS865C	5.383	4,235	4,514	4,646	4,500	6.6%	9.7%	6.3%
BAS887C	7.517	4,519	4,805	4,953	4,791	6.3%	9.6%	6.0%
BAS906C	10.652	4,836	5,122	5,256	5,105	5.9%	8.7%	5.6%
BA1022C	13.091	5,145	5,379	5,474	5,417	4.5%	6.4%	5.3%
BA1021C	15.266	5,340	5,566	5,658	5,578	4.2%	6.0%	4.5%
McMullen Creek Tributary								
BAS775C	0.842	1,412	1,517	1,553	1,513	7.5%	10.0%	7.2%
BAS790C	1.169	1,646	1,764	1,807	1,767	7.2%	9.8%	7.3%
BAS803C	1.422	1,870	2,003	2,055	2,005	7.1%	9.9%	7.2%

Peak discharges reported for flow change locations.

Similarly, the Compact Growth scenario leads to the greatest increase in base flood elevation on McMullen Creek and the Planned Future scenario results in the greatest increase in base flood elevation on Fourmile Creek (Table 8). The Compact Growth scenario results in the least increase in base flood elevation on Fourmile Creek. The Planned Future and TOD scenarios affect base flood elevation almost identically on McMullen Creek, but the TOD scenario results in slightly lower base flood elevations on a few cross sections.

Table 8. Summary of Water Surface Elevations

	Existing Conditions 100-Year		**Existing Conditions 500-Year**		**Future Conditions 100-Year**		**Compact Growth 100-Year**		**TOD Scenario 100-Year**	
River Station	Peak Q (cfs)	Flood Elevation (ft)	Peak Q (cfs)	Flood Elevation (ft)	Peak Q (cfs)	Flood Elevation (ft)	Peak Q (cfs)	Flood Elevation (ft)	Peak Q (cfs)	Flood Elevation (ft)
Fourmile Creek										
50900	575	666.2	876	668.2	741	667.3	578	666.2	665	666.8
45617	1,801	635.7	2,662	637.1	2,155	636.2	1,840	635.7	2,096	636.1
44356	2,451	630.0	3,566	633.7	2,796	630.7	2,506	630.1	2,760	630.6
41700	3,076	615.7	4,472	617.4	3,497	616.3	3,143	615.8	3,383	616.1
39832	3,544	607.3	5,140	609.4	3,994	607.9	3,654	607.5	3,921	607.8
33500	3,812	590.3	5,585	591.8	4,295	590.7	3,944	590.4	4,180	590.6
29700	4,564	584.2	6,749	586.3	4,879	584.5	4,528	584.1	4,739	584.4
15968	5,026	556.6	7,525	558.3	5,525	557.0	5,170	556.7	5,338	556.8
Rocky Branch										
9300	756	630.5	1,045	631.2	818	630.6	780	630.5	780	630.5
7100	1,164	608.9	1,637	609.9	1,265	609.1	1,193	608.9	1,193	608.9
2900	1,337	566.8	1,972	567.7	1,461	567.1	1,380	566.9	1,380	566.9
McMullen Creek										
57300	1,958	684.0	2,724	684.8	2,102	684.1	2,152	684.2	2,101	684.1
52980	2,051	666.0	2,846	667.5	2,198	666.3	2,253	666.4	2,198	666.3
47152	3,964	648.7	5,521	653.5	4,215	649.3	4,320	649.7	4,209	649.3
44164	4,235	637.1	5,886	638.5	4,514	637.5	4,646	637.6	4,500	637.4
39383	4,519	618.2	6,307	620.4	4,805	618.6	4,953	618.8	4,791	618.6
26055	4,836	572.0	6,687	574.7	5,122	572.4	5,256	572.6	5,105	572.4
17620	5,145	551.2	7,164	553.1	5,379	551.5	5,474	551.5	5,417	551.5
9400	5,340	540.6	7,428	544.0	5,566	540.9	5,658	541.0	5,578	540.9
McMullen Creek Tributary										
3700	1,412	686.9	1,995	687.4	1,517	687.0	1,553	686.9	1,513	687.0
2650	1,646	676.0	2,302	676.9	1,764	676.2	1,807	676.3	1,767	676.2
700	1,870	666.5	2,629	667.4	2,003	666.7	2,055	666.8	2,005	666.7

Water Surface Elevations reported for flow change locations.

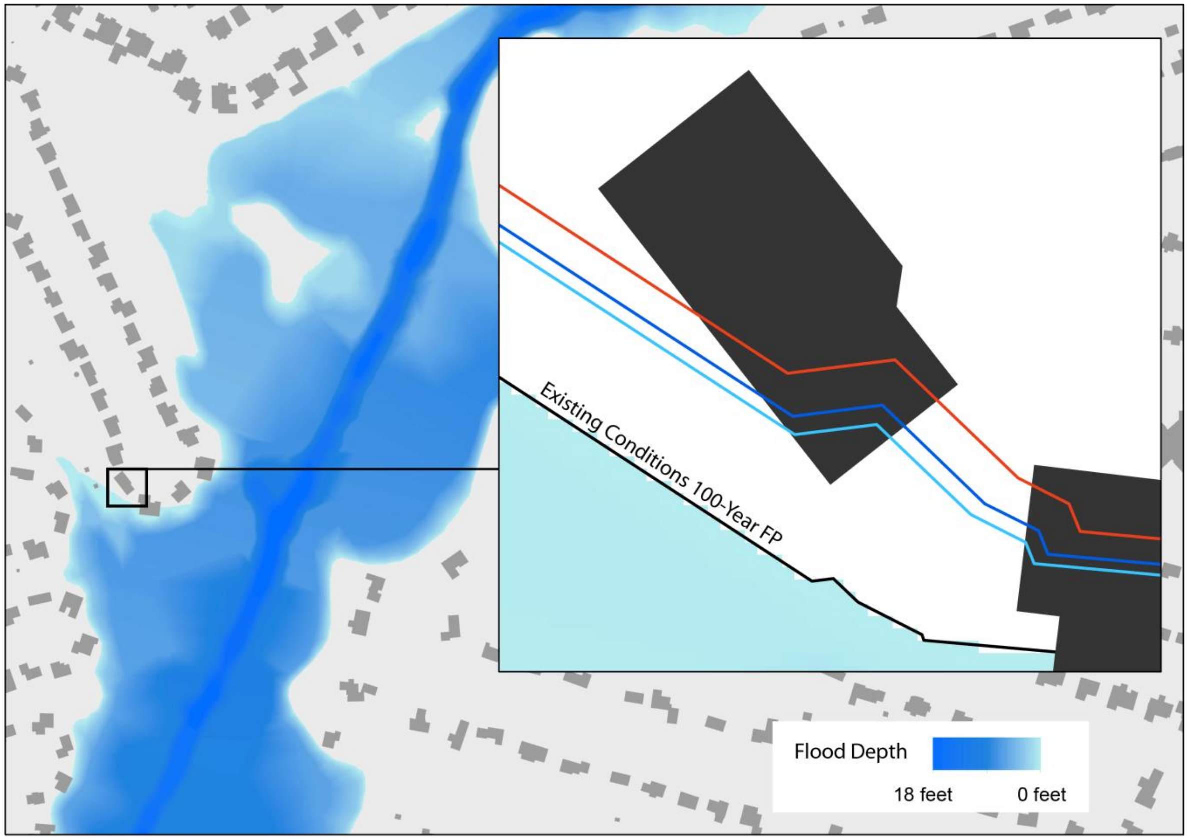
All three future land use scenarios lead to increases in base flood elevation over existing conditions. However, it should be recognized that at the most, the base flood elevation increases by 1.0-foot on McMullen Creek, and by 1.1-foot on Fourmile Creek over existing conditions. All three scenarios lead to base flood elevations well below the existing conditions 500-Year flood. Thus, for the expected level of new development in the study area, the 500-Year floodplain is not an adequate proxy for the level of risk associated with the future conditions 100-Year floodplain.

While these results indicate that the alternative future land use scenarios have differing effects on peak discharge and base flood elevation in the two drainage basins, the impacts are not directly comparable. The scenario that maintains base flood elevations closest to existing conditions in one watershed is not the same as the scenario that maintains the lowest base flood elevations in the other watershed. The results of the flood risk assessment provide information that can be compared across the two watersheds, to better understand the overall impacts of each scenario.

Flood Risk Impacts

The three future land use scenarios result in a broader floodplain extent relative to the existing conditions 100-Year floodplain. The Compact Growth scenario results in the broadest floodplain along McMullen Creek, while the Planned Future scenario results in the broadest floodplain on Fourmile Creek. In most portions of the study area, the variation in floodplain extent among the three future scenarios is negligible. However, in a handful of areas, the floodplain extents vary enough to have differing effects on existing structures (Figure 7).

Figure 7. Future Floodplain Extents on McMullen Creek



The exposure statistics demonstrate the relative impacts of each future land use scenario on flood risk. The Planned Future scenario results in the greatest increase in the number of structures intersecting with the 100-Year floodplain on Fourmile Creek, while the Compact Growth scenario results in the least amount of change (Table 9). In contrast, the Compact Growth scenario results in the greatest increase in exposed structures on McMullen Creek, while the TOD scenario results in the lowest amount of exposure. By summing the total exposure in each watershed for each scenario, it is evident that the TOD scenario results in the lowest overall exposure of existing structures to the 100-Year flood.

Table 9. Exposure to the 100-Year Floodplain

	Planned Future	Compact Growth	TOD
Change in No. Existing Structures - Fourmile Creek	4	1	2
Change in No. Existing Structures - McMullen Creek	23	29	22
Total Change in No. Existing Structures	**27**	**30**	**24**

A more conservative measure of exposure is the total number of *primary* structures intersecting with the 100-Year floodplain (Table 10). Building size was used as a proxy to determine whether a structure served as a primary, habitable structure; all buildings over 1,200 square feet in area were included. Again, the TOD scenario resulted in the lowest overall exposure of existing development. The TOD scenario also resulted in the lowest amount of existing building area and building value exposed to the 100-Year flood.

Table 10. Exposure to the 100-Year Floodplain

Measure of Exposure	Planned Future	Compact Growth	TOD
Total Primary Structures in 100-Year floodplain	141	143	139
Total Building Area (ft^2) in 100-Year floodplain	207,764	218,817	207,107
Total Building Value in 100-Year floodplain	$67.9 M	$70.2 M	$67.2 M

There was no notable difference in average flood depths (within 0.1 foot) for exposed structures overall between the three scenarios.

DISCUSSION

The results of the hydrologic and hydraulic analysis demonstrate that different future land use scenarios can influence the degree of expansion of the 100-Year floodplain, and that the response of individual watersheds to different land use scenarios varies depending on the degree to which development is intensified. As suggested by previous studies, there are direct trade-offs between the intensity and configuration of urban development, and the expansion of the floodplain. Under the Compact Growth scenario, which reallocated most of the expected future development to McMullen Creek watershed, the 100-Year floodplain along McMullen Creek expanded to the broadest point. The Planned Future scenario, which locates significant new development in Fourmile Creek watershed, resulted in the broadest floodplain on Fourmile Creek and the smallest expansion in the floodplain on McMullen Creek. Thus, the degree to which development is allocated to one watershed and not others will contribute to the degree to which the floodplain in that watershed expands beyond its existing delineation.

The Transit-Oriented Development scenario offered an interesting modification of the other two scenarios. Rather than shifting new development back and forth between watersheds, the TOD scenario essentially intensified residential development, concentrating more households in smaller, denser areas around transit. The overall area required to meet housing demand was lower under the TOD scenario because more households could be accommodated in a few, high density developments. As a result, more open space and forest cover was preserved in the TOD scenario relative to the Planned Future scenario. Although high-density residential development is associated with more impervious cover and a higher curve number, it appears that the maintenance of open space and forest cover more than compensated for the increased density of residential development. Thus, the TOD scenario resulted in a 100-Year floodplain that was greater than existing conditions, but less than the most-extreme scenario for both Fourmile and McMullen Creeks.

The results of the flood risk assessment allow for direct comparison between the outcomes in each watershed. Even a very extreme expansion of the 100-Year floodplain does not affect risk unless there is existing development (or other property, assets, infrastructure, or populations) intersecting with the expanded area. The McMullen Creek drainage basin contained more existing development than Fourmile Creek, such that the change in exposure among the three scenarios was weighted more heavily towards the impacts felt by McMullen Creek. Thus, while the Compact Growth scenario resulted in the least exposure on Fourmile Creek, it had the worst overall effects on flood risk once the exposure of development along McMullen Creek was accounted for. By translating the floodplain extents along multiple streams into a single, objective measure of risk, the flood risk assessment allowed for better comparison and evaluation of the three scenarios.

Ideally, this scenario analysis should be conducted at the same scale at which land use planning is conducted – either citywide or regionally. The Compact Growth scenario resulted in the greatest increase in flood risk for the study area; however, if a Compact Growth concept was used to reallocate future urban development across the entire City of Charlotte, and the flood risk impacts evaluated at that same scale, the balance could theoretically be tipped more favorably toward this type of smart growth configuration. Similarly, the TOD scenario resulted in the best outcome for these two watersheds, but may not reflect the overall change in flood risk that would result from implementing a TOD development policy citywide. This project does not attempt to draw conclusions about whether one planning paradigm is a better hazard mitigation strategy than others. The outcomes are largely dependent on the individual watersheds included in the analysis and the level of existing development in those watersheds.

Under any scenario involving an increase in urban development, some watersheds will fare better than others. Estimating the total amount of exposure on the basis of future flood conditions provides a salient indicator of citywide or regional risk - one that local decision-makers could include when considering the costs and benefits of different future land use configurations.

Coordination and the Shared Governance Dilemma

A challenge implicit in this finding is that conducting a full scenario analysis will require future land use data from all jurisdictions sharing watershed boundaries. In order to maximize the increment of future development under consideration in the various scenarios, future land use data should share a similar plan horizon date. In other words, if the City of Charlotte were conducting a comprehensive land use plan update and using a scenario analysis to evaluate the effects of multiple land use configurations on flood risk, it would be helpful if surrounding municipalities participated in the same scenario planning process. Of course, Charlotte’s land area is substantially larger than that of adjacent municipalities and so changes in flood risk resulting from Charlotte’s future land use plan may outweigh any changes resulting from the land use choices in other communities. The sensitivity of flood risk in large cities to the land use plans of adjacent communities is an interesting issue for further research.

A related issue involving inter-jurisdictional coordination is that the actions of one local government may adversely affect the flood risk of another. This is not a problem unique to flood hazards, and as such is a challenge in any regional scenario planning exercise; environmental problems, including flood hazards, generally do not respect jurisdictional boundaries. Local jurisdictions with advanced growth management programs may still experience the byproducts of poorly managed development, such as air pollution or impaired water quality, if upwind or upstream communities do not adhere to the same standards (Bengston, Fletcher, & Nelson, 2004). Communities located outside of the floodplain may soon find the floodplain expanding into previously low hazard areas if upstream communities allow new development to increase impervious surface cover without providing for stormwater management infrastructure (Merz et al., 2011).

The challenge of addressing environmental problems that affect jurisdictions at different scales of government unevenly is a *shared governance dilemma*. Berke (1998) linked this concept to natural hazard mitigation, noting that local governments have little incentive to mitigate hazards when the fiscal impacts are felt most strongly at the state and federal levels. Additionally, there are likely to be outcomes in which the scenario that best mitigates flood hazards for one local jurisdiction is not the optimal scenario for all other local jurisdictions with which it shares watershed boundaries. While the process illustrated in this project provides a strategy for mitigating hazards within a major growth center, individual local governments may not have the incentive to act due to the shared governance dilemma.

Accuracy, Precision & Uncertainty

The magnitude of difference between the outcomes of each scenario may be an area of concern for local governments, as well. Because scenario analyses rely on forecasts, there is no way to test the statistical significance of the difference. The three scenarios in this project produced base flood elevations that varied by less than one foot of vertical elevation. A one foot change in vertical elevation is used to determine the extent of the 100-Year floodway (44 CFR Ch. I § 9.4), and as such could be considered a benchmark value for determining a significant difference in BFE. Even a few inches of increase in elevation could result in a greater number of structures flooded, as evidenced by the flood risk assessment. The difference in terms of the number of primary structures exposed to the 100-Year flood under each scenario was minimal, but the value of each additional structure meant that the difference in terms of total building value exposed to the 100-Year flood under each scenario was hundreds of thousands of dollars. In sum, the magnitude of the difference in outcomes depends on the outcome measure. This study presented multiple outcome measures for each scenario, including the change in peak discharge, the change in base flood elevation, the floodplain extent, and several measures of exposure to the 100-Year flood.

Nevertheless, it is important to acknowledge that all of these outcome measures are based on hydrologic and hydraulic models which incorporate considerable error and uncertainty (National Research Council, 2009). The quality of elevation data is a known contributor to error in both models. Elevation data is used to delineate sub-basins and flow paths, and determine time of concentration in hydrologic models; and is also used to determine channel cross-section measurements in hydraulic models. The National Elevation Dataset, the most accessible elevation data for the continental U.S., contains error that exceeds FEMA's floodplain mapping standards by more than a factor of 10 (National Research Council, 2007). In North Carolina, superior quality elevation data is available thanks to statewide LiDAR data with 2-foot equivalent contour accuracy. In addition, CMSWS requires consultants working in Mecklenburg County to verify stream alignment, crossings, and channel geometries with field measurements (Baker & Dewberry, 2012), providing further validation of the elevation data used to produce this project. However, this level of detail is not readily available to all local governments and is very expensive to procure.

Additionally, the precision of the estimates from the hydrologic and hydraulic models, which are calculated to the 1/100th foot, do not reflect the overall precision of the model inputs. Interpolated elevation data, even based on highly-accurate 2-foot contours, corresponds to an average error of 0.61 feet (National Research Council, 2007). Streamflow data used to develop storage-discharge functions and to calibrate hydrologic and hydraulic models is reported to the nearest cubic foot and may also include considerable error. Thus, local decision-makers may be hesitant to base decisions on differences in base flood elevation that are equivalent to or less than the precision or known potential error of the inputs.

Despite issues with accuracy, precision and uncertainty, the effects of land use change should not be ignored. The shortcomings of model inputs and assumptions are a matter of considerable concern even with existing floodplain mapping procedures (Brath et al., 2006; Highfield et al., 2013; National Research Council, 2007, 2009; Patterson & Doyle, 2009; Smemoe, Nelson, Zundel, & Miller, 2007), and even for existing flood insurance studies and engineering models in North Carolina (Merwade, Olivera, Arabi, & Edleman, 2008). Continuous refinement of elevation data, additions to streamflow records, and maintenance of engineering models will continue to improve the reliability of base flood elevation estimates and floodplain maps over time. Moreover, the relationships between scenario outputs are less likely to be affected than the magnitude of the discrepancies between them.

Climate Change Impacts

A final consideration for predicting future flood risk is the potential effect of climate change. An altered precipitation regime is expected to interact with, and in some cases compound the effects of land use change in terms of average and peak discharges (Hejazi & Moglen, 2008; Patterson, Lutz, & Doyle, 2013). For example, Olivera & DeFee (2007) found that changes in precipitation caused a 96% increase in peak flows in a study basin in Texas between 1949 and 2000, while urbanization contributed to only a 32% increase. A recent study found potential increases of 50 to 60% in the magnitude of the 100-Year flood in some regions of the US based on climate change and population growth (Kollat et al., 2012).

Climate change is notably absent from the scenario planning framework presented in this project, which focused solely on land use change. The spatial and temporal resolution at which climate models forecast changes in rainfall patterns are far coarser than the resolution at which flood insurance studies are conducted (National Research Council, 2011). Incorporating climate projections into future conditions flood models could compound the existing shortcomings of the precision and uncertainty of model inputs, and finer resolution models are needed for hydrologic impact assessments (Fowler, Blenkinsop, & Tebaldi, 2007; Xu, 1999). The uncertainty surrounding the magnitude of climate change impacts on local flood regimes presents challenges for accurately managing local development in flood-prone areas.

Nevertheless, there is a growing body of research suggesting that hazard mitigation and climate action planning can be integrated through their mutual connection to land use planning (Glavovic & Smith, 2014). These strategies may be implemented while recognizing the shortcomings of existing hazard mitigation frameworks both for the purposes of hazard mitigation itself and for adaptation to climate impacts. The shortcomings of this process reflect those associated with flood insurance studies generally, and are priorities for future research and investment.

CONCLUSION

There is a growing recognition of the important linkages between land use planning and flood hazard mitigation. However, there are many challenges to integrating best practices from these two disciplines including outdated 100-Year floodplain delineations, competing local objectives, and a lack information about the flood risk outcomes of land use plans. This project demonstrates a process that connects future conditions flood models to the need for more context-specific land use plans and hazard mitigation interventions. The application of this process to two watersheds in Mecklenburg County, North Carolina shows that land use configurations are a controlling factor influencing the 100-Year floodplain extent, and that different land use configurations can result in different levels of future flood risk. The choice to locate new development in one watershed over another has implications for a community’s overall level of flood risk.

The scale of analysis is the main hurdle in applying this process to a real-world comprehensive planning process. The boundaries of flood insurance studies do not necessarily align with the boundaries of cities and counties, such that maximizing the spatial and time scales of scenarios requires some degree of interagency and inter-jurisdictional cooperation. Despite similar challenges of scale, integrated transportation and land use scenario planning has become the norm for many fast-growing regions in the U.S., and there is no reason that flood risk assessment and land use scenario planning cannot also be integrated at the local or regional level.

Greater awareness, funding, and technical assistance are needed to spur broader local adoption of new hazard mitigation tools, including both future conditions flood models and scenario planning. At the federal level, FEMAs guidance sets the stage for hazard mitigation, flood insurance studies, and the use of future conditions floodplain models. Guidance that encourages the use of future conditions models and that enables local governments to include alternative land use and climate change scenarios could help address gaps in existing hazard mitigation efforts and improve the outlook for the NFIP.

ACKNOWLEDGMENTS

I would like to thank my advisor Mukesh Kumar for his guidance in developing this project and James Scanlon at Charlotte-Mecklenburg Storm Water Services for providing me with the models and data needed to carry out the analysis. Additionally, I would like to thank Martin Doyle, John Fay, Yanlan Liu, and Christa Kelleher at the Nicholas School of the Environment; Gavin Smith at the UNC Coastal Hazards Center; and Kurt Golembesky at the North Carolina Division of Emergency Management for their advice and support.

I would also like to acknowledge the following people who were kind enough to speak with me about floodplain mapping and planning practices in their local communities and/or the communities they advise: Graham Summerson, City of Durham, NC; Dave Canaan, Charlotte-Mecklenburg Storm Water Services, NC; Jason Lawrence, City of Charlotte, NC; Lori Quinn, City of Charlotte, NC; Darrin Punchard, AECOM; Brian Varrella, Olsson Associates; Bill Robison, City of Tulsa, OK; Carl Walker, City of Roseville, CA; Beck Anderson, City of Fort Collins, CO; Terri Fead, UDFCD, CO; Jill Bazinet, City of Alpharetta, GA; David Lucas, Snohomish County, WA; Dennis Dixon, Pierce County, WA; Donald Demetrius, Fairfax County, VA; and Daniel Habete, Fairfax County, VA. These conversations were extremely helpful in formulating my project design and gave me a better understanding of the practical applications and limitations of future conditions floodplain maps. Thank you.

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APPENDIX

Table A1. Existing and Future Land Use - Planned Future Scenario

Land Use Description	**Four Mile Creek**					**McMullen Creek**					**TOTAL**
	Existing Conditions		**Planned Future**		**Change**	**Existing Conditions**		**Planned Future**		**Change**	**Change**
	Acres	Percent	Acres	Percent	Acres	Acres	Percent	Acres	Percent	Acres	Acres
Woods/Brush	2,475	20.2%	694	5.7%	-1,781	990	10.1%	501	5.1%	-489	-2,270
>2 Acre Residential & Open Space	1,250	10.2%	1,111	9.1%	-139	436	4.5%	433	4.4%	-4	-142
0.5 to 2 Acre Residential	2,258	18.5%	2,507	20.5%	249	1,521	15.6%	1,579	16.2%	58	308
0.25 to 0.5 Acre Residential	3,107	25.4%	4,352	35.6%	1,246	3,358	34.4%	3,517	36.0%	159	1,404
<0.25 Acre Residential	287	2.3%	305	2.5%	17	185	1.9%	178	1.8%	-8	10
Institutional	329	2.7%	521	4.3%	192	389	4.0%	495	5.1%	106	297
Industrial – Light	28	0.2%	107	0.9%	78	46	0.5%	46	0.5%	1	79
Industrial – Heavy	349	2.9%	413	3.4%	64	943	9.7%	993	10.2%	50	115
Commercial – Light	182	1.5%	231	1.9%	49	298	3.1%	409	4.2%	111	160
Commercial – Heavy	279	2.3%	304	2.5%	25	321	3.3%	336	3.4%	15	40
Water Bodies	104	0.8%	104	0.9%	0	21	0.2%	21	0.2%	0	0
Transportation	1,582	12.9%	1,581	12.9%	-1	1,259	12.9%	1,259	12.9%	0	-1
TOTAL	**12,230**		**12,230**		**0**	**9,767**		**9,767**		**0**	**0**

Table A2. Existing and Future Land Use – Compact Growth Scenario

Land Use Description	**Four Mile Creek**					**McMullen Creek**					**TOTAL**
	Existing Conditions		**Compact Growth**		**Change**	**Existing Conditions**		**Compact Growth**		**Change**	**Change**
	Acres	Percent	Acres	Percent	Acres	Acres	Percent	Acres	Percent	Acres	Acres
Woods/Brush	2,475	20.2%	2,385	19.5%	-90	990	10.1%	636	6.5%	-354	-444
>2 Acre Residential & Open Space	1,250	10.2%	1,250	10.2%	0	436	4.5%	77	0.8%	-360	-360
0.5 to 2 Acre Residential	2,258	18.5%	2,348	19.2%	90	1,521	15.6%	1142	11.7%	-379	-289
0.25 to 0.5 Acre Residential	3,107	25.4%	3,107	25.4%	0	3,358	34.4%	3213	32.9%	-145	-145
<0.25 Acre Residential	287	2.3%	287	2.3%	0	185	1.9%	747	7.7%	562	562
Institutional	329	2.7%	329	2.7%	0	389	4.0%	677	6.9%	288	288
Industrial – Light	28	0.2%	28	0.2%	0	46	0.5%	127	1.3%	81	81
Industrial – Heavy	349	2.9%	349	2.9%	0	943	9.7%	1057	10.8%	115	115
Commercial – Light	182	1.5%	182	1.5%	0	298	3.1%	449	4.6%	150	150
Commercial – Heavy	279	2.3%	279	2.3%	0	321	3.3%	361	3.7%	40	40
Water Bodies	104	0.8%	104	0.8%	0	21	0.2%	21	0.2%	0	0
Transportation	1,582	12.9%	1,582	12.9%	0	1,259	12.9%	1259	12.9%	0	0
TOTAL	**12,230**	**100.0%**	**12,230**	**100.0%**	**0**	**9,767**	**100.0%**	**9767**	**100.0%**	**0**	**0**

Table A3. Existing and Future Land Use – Transit-Oriented Development Scenario

Land Use Description	**Four Mile Creek**					**McMullen Creek**					**TOTAL**
	Existing Conditions		**TOD**		**Change**	**Existing Conditions**		**TOD**		**Change**	**Change**
	Acres	Percent	Acres	Percent	Acres	Acres	Percent	Acres	Percent	Acres	Acres
Woods/Brush	2,475	20.2%	1,990	16.3%	-486	990	10.1%	777	8.0%	-213	-698
>2 Acre Residential & Open Space	1,250	10.2%	1,111	9.1%	-139	436	4.5%	288	3.0%	-148	-286
0.5 to 2 Acre Residential	2,258	18.5%	2,010	16.4%	-248	1,521	15.6%	1,262	12.9%	-258	-506
0.25 to 0.5 Acre Residential	3,107	25.4%	3,394	27.8%	287	3,358	34.4%	3,507	35.9%	148	435
<0.25 Acre Residential	287	2.3%	475	3.9%	188	185	1.9%	379	3.9%	194	382
Institutional	329	2.7%	511	4.2%	182	389	4.0%	516	5.3%	127	308
Industrial – Light	28	0.2%	95	0.8%	66	46	0.5%	46	0.5%	0	66
Industrial – Heavy	349	2.9%	415	3.4%	66	943	9.7%	983	10.1%	41	107
Commercial – Light	182	1.5%	234	1.9%	53	298	3.1%	407	4.2%	109	162
Commercial – Heavy	279	2.3%	310	2.5%	31	321	3.3%	321	3.3%	0	31
Water Bodies	104	0.8%	104	0.8%	0	21	0.2%	21	0.2%	0	0
Transportation	1,582	12.9%	1,582	12.9%	0	1,259	12.9%	1,259	12.9%	0	0
TOTAL	**12,230**	**100.0%**	**12,230**	**100.0%**	**0**	**9,767**	**100.0%**	**9,767**	**100.0%**	**0**	**0**

Table A4. Future Land Use – Summary Table

Land Use Description	Change over Existing Conditions (Acres)		
	Planned Future	Compact Growth	TOD
Woods/Brush	-2,270	-444	-698
>2 Acre Residential & Open Space	-142	-360	-286
Institutional	297	288	308
Industrial – Light	79	81	66
Industrial – Heavy	115	115	107
Commercial – Light	160	150	162
Commercial – Heavy	40	40	31
Water Bodies	0	0	0
Transportation	-1	0	0
TOTAL	**0**	**0**	**0**

Table A5. Future Residential Dwelling Units – Summary Table

Land Use Description	Residential Dwelling Units		
	Planned Future	Compact Growth	TOD
0.5 to 2 Acre Residential	3,269	2,792	2,618
0.25 to 0.5 Acre Residential	20,985	16,854	18,401
<0.25 Acre Residential	3,859	8,279	6,836
TOTAL	**28,112**	**27,924**	**27,855**