# SPATIOTEMPORAL ANALYSIS OF SOCIOECONOMIC EXPOSURE TO ASSESS FLOOD POLICY EFFECTIVENESS

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**ABSTRACT**

LAUREN PATTERSON: Spatiotemporal Analysis of Socioeconomic Exposure to Assess Flood Policy Effectiveness
(Under the direction of Martin Doyle)

After nearly a century of flood policies in the U.S., losses have continued to increase. This thesis examined the potential increase in losses related to the 100-yr floodplain, which is the minimum standard for implementing policies. Despite this core role, as much as 1.5 vertical meters of uncertainty exists when delineating the boundray. However, no uncertainty is provided on flood maps, which could result in increased socioeconomic exposure adjacent to the boundary when a larger flood occurs.

This thesis quantified the effectiveness of mitigation from 1990 to 2000 for five North Carolina counties by examining changes in exposure inside and adjacent to the 100-yr floodplain. Findings indicated mitigation efforts have been effective inside the 100-yr floodplain; however, there was a significant increase in exposure adjacent to this floodplain. Stream scale analyses indicated mitigation effectiveness was influenced by stream size, distance from the stream, and location in urban versus rural areas.

## DEDICATION

I would like to dedicate this thesis to my family for all their love and support. And to my Purdue family, who through their invaluable advice, numerous generous opportunities, and patient guidance has led me to this thesis.

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# ABBREVIATIONS

| | |
|---|---|
| ASFPM | Association of State Floodplain Managers |
| cms | cubic meters per second |
| DEM | Digital Elevation Model |
| DFIRM | Digital flood insurance rate map |
| ESRI | Environmental Systems Research Institute |
| FEMA | Federal Emergency Management Agency |
| FIRM | Flood insurance rate map |
| FLEM | Flood Loss Exposure Model |
| GIS | Geographic Information Systems |
| HMGP | Hazard Mitigation Grant Program |
| HMPI | Hazard Mitigation Planning Initiative |
| IPD | Integrated population density |
| LiDAR | Light Detection and Ranging |
| NFIP | National Flood Insurance Program |
| NLCD | National Land Cover Data |
| NPD | Normalized population density |
| (T)FLEM | (Temporal) Flood Loss Exposure Model |
| TIGER | Topological Integrated Geographic Encoding and Referencing |
| USGS | United States Geological Survey |

# CHAPTER 1

## INTRODUCTION TO FLOOD HAZARDS AND POLICIES

### 1.1 Introduction to Hazards and Flood Losses:

Floods are spatially one of the most dynamic of natural hazards, as the geographic impact is dependent on both the size of the flood event and the physiographic characteristics of the region. Floods are frequent events, accounting for 1/3 of all natural hazards and impacting societies throughout the world. During the 20$^{th}$ century, floods caused seven million fatalities and $250 billion in damages (Cohen, 2004; Linnerooth-Bayer, 2001); however, neither are the distribution of mortality and economic losses uniform because flood losses are correlated with the resources and management strategies of a society (Berz, 2006). For example, societies choosing to live with floods or lacking advanced warning technology (Wong & Zhao, 2001) are more likely to suffer higher mortality losses; whereas, societies with flood control and warning methods might heavily develop floodplains and suffer greater economic losses (e.g. Pinter, 2005; Burby, 2002). Despite societies' efforts to limit flood impacts, the frequency of major flood events and losses has continued to increase (Berz, 2006; van Aalst, 2006).

The United States, a nation with resources, technology, and capital, has not been immune to the global trends of increasing hazard losses. It is currently estimated that natural hazards cost the U.S. government an average of $6 - $10 billion annually (Mileti, 1999). The largest expenditure is spent on riverine floods (21%) (Cutter & Emrich, 2005), which also represents 90% of natural disaster occurrences in the U.S. (GAO, 2005). In conjunct with increasing hazard losses, the costs of national flood damages are annually increasing at a rate of 3.45% (Cartwright, 2005; Pielke et al, 2002).

**1.2 Introduction to Floodplain Management Strategies:**

National flood management strategies in the U.S. have evolved over the past 90 years in an attempt to decrease mortality and economic losses. Initially, flood policy was preventative, using structural flood control measures to contain flooding (1917 - present) through dams and levees. This effort was followed by the National Flood Insurance Program (NFIP) (1968 – present) as a reactive policy to spread the costs and provide public relief after a flood event. However, extensive flooding in the Mississippi River Basin in 1993 resulted in 49 deaths and $16 billion in damages (IFMRC, 1994), after which the effectiveness of our flood policies were debated. The resulting formal reviews found the optimal strategy for reducing flood losses was to "limit or even reduce infrastructure on floodplains" (Pinter 2005). Accordingly, U.S. national policy entered the "mitigation era" (Godschalk et al. 1999) as the Federal Emergency Management Agency's (FEMA) began a proactive effort to remove and limit floodplain development.

Billions of dollars have been spent trying to *decrease* flood losses, yet flood losses have steadily *increased* throughout each geographic and climatologic region of the country. Rising flood losses suggests floods and humans are increasingly intersecting through space and time, as Mitchell (2006) noted that natural hazards are "constructed by human interactions with the physical environment and that their importance is likely to grow-not diminish-as societies develop." The recognition that development in floodplains increases exposure to flooding and is culminating in increased flood losses suggests the potential for decreasing future impacts requires a refocusing of floodplain management.

One of the most important issues that need to be considered when developing floodplains is how system uncertainty is handled in our nation's flood policy. Sources of uncertainty in decision-making can arise from lack of data, deficiencies in models, and stochastic environments (Mitchell, 2002). It has been recommended by the Rio Declaration Principle 15 (Johnson, 1993) that the precautionary principle is utilized when dealing with uncertainty; whereby, activities are managed to minimize both known and unknown risks; thereby erring on the side of caution to protect potential victims. With regards to floodplain management, all of the sources of uncertainty outlined above are present in the floodplain policies utilized today, yet flood policy has not been precautionary.

Flood policy is based on 100-yr floodplain boundary, which is the horizontal extent of inundation for a flood that statistically occurs once every hundred years. The selection of the 100-yr floodplain was chosen as a standard guideline for policy enforcement (Robinson, 2004 & Reuss, 2004). However, the process of delineating the 100-yr floodplain boundary has uncertainty due to missing and low resolution data, the stochastic nature of floods, and epistemic errors in model assumptions. Floodplain boundaries are displayed on Flood Insurance Rate Maps (FIRM) without any indication of uncertainty. Flood policy in the U.S. is such that those located inside the 100-yr floodplain are required to obtain flood insurance, adhere to stricter building codes and participate in mitigation activities. Outside the 100-yr floodplain, there are no development requirements to reduce flood losses.

The mitigation policy in 1994 used the 100-yr floodplain boundary to establish a spatial boundary within which infrastructure should be limited or reduced. Since risk is a function of the intersection between the spatial location of a hazard and socioeconomic value, the risk of flood losses is greatest when people and property are concentrated on the floodplain. Floodplain management activities need to focus on reducing the exposure of urban areas to the most significant flood expected to occur (IFMRC, 1994). This boundary might not coincide with the 100-yr floodplain due to delineation errors or if the FIRM is outdated. Moreover, IFMRC (1994) emphasizes that the magnitude of flood that should be managed for needs to be based on the spatial distribution of social and economic assets within the floodplain. According to James (2004), an objective approach to floodplain management requires discontinuing the use of the 100-yr floodplain and instead uses the "fundamental principles from economic analysis, environmental quality, and social well-being" in delineating FIRMs. The risk based approach would also alleviate the problem of the 100-yr flood standard in not addressing the risk of larger floods to floodplain occupants located outside the 100-yr boundary (Davis, 2004). A potential solution would be to maintain the 100-yr floodplain as a bare minimum standard and utilize the precautionary principle in areas where risk-based analysis indicates a high potential for flood loss outside the 100-yr boundary.

One of the conditions associated with effective management strategies is the transfer of policy goals into specific measurable terms that can be monitored (NCDEM, 2007). The focus of monitoring programs is to assess policy effectiveness by measuring indicators for changes and explaining cause effect relationships. Monitoring and feedback regarding the effectiveness of policy on reducing flood losses will assist in the creation of more efficient and cost-effective policies (Figure 1.1). The broad goal for floodplain management is to reduce flood losses, which can be translated into tangible measures of population and property exposure. Assessing changes in exposure can inform floodplain managers where and under what conditions policy has been effective. Quantification and monitoring of exposure can allow policies to be modified to increase effectiveness. Thus far, floodplain management strategies have been monitored ad hoc and the lack of national guidelines and data collection standards for flood loss events has prevented the effective monitoring and assessment of flood control policies (Cartwright, 2005; Pielke et al, 2002).

### 1. 3 Thesis Outline

The objective of this thesis was to examine the sustainable development of five counties in North Carolina by quantifying changes in social and economic exposure. The methodology established used freely available data to enable consistent analysis of exposure and hazards throughout the U.S. The effectiveness of the 1994 mitigation policy was assessed by examining changes in exposure through time inside and adjacent to the 100-yr floodplain. Chapter 2 assessed the changing spatiotemporal exposure at the county scale to examine changes in exposure inside and adjacent to the 100-yr floodplain from 1990 to 2000 and changes in socioeconomic value from the original FIRM to the newly created digital FIRM. Chapter 3 continued the exploratory analysis by assessing socioeconomic exposure to the flood hazard in relation to fluvial proximity. Changes in exposure were further subdivided by stream size, urbanization and floodplain boundaries, to determine the contribution of each factor to flood exposure. Chapter 4 examined exposure as a function of elevation at multiple spatial scales to assess the potential for establishing FIRMs using elevation criteria; thereby reducing some of the uncertainty in calculating the 100-yr floodplain. The thesis ends with an overall summary of findings and their usefulness for assessing and guiding flood policy to reduce the imacts of future floods.

**1.4 Figure:**

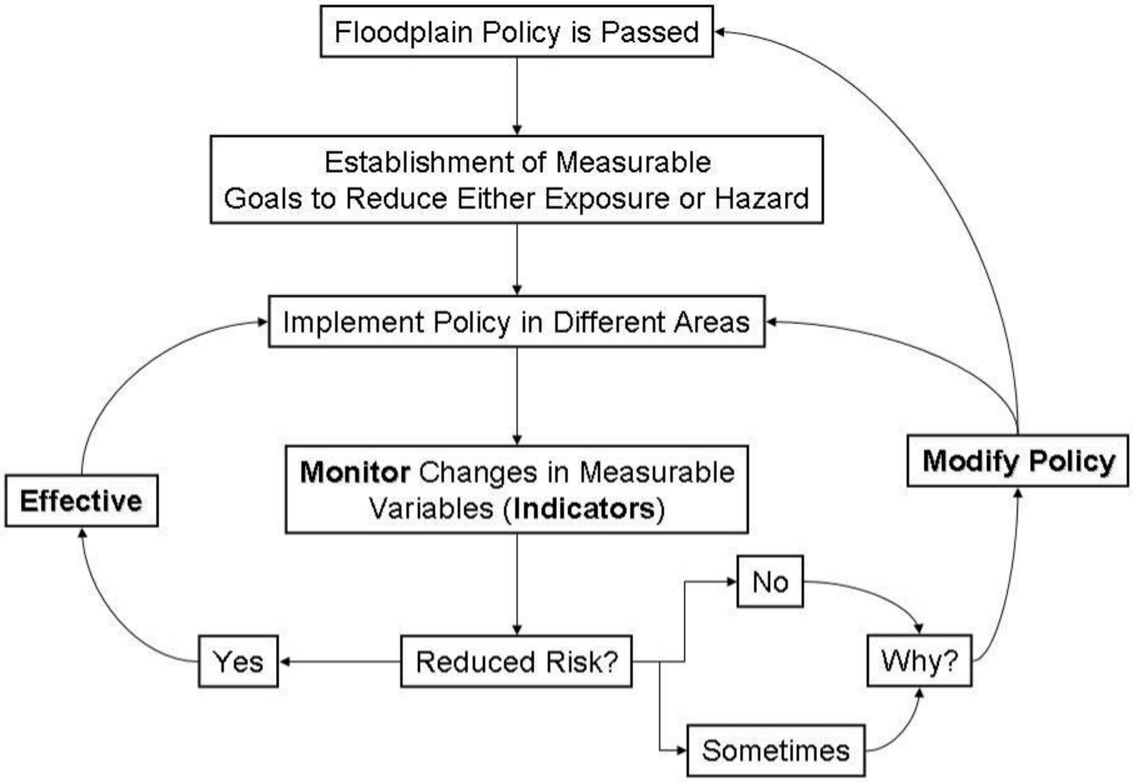


**Figure 1.1:** Use of indicators and monitoring to assess policy effectiveness. Once a policy is passed, measurable goals and indicators must be created and monitored in order to determine policy effectiveness and enhance successfulness of the policy.

# CHAPTER 2

## EXPLORATORY ANALYSIS OF SOCIOECONOMIC EXPOSURE IN RELATION TO THE 100-YR FLOODPLAIN AT THE COUNTY SCALE

### 2.1 Introduction:

The most costly natural hazard in the United States with respect to lives lost and dollars spent is flooding. After 90 years of nationally focused flood policy efforts, riverine floods and coastal storms are annually responsible for losses of $2.4 to 4 billion and account for 40% of damage costs from all natural hazards (Cutter & Emrich, 2005; Mileti, 1999). There are seven to eight million households located in areas of significant flood risk that potentially contribute to extensive future social and economic (socioeconomic) flood losses (Riggs, 2004 & Burby et al, 2002). Between 1992 and 2001, flooding accounted for 90% of all natural disasters in the U.S. (GAO, 2005) and contributed to 900 deaths and $55 billion in damages, with an annual average of $1 billion in property damages alone (GAO, 2004). Moreover, global climate change models are predicting increases in the intensity and frequency of extreme precipitation events that could result in flooding (van Aalst, 2006), especially in the Southeast portion of the U.S. (Milly et al, 2005). In conjunct with increasing frequency and intensity of flood events, the costs of floods are annually increasing at a rate of 3.45% (Cartwright, 2005; Pielke et al, 2002).

United States flood control policies have evolved in three main stages during the 20$^{th}$ century: 1) structural approaches to control rivers (1917 to present), 2) national flood insurance program to offer relief (NFIP) (1968 to present), and 3) mitigation by removing people and objects from the floodplain (1994 to present). Gilbert White (1945) questioned the effectiveness of flood control polices after observing that the presence of large structures to control rivers created a false sense of security and the misconception that floodplains were safe to develop. The structural control of rivers has resulted in further encroachment in high risk flood areas, which increases the potential for flood catastrophes (Burby, 2006; Burby et al, 2000; Thaler, 1999). The World Commission on Dams (2000) has found the development of flood control structures has coincided with economic development in the United States.

The NFIP formed in an effort to spread the costs of flood disasters after they occurred. The NFIP has undergone several significant reforms in an effort to increase effectiveness and expand its market (Burby, 2002); however, only 20 to 30% of floodplain occupants have flood insurance (Linnerooth-Bayer et al, 2001; IFMRC, 1994). The lack of participation has limited the potential success of the NFIP; and after extensive flooding of the Mississippi in 1993, it was found that only 12% of $16 billion in flood losses were insured (Linnerooth-Bayer et al, 2001; IFMRC, 1994). The resulting formal reviews of U.S. flood-control policy found the optimal strategy for reducing flood losses was to “limit or even reduce infrastructure on floodplains” (Pinter 2005). Accordingly, U.S. national policy entered the “mitigation era” (Godschalk et al. 1999) as the Federal Emergency Management Agency (FEMA) began programs to remove people from the floodplain.

## 2.2 Background:

### *2.2.1 Establishing the 100-yr Floodplain in our Nation’s Flood Policy*

The underlying assumption of U.S. flood control policies, whose success has been measured by an increase in mortality and economic costs throughout the 1990’s as “more people and property are placed in harm's way" (Cutter & Emrich, 2005), relies on the concept of the 100 year (100-yr) floodplain. The 100-yr floodplain is the maximum extent of land that would be inundated by a flood with a one percent chance of occurring in any year. Three hydrologic methods are most commonly used to estimate the 100-yr flood discharge: 1) gauging station data, 2) regional regression equations, and 3) rainfall-runoff models (Thomas & Baker, 2004). Hydrologic models are typically used to simulate the surface runoff in a watershed by calculating peak discharge for a variety of precipitation events. The generated flood distribution curves plot discharge with the frequency of occurrence. However, most areas have limited precipitation or stream flow records, and the peak flow must be extrapolated both spatially and temporally. A hydraulic model then incorporates the topographic, frictional loss, and hydrologic data to calculate vertical flood depths and the corresponding horizontal flood extent throughout the watershed.

The decision to use the 100-yr floodplain as the baseline standard was arbitrarily established as an enforceable boundary (Robinson, 2004 & Reuss, 2004) during the creation of the NFIP. The rational was that the 100-yr floodplain provided a uniform standard to administer the NFIP and it was anticipated to balance the economic benefit of development with the potential costs from a flood event. The establishment of the 100-yr floodplain was questioned prior to its inception, as scientists such as Gilbert White argued that the standard was not restrictive enough (Robinson, 2004). However, the 100-yr floodplain has since been incorporated into all levels of government flood policy, with those located inside the boundary being responsible for obtaining flood insurance, adhering to building requirements and mitigating their homes. Creating a stricter standard would initially be costly because areas previously located outside the 100-yr floodplain have developed without insurance or building requirements.

The NFIP is a government sponsored venture requiring community participation in the program prior to offering prorated insurance. Communities can only fully participate after FEMA has created Flood Insurance Rate Maps (FIRM) depicting the 100-yr floodplain for the area. FEMA is responsible for creating FIRMs, as well as administering flood management policies in 19,700 participating communities (FEMA, 2002). FIRMs illustrate the 100 and 500-yr floodplain boundary, with 1) flood zone types that are classified as riverine or coastal and whether the boundary was obtained from an approximate or detailed study, 2) base flood elevations, and 3) the date of map creation. Both detailed and approximate floodplain boundaries are illustrated as a well defined boundary. FIRMs are the maps used to enforce the 100-yr boundary in flood policies. FEMA estimates that for every $3 paid in flood insurance claims, $1 is saved in disaster assistance payments, and buildings constructed in compliance with NFIP standards incur 80% less damage than buildings that do not meet those standards (Reilly, 2004). However, only those located within the 100-yr FIRM are required to have flood insurance and mitigate their homes, while those adjacent to this boundary have no official requirements.

FIRMs are depicted on maps, which are often perceived by the general public to be completely accurate. According to Wood (2007), there are three main stages in creating and establishing a map's legitimacy to the general public. First, maps are great tools for management and establishing protocols regarding territory because they are concise, condensed and portable. The use of maps as a media for decision-making processes has become an accepted practice. Secondly, the authority of the map is created via the social manifestation of maps as a type of reference object; whereby, the map is used to determine the legitimacy of decisions and actions. For example, if a person is located inside the 100-yr floodplain on the FIRM, then they are held accountable to cohere to flood policy regulations because the map declares their location is in the floodplain. FIRMs relieve the agency of some degree of responsibility. Thirdly, the accuracy of a map is given through social descent as it is critiqued by competent observers who agree with the results and the language of the map. If the experts say this is the location of the 100-yr floodplain, then it must be true and people are shocked when an error occurs (similar to the shock experienced when Mapquest is wrong). The combination of the general public's absolute trust in maps and the cartographer's choice to not represent uncertainty in FIRMs has created a potentially more hazardous situation (Robinson, 1979).

*2.2.2 Uncertainty of the 100-yr floodplain boundary – uncertainty:*

There is a plethora of uncertainty regarding the delineation of the 100-yr floodplain, and its use as a standard for flood policy has been questioned for several reasons. First, aleatory uncertainty exists in predicting extreme precipitation events because most areas have limited records and extreme events are inherently stochastic (Apel et al, 2004; IFMRC, 1994). Areas without records must have their flood discharge spatially extrapolated using standard regression or modeling techniques. Vaill (2000) found standard errors in the regressions used to create FIRM ranged from 204 to 306% in the Colorado Plains.

Secondly, epistemic uncertainty is presented by the range of techniques and extrapolation curves used to estimate the 100-yr flood discharge in streams, with a range of 5 to 45% estimation error (Thomas & Baker, 2004; IFMRC, 1994). Once the discharge has been estimated, the conversion of discharge to flood elevations has an estimated error of 0.15

to 0.61 m (0.5 – 2 ft), plus an additional 0.91 m (3 ft) of uncertainty attributed to elevation data (IFMRC, 1994). Depending on the topographic profile of the floodplain, 0.91 m vertically can cause a significant change in the horizontal floodplain extent. Thus, the boundary of 100-yr floodplain is associated with a high level of uncertainty (Smemoe et al, 2007; Lawlor, 2004; Burby, 2002) that is not displayed on FIRMs; thereby, resulting in an unprepared population located within a vertical meter of the boundary at risk for the 100-yr flood.

FIRMs display the 100-yr floodplain as being spatially stationary, with the assumption that flood discharges and frequencies remain constant through time. However, climate change studies have found a positive relationship between temperature and precipitation, with warmer temperatures resulting in an increasingly energetic hydrological cycle, producing more intense and frequent precipitation events (O'Brien et al, 2006; Hirsh et al, 2004; Piekle & Downton, 2000); thereby, resulting in more frequent and larger floods.

In addition, development of land in watersheds have been responsible for causing as much as a two-fold increase in the magnitude of the 100-yr peak flow (Hirsh et al, 2004; Bana E Costa et al, 2004). Tobin (2004) attributed an increase in the 100-yr boundary over a 20 year period to both urbanization and improved mapping techniques. Charlotte, NC mapped the 100-yr flood boundary using urbanization and climate change projections to find increases in flood depth of 1.2 to 2.7 m (4 to 9 ft) in the most urbanized streams (Lulloff, 2004; Burby, 2002). The spatiotemporally dynamic nature of floods is problematic because they change faster than FIRMs have been updated, which is about once every 10-20 years at the county level (FEMA, 2002). The result is generally an underestimated prediction of the

100-yr floodplain boundary and the risk for flooding. As Monmonier (1996) so eloquently stated, "maps are like milk: their information is perishable, and it is wise to check the date."

As of 2002, over $2.8 billion has been spent to create FIRMs for 19,200 communities (FEMA, 2002). Prohibitive costs and inadequate funding have resulted in over 75% of FIRMs being older than 10 years which can no longer be treated as accurate with confidence (FEMA, 2002). Improved technology and digital data are driving the costs and speed of FIRM production down, with an estimated initial cost to digitally create, update and distribute new flood maps of $700 to $800 million (Riggs, 2004). FEMA has initiated the map modernization program to update and create digital FIRMs throughout the U.S., with North Carolina serving as its pilot state.

*2.2.3 The costs of not representing uncertainty in the 100-yr boundary*

The aleatory and epistemic uncertainty in FIRMs can lead to increased social (population) and economic (property) exposure to flood hazards adjacent to the 100-yr floodplain. Those adjacent to the 100-yr floodplain are not required to participate in flood policy and may be unaware of the hazard. Goodwin (2004) found ¼ of flood losses occurred outside 100-yr FIRM boundaries. Furthermore, 66% of flood losses have occurred from flood events with a frequency of less than 100 years (Burby, 2002).

A remapped Wisconsin county removed 2,400 structures from the 100-yr floodplain in an updated FIRM while adding 1,800 other structures (Lulloff, 2004). In a North Carolina county, 187 parcels were removed and 664 parcels were added in the 100-yr floodplain of an updated FIRM (Aycock & Wang, 2004). Furthermore, several detailed community elevation surveys found that 50% of structures inside 100-yr FIRMs were located above the 100-yr flood elevation, while in the same communities 30% of their flood claims originated outside the 100-yr FIRM (Maune, 2004). The number of changes occurring with small differences in the location of the 100-yr floodplain further supports the unreasonable statuate that digital lines can entirely separate safe from unsafe areas.

The uncertainty, out-of-date, and non-digital nature of FIRMs in the past have given states and community flood managers the perception that FIRMs are inaccurate and hard to obtain (IFMRC, 2004; Downton et al, 2002). This lack of confidence has resulted in noncompliance with flood policy, as 90% of states reported reluctance in adopting and enforcing floodplain regulations to restrict development (Lawlor, 2004). Local and state enforcement of the national flood policy is critical to reduce flood losses, but it is unreasonable to expect their participation when the standard upon which flood policies are based is inaccurate. The advantages of having a standard boundary defined for policy purposes must have its accuracy, visual representation, and flood cost to development benefit ratio critically evaluated prior to policy managers gaining the confidence to use these boundaries. An example of how inaccurate FIRMs contributed to significant flood losses from increased exposure occurred when Hurricane Floyd impacted North Carolina in 1999.

*2.2.4 Hurricane Floyd and the Map Modernization Program*

The catalyst for all major flood policies changes has been the occurrence of catastrophic losses resulting from significant hydrometeorological events (Pinter, 2005; Platt, 1986). Large policy shifts often follow focusing events, which are characterized by being catastrophic, wide impacting, and alarming to both policy-makers and the public (Bin & Polasky, 2006). Hurricane Floyd was a focusing event for North Carolina (Figure 2.1), causing 56 deaths and tangible economic losses ranging from to $3 to $6 billion (Pielke et al, 2002; Dorman & Bakolia, 2002; Jackson, 2001).

Studies examining this catastrophic and wide impacting event found that FIRMs underestimated the extent of the 100-yr floodplain. Floyd was considered to be less than a 100 or 500-yr event in most areas (Dorman & Bakolia, 2002); however, it was found that 80% of flooded homes were located outside both the 100 and 500-yr FIRMs (Dorman & Bakolia, 2002; Jackson, 2001). Thus, 80% of damaged buildings did not have to meet building regulations or obtain flood insurance, and unregulated development was allowed to occur in areas of high risk for flood losses (Dorman & Bakolia, 2002). Clearly, the underestimated FIRM boundaries contributed to increased socioeconomic vulnerability as areas adjacent to the floodplain were inundated.

The end product of this focusing event on floodplain management was the start of the map modernization program between North Carolina and FEMA to produce Digital Flood Insurance Rate Maps (DFIRMs). The underlying assumption is that DFIRMs will decrease future flood losses because of their increased accessibility, accuracy, and up-to-date status. Prior to the map modernization program, 75% of North Carolina FIRMs were at least five years old, with one county updated annually (Aycock & Wang, 2004).

The collaboration between North Carolina and FEMA to create DFIRMs has several advantages. First, the shift from hardcopies to digital data allows map revisions and distributions to be handled digitally; thereby, reducing mapping costs with an estimated 2.8:1 benefit-cost ratio (Raber, 2003; Dorman & Bakolia, 2002). Secondly, the use of digital data promotes spatial data sharing between government officials and increases accessibility to both policy makers and the general public. Lastly, DFIRMs are created using light detection and ranging (LiDAR) digital elevation models (DEM) with a published vertical accuracy of 0.20 m (0.65 ft) and a horizontal accuracy of 3 m (9.8 ft) (Sanders, 2007; Mitasova et al, 2005). This is a much higher resolution than the current FIRM topography with a horizontal accuracy of 30 m (98 ft) and a vertical root mean square error of 7 m (23 ft). Prior to LiDAR, FIRMs had a potential error of 0.91 m (3 ft) at the 50% confidence interval in floodplain delineation due to elevation data quality (IFMRC, 1994). The use of LiDAR reduces that error to less than 0.49 m (1.6 ft) at the 95% confidence interval (Raber, 2003). However, DFIRMs are plagued with the same problems as FIRMs with regards to inherent and epistemic uncertainties in floodplain delineation from the hydrologic and hydraulic modeling.

*2.2.5 DFIRM – Maintaining the Legacy of Not Representing Uncertainty:*

Differences in flood elevation between a 100 and 500-yr event is on the order of decimeters; yet, the level of acceptable uncertainty in the DFIRM maps is 0.3 m (0.9 ft) (FEMA, 2003). DFIRMs are produced using the same methodologies and assumptions as FIRMs, with the key difference being the enhanced quality of the elevation data. DEM errors contribute to floodplain boundary uncertainty in the 1) hydraulic model relating discharge to stage height and 2) in delineating the horizontal flood extent (Raber, 2003). Thus, while topographic uncertainty has decreased, errors are still present in the floodplain delineation from data inaccuracies, as well as stochastic and epistemic uncertainty.

Yet, DFIRMs are displayed as a definitive boundary with no indication of uncertainty in floodplain extents. The digital nature of these maps encourages the public "to readily entrust mapmaking to a priesthood of technically competent designers and drafters working for government agencies…[who] seldom, if ever, question these authorities" (Monmonier, 1996). While the presence of uncertainty does not negate the model, it should be acknowledged and displayed. DFIRMs are digitally produced and distributed, and have the capability of being cheaply generated and illustrated as a range of flood probability from the 100 to 500-yr floodplain (Smemoe et al, 2007). The institutionalization of flood probabilities displayed on DFIRMs can provide managers with an increased confidence in flood maps and a sense of the social and economic exposure at different flood magnitudes.

The provision of the 100-yr floodplain as a single, non-fuzzy boundary is associated with an increase in exposure, because decision-making and preparedness are based on regulations that exist only for those living within the 100-yr FIRM. No official flood protection measures are advocated for those living adjacent to the 100-yr floodplain, so it is unlikely people’s behaviors are favorably altered in preparation for a flood. The indirect impact of increasing flood hazard exposure from displaying the 100-yr floodplain as a clearly defined boundary can be assessed by examining whether population and property values have significantly increased adjacent to the 100-yr FIRM.

**2.3 Theoretical Framework:**

A spatiotemporal geographic approach was required to develop a holistic and integrative understanding of the relationship between floodplain management and exposure. The framework utilized Geographic Information Sciences (GIS) literature to address the methodology for creating the (Temporal) Flood Loss Exposure Model ((T)FLEM), and the natural hazards paradigm’s literature on the creation of hazardous landscapes through the intersection of socioeconomic value and the spatiotemporal parameters of the hazard.

A GIS is an ideal method for storing, distributing, and analyzing floodplain boundaries in relation to the spatial distribution of populations and property through time. Furthermore, FEMA is increasingly incorporating GIS frameworks in their emergency management and planning processes (Jackson, 2001). For example, during the emergency response to Hurricane Floyd, FEMA became aware of how out-dated FIRMs were and the importance of having accurate FIRMs to limit floodplain development, establish proper insurance rates, and shorten decision-making and response time during emergencies (Jackson, 2001). Since then, North Carolina and FEMA have collaborated in the creation of DFIRMs (NCFloodmaps 2006), which can be placed in a GIS and analyzed with other digital spatial data (e.g. parcel and census data). Integrating digital data into an interoperable database that can combine flood maps, populations, parcels and other spatial data has multiple uses, including comprehensive disaster mitigation and intergovernmental projects (Dorman & Bakolia, 2001).

Additionally, flood control structures, flood zones, and characteristics of floodplain development are spatially related and suited for analysis in a GIS. As Cartwright (2005) stated, the utilization of GIS technologies to track demographic, economic and land use trends within floodplains would greatly enhance our understanding of flood damage. (T)FLEM was developed as a tool that examines population and parcel values, as socioeconomic indicators, to examine development trends in relation to floodplain boundaries (Figure 2.2). This framework guided the examination of the spatiotemporal intersection of the physical flood hazard and maximum socioeconomic exposure to calculate flood risk. However, while GIS is adept at mapping spatiotemporal relationships, it cannot determine causal factors behind why these relationships exist.

Natural hazards research (Mileti, 1999) is constructed around the juxtaposition of physical, social and economic factors in space and time. Natural hazards are defined as naturally occurring events in the physical environment (e.g. floods, volcanoes, hurricanes) that are potentially damaging to human societies. The interchange of economic, social, technological and political aspects at multiple temporal scales creates what Sauer termed as 'cultural landscapes' (Sauer, 1925). As physical hazards, such as floods, coincide spatially with populated areas, hazardscapes are formed. The main assumption of hazardscapes is that they are produced through time by nonrandom patterns of social interaction and organization (Morrow, 1999). Therefore, it is reasonable to assume that increasing flood losses can be attributed to both increasingly frequent floods, as well as human decision-making to populate floodplains. As Wong & Zhao (2001) stated, "it is the recognition of human involvement that extended the scope of hazard research and led many to advocate comprehensive development planning to mitigate the impact of natural hazards."

The concept of risk combines the probability of hazard occurrence with vulnerability (Vatsa, 2004; Handmer, 2003; Cutter et al, 2000), which is defined here as the exposed socioeconomic (population counts and building tax value) assets. Risk analysis has traditionally involved empirical research that quantitatively describes the frequency of natural events and their impacts on society (Merz et al, 2006) using the general equation:

$$Risk = Hazard * Exposure \qquad (2.1)$$

Where *Hazard* refers to the probability of an event and *Exposure* relates to potential losses, usually expressed in terms of mortality or economic value (Merz et al, 2006; Vatsa, 2004). The quantifiable nature of hazard probability and exposed assets enables risk to be quantified spatially in a meaningful way to assist emergency management planners. The probability of experiencing a flood hazard has already been spatially defined for the study area as the 100-yr (1%) and the 500-yr (0.2%) floodplain. Exposure to flood damage is dependent on floodplain occupancy and reflects the enforcement of flood policy. (T)FLEM quantifies the exposure of people (social indicator) and property (economic indicator) within floodplain boundaries. The selection of these indicators was focused on addressing the potential reasons for increasing flood losses through development of floodplain zones following the 1994 Flood Mitigation Act.

**2.4 Research Objectives:**

The overall goal of floodplain management is to reduce flood losses, and billions have been spent trying to *decrease* the impacts of flooding, yet losses have *increased* at an annual rate of 3.45% (Cartwright, 2005). It is essential to understand the underlying causes of increasing flood damages prior to expending limited resources on policies that might not address the most critical factors, and thereby be rendered ineffective. This chapter examined the 1) effectiveness of floodplain zoning, 2) presence of increased exposure outside floodplain boundaries, and 3) changes in floodplain exposure using DFIRMs. Specifically, (T)FLEM calculated population exposure inside the 100-yr floodplain before and after the 1994 mitigation policy to monitor its effectiveness at reducing floodplain occupancy. Secondly, exposure was calculated adjacent to the 100-yr floodplain to determine if development has occurred adjacent to the 100-yr floodplain. Lastly, the socioeconomic value contained inside FIRMs was compared to DFIRMs to assess the ability of DFIRMs to reduce future flood losses.

The remainder of this chapter introduces the study area, describes the methods utilized in the development of (T)FLEM, explores the changes in socioeconomic vulnerability through space and time, and concludes with the applicability of these findings to floodplain managers and the implications for flood policy.

## 2.5 Study Area:

North Carolina is topographically (0 m (0 ft) in the Coastal Plains to 2,038 m (6,686 ft) in the Mountain Region) and climatologically (annual precipitation averages of 1067 to 2642 mm (42 to 104 in)) diverse (Figure 2.3), yet the entire state is subject to significant hydrological and damaging flood events. North Carolina has been divided into three geographic regions for discussion by physical and climatic attributes: the Mountain Region (20% of NC), the Piedmont (35% of NC) and the Coastal Plain (45% of NC).

Since 1980, North Carolina has experienced over 20 weather related hazard events, of which 12 resulted from tropical cyclones (Lott & Ross, 2007). According to Konrad (2007), the Mountain Region experiences an average of 1 tropical cyclone every 3 years, the Piedmont every 1.5 years and the Coastal Plain every year. The Mountain Region has a strong, unimodal winter precipitation regime, while the Piedmont and Coastal Plains have a slight bimodal bias for precipitation in the winter and fall (Lecce, 2000). Increasing hydrologic energy has been evident with over half of the largest precipitation events since 1950 occurring during the last 10 years (Konrad, 2007). Increasing numbers of extreme precipitation events is concurrent with climate change models for the Southeast (Cartwright, 2005; van Aalst, 2004).

### *2.5.1 Study Area Description:*

The study area consists of five North Carolina counties, each reflecting different physiographic areas. The county scale was selected because FIRMs are produced at that scale. The counties examined are Buncombe (Mountain Region), Orange, Durham, and Wake (Piedmont), and Craven (Coastal Plain). Three contiguous Piedmont counties were analyzed to examine how risk changes as floodplain extents progress from headwaters (Orange) to the larger rivers and floodplains of Durham and Wake County.

Buncombe County has an area of 1709 $km^2$ (660 $mi^2$) and is located on the western slopes of the eastern continental divide. Buncombe receives 914 to 1270 mm (36-50 in) of precipitation annually via orgraphic uplift, frontal and convective storms. The North flowing French Broad River roughly bisects the county and Asheville, Buncombe's largest city, is located at the confluence of the Swannanoa and French Broad River. In the 2000 census, 206,330 people resided in Buncombe, a 15.4% increase from the 1990 population. Sixty seven percent of all tax value is attributed to building property value (Table 2.1).

Craven County is 2005 $km^2$ (774 $mi^2$) and is adjacent to the Neuse Estuary near the Atlantic Coast. Craven receives the largest annual precipitation in the study area with 1270 to 1575 mm (50-62 in). New Bern is the largest city and is located at the confluence of the Neuse River and Pamlico Sound. The Neuse originates in the Piedmont, draining 14,582 $km^2$ (5630 $mi^2$) over 325 km (202 mi) before emptying into the Atlantic. The flat topography and the large volume of water carried in the Neuse results in an expansive floodplain and wetlands system. The population of Craven was 91,436 in 2000, an 11.7% increase from 1990. Seventy percent of all tax value is attributed to building property values.

Orange (1139 $km^2$ or 440 $mi^2$), Durham (771 $km^2$ or 298 $mi^2$), and Wake (2217 $km^2$ or 856 $mi^2$) County are located in the Piedmont. The Piedmont is the most densely developed and urbanized region, containing the six largest cities in North Carolina (Charlotte, Raleigh, Greensboro, Winston-Salem, Fayetteville, and Durham). Annual precipitation averages between 1118 to 1219 mm (44-48 in). The major urban areas for each county are Chapel Hill, Durham, and Raleigh respectively. Orange contains the headwaters for the Neuse Watershed, and is partially drained by the Eno River, a 64 km tributary of the Neuse. Durham is located downstream in the Eno watershed, with the Eastern border located at the confluence of the Eno and Neuse River. The Raleigh-Durham area is one of the fastest growing and sprawling urban populations in the United States (Ewing et al, 2002). The socioeconomic characteristics of the Piedmont counties are described in Table 2.1.

The percent area contained inside the 100-yr FIRM for each county is reflective of its topography, with the Mountain Region having the smallest (3.6%) and the Coastal Plain having the largest percentage (22.9%) of area covered with water. The percent land cover associated with water in the Piedmont varied from the headwaters of Orange County (3.6%) downstream to Wake County (9.2%). Flood damage characteristics for the study area from 1995 to 2005 were gathered from the National Weather Service's (NWS, 2007) flood data (Table 2.2). Buncombe suffered the smallest number of fatalities and property damages, while Craven suffered the highest number of fatalities. The Piedmont experienced fewer catastrophic flood events than Buncombe and Craven, but had the greatest economic flood losses since it contains the greatest amount of socioeconomic exposure in the study area. However, when compared with the economic resources for recovery, Buncombe and Craven suffered relatively greater economic losses than the Piedmont.

*2.5.2 Data Description*

Mileti (1999) called for a comprehensive and consistent database containing current levels of vulnerability to hazards at the local and national scale. FLEM meets some of those needs by using national databases that are freely available coupled with county level parcel data to calculate flood exposure. After establishing a general methodology, it is anticipated that localities can substitute higher spatiotemporal resolution data and intersect local context to create a better estimate of potential flood impacts.

The flood hazard, in the original FIRMs, was obtained in spatial format from FEMA, while the DFIRMs were freely obtained from the North Carolina Floodplain Maps website (ncfloodmaps.com, 2006) for all counties except Buncombe. The map modernization program has not been completed for the Mountain Region at the time of this study. Nor was the 500-yr DFIRM completed for Durham.

The spatial data utilized to assess exposure are population (social indicator) and building tax value (economic indicator). ESRI's Topological Integrated Geographic Encoding and Referencing (TIGER) data provided census population counts in spatial block group boundaries for the nation (TIGER, 2004) in 1990 and 2000. Block groups were used rather than higher resolution block data, because they contain more demographic information in case other socioeconomic attributes are desired for analysis. County parcels were obtained from each county (one assumes this would be freely available to counties using FLEM). Parcels are not a national dataset, so the attributes might vary between counties; however, all counties in the study area kept records of building and total tax values. Lastly, the National Land Cover Dataset (NLCD) was freely available from the USGS seamless website (USGS, 2006) for both 1992 and 2001. The NLCD was utilized in this project as an ancillary variable to distribute population and parcel values at a higher spatial resolution.

**2.6 Methodology:**

FLEM's methodology encompassed data preparation, creating socioeconomic distributions, and spatial analysis. Data preparation involved projecting all spatial data into NAD 1983 NC FIPS 3200 (m) and clipping them to the county (Appendix). The attributes of the floodplain shapefiles were utilized to extract the geographic location of the 100-yr floodplain. The area associated with only a 500-yr flood event (the 100-yr FIRM is not included), referred to as the marginal 500-yr floodplain, was extracted to assess development adjacent to the 100-yr FIRM. The marginal 500-yr FIRM was used as a proxy for the uncertainty in the delineation of the 100-yr FIRM, because it lies directly adjacent to the 100-yr floodplain and usually varies on the order of decimeters in elevation difference. This process was repeated to extract the 100 and marginal 500-yr floodplain boundaries from the DFIRMs.

Population and tax values are formatted in a GIS as discrete vector polygons. Furthermore, the spatial resolution of census block groups and parcels does not allow the analyst to discern how much of the population or tax value are located within the floodplain when it intersects only a portion of the shapefile. There are two common approaches to address this problem. First, it is assumed that all population/tax are uniformly distributed throughout the block, and the percent area contained in the floodplain is correlated to the percent of population/tax in the floodplain. The second method is an all or nothing approach; whereby, if the center of the block is inside the floodplain, all population/tax are included. But, if the center of the block is outside the floodplain, nothing is included. Neither method is based on valid assumptions. FLEM addressed this dilemma by utilizing NLCD as an ancillary variable to logically distribute population and building tax. The population and parcel surfaces were created at the same resolution as the LiDAR data (6.091 $m^2$ or 20 $ft^2$) used to create DFIRMs, which was needed to capture the attributes of smaller parcels. The goal was not to create a perfect socioeconomic surface, but to create a better distribution than national level vector data provided.

The distribution process involved reclassifying NLCD into two coefficient files (one for parcels and one for population). Key assumptions were that the NLCD a) was reasonably accurate (2001 is 74% and 1992 is 64% for classification accuracy, (Khorram et al, 2000 & USGS, 2007)), b) can be used to estimate land use, and c) was temporally close to parcel and population data to be relevant. The change in quality for the NLCD between 1992 and 2001 could be responsible for some of the changes in floodplain population values from 1990 to 2000. Rather than only relating socioeconomic value to the percent area in the floodplain, FLEM used land cover to place more socioeconomic value in developed pixels. The error for population and parcel redistribution was constrained by the spatial boundaries of the vector blocks. Thus, because the parcel resolution is higher than population block groups, the quality of the parcel distribution surface is better than the population surfaces. A 6.09 $m^2$ (20 $ft^2$) resolution is unrealistic for accurately assessing population and tax value location; however, only the cumulative sum of pixel values located inside the floodplain boundaries were used and decreased the significance of resolution errors.

*2.6.1 Creating Building, Land and Total Tax Surfaces:*

The parcel coefficient file was created to redistribute building tax values. The underlying assumption was that more buildings are located in developed areas (commercial and residential land cover) than undeveloped areas (agriculture, wetlands). The authors were not aware of any previous research associating a weight between NLCD and building tax value, so a logarithmic weight scheme was used (Table 2.3). There were no zero values because the spatial resolution of some parcels is equivalent to one pixel. Land tax was distributed uniformly across each parcel because no logical rubric could be found that had examined the relationship between land cover and land tax.

The parcel shapefile was converted into two rasters surfaces using the building and land tax attribute. The reclassified NLCD for the building property value ($NLCD_{BuildReclass}$) was divided by the sum of $NLCD_{BuildReclass}$ per parcel block to get the percentage of building tax value attributed to each pixel. The percent building tax attributed to each pixel was multiplied by the value of the building tax in each parcel (*BuildingParcelRaster*) to create the *BuildingTax Surface* (Equation 2.2).

$$BuildingTaxSurface = \frac{NLCD_{Build\,\mathrm{Re}class}}{\sum NLCD_{SumBuild\,\mathrm{Re}class}} \times BuildingParcelRaster \qquad (2.2)$$

The Land Tax Surface was created by dividing the land tax raster by the number of pixels in each parcel group to get the percentage of land tax associated with each pixel (Equation 2.3). The total tax surface was created by adding the *LandTaxSurface* and *BuildingTaxSurface* (Equation 2.4).

$$LandTaxSurface = \frac{LandParcelRaster}{\sum Pixels_{ParcelBlock}} \qquad (2.3)$$

$$TaxSurface = BuildTaxSurface + LandTaxSurface \qquad (2.4)$$

*2.6.2 Creating Population Surfaces:*

The population coefficient file represents an ambient population surface. The weights (Table 2.3) were modified from the percentage of development used to classify the NLCD ($NLCD_{ReclassPop}$) from low to high density residential and commercial areas (Homer et al, 2004). Forest values were half the weight of low density developed pixels, because North Carolina is heavily forested and populations are often located beneath tree canopies, which are not captured by satellite imagery. Values of zero were used for water, wetland, and barren land cover, since the block group's spatial resolution is coarse enough to guarantee a non-zero land cover type inside a block group.

The population surface was created following the steps outlined for the building tax surface (Equation 2.5, Figure 2.4). The 6.09 $m^2$ (20 $ft^2$) spatial resolution resulted in population pixel values less than one, which is reasonable for such a fine resolution as it is the probability of finding X number of people at any given time in a pixel (Figure 2.5). The socioeconomic surfaces were only utilized as cumulative sums within floodplain boundaries; thereby, mediating the significance of distribution error.

$$PopSurface = \frac{NLCD_{\mathrm{Re}\,classPop}}{\sum NLCD_{PopBlockGroup}} \times Population \qquad (2.5)$$

*2.6.3 Intersecting Flood Hazards and Socioeconomic Exposure:*

Zonal statistics (ESRI, 2007) were used to calculate the sum of population and parcel value inside each block group / parcel boundary. Comparing total raster population and parcel surfaces to the original vector boundaries resulted in less than a 1% difference due to edge effects; whereby, raster cells and polygon boundaries are not perfectly aligned. Zonal statistics extracted the socioeconomic value inside the 100 and marginal 500-yr floodplain.

(T)FLEM created a population surface using the 1990 block groups and 1992 NLCD. Zonal statistics were used to extract the cumulative population in the floodplains for comparison with the 2000 population to examine how exposure changed since the ‘mitigation era’ commenced. A t-test two sample statistical analysis assuming unequal variance (SAS, 1988) was conducted to determine if significant changes ($p < 0.05$) in population density occurred within the floodplain boundaries.

The extraction of socioeconomic indicators within the 100 and marginal 500-yr floodplain provided the information needed to compare development inside and outside the 100-yr floodplain. A t-test two sample statistical analysis assuming equal variance (SAS,

1988) was conducted to determine whether socioeconomic development significantly ($p < 0.05$) changed adjacent to the 100-yr FIRM.

DFIRMS were created with the assumption that they will decrease floodplain losses by decreasing flood map uncertainty. The changes between DFIRM and FIRM boundaries may be small, leanding to numerous small and spurious intersections. Hence, the final functionality of FLEM was to examine cumulative changes in physical (aereal extent), social (population) and economic (building tax) located inside the original and the new FIRMs. The comparison of indicators between floodplains used zonal statistics to extract the sum of these variables for both the 100 and marginal 500-yr floodplain in: a) areas that overlap, b) areas only inside DFIRMs, and c) areas only inside FIRMs. The change between DFIRM and FIRM boundaries was assessed for significance using a t-test assuming equal variance.

*2.6.4 Model Uncertainty Boundaries:*

The value of FLEM's results is dependent on the amount of confidence that can be placed on the socioeconomic distribution model. Results are given in density format to enable comparisons between the floodplains of different counties and frequencies, as well as between FIRMs and DFIRMs. The difference between FLEM socioeconomic density and the two standard vector methods described above was calculated using parcel blocks and census blocks (finer resolution than block groups). The first method included the total value of any polygon whose center was located inside the floodplain. The second method took the sum of all socioeconomic value ($SEI$) within any block ($i$) that intersected the floodplain. The floodplain area ($Area_F$) was divided by the total area ($Area_i$) of the intersecting blocks to create a percent area of the blocks located in the floodplain. The socioeconomic total of the intersecting blocks were multiplied by the percent area located within the floodplain:

$$\eta = \sum_i SEI_i \times \frac{Area_F}{\sum_i Area_i} \qquad (2.6)$$

**2.7 Results:**

*2.7.1 Difference between FLEM and Vector Methods for Socioeconomic Distribution:*

The block center method generally had a higher value, while the percent floodplain method tended to have a lower value than FLEM for the socioeconomic density. The average difference between FLEM and vector estimates of socioeconomic value was less than 25% for population and 18% for building tax value. Buncombe consistently resulted in the greatest difference, with FLEM constantly overestimating socioeconomic value. However, a study by the Buncombe County Hazard Mitigation Group (2004) used aereal photography to assess tax value inside the 100-yr floodplain was only 2.6% lower than FLEM's estimate for the land value and 14% higher for the building tax value. The population range was larger than the parcel range because block groups have a lower resolution. The difference between FLEM and the average value of the vector methods is illustrated in Table 2.4. Overall, FLEM seemed to be an adequate representation of population and tax distribution for monitoring floodplain exposure (Table 2.4).

The results from FLEM are divided into three sections to address 1) the effectiveness of the mitigation efforts to remove people and property from the floodplain, 2) the potential costs of floodplain uncertainty, and 3) the effect of changing floodplain boundaries.

*2.7.2 Changes in temporal exposure*

Population density increased throughout the study area at the county scale from as 10.5% in Craven to 32.6% in Wake from 1990 to 2000 (Table 2.5; Figure 2.6). (T)FLEM found Buncombe and Durham's 100-yr floodplain population density increased by 6 and

13% respectively, which was less than the county level population increase (Figure 2.7). Orange's floodplain density increased by less than 1%, which is insignificant compared to the 21% countywide population density increase between 1990 and 2000. Craven and Wake County experienced a decrease in population density in the 100-yr floodplain despite an overall county increase in population density. No statistically significant (p-value = 0.45 for the 100-yr FIRM) population density change from 1990 to 2000 were found, indicating that generalizations regarding floodplain development cannot be made across counties.

Both Buncombe and Orange have a higher population density in the floodplain than the county population density (Figure 2.7). On the other hand, Durham, Wake, and Craven County's 100-yr floodplain have a smaller population density than the county average, because the topography for these areas enables more space to build outside of the floodplains than in Buncombe. Therefore, despite an increasing population density between 1990 and 2000, Durham's floodplain population density remained less than the total county population density. It is imperative that the temporal trend of floodplain population change be placed into the context of the county status, which influences floodplain management.

Population density increased in the marginal 500-yr floodplain, which is adjacent to the 100-yr floodplain, for all counties but Orange (Figure 2.7). The decrease in population density from the 100-yr FIRM in Craven coincided with an equivalent increase in population density in the marginal 500-yr FIRM, and might be indicative of a population shift directly across the clear-cut 100-yr boundary (Table 2.5). Orange's population density remained constant in the marginal 500-yr FIRM. No statistically significant (p-value = 0.44) trend was present for the temporal population change in the 500-yr FIRM between counties in the study area. However, it should be noted that no county experienced a greater increase in population density for either floodplain, than the overall county population increase between 1990 and 2000.

*2.7.3 Socioeconomic exposure adjacent to the 100-yr FIRM*

The social indicator for each county consistently increased from the 100 to the marginal 500-yr FIRM (Figure 2.8; Table 2.6). Orange had the largest increase in population density (486%), while Wake and Craven's population density more than doubled from the 100 to marginal 500-yr floodplain. Population density clearly and significantly ($p = 0.027$) increased from inside to directly outside the 100-yr FIRM for the study area.

The economic indicator also increased in density from the 100-yr to the marginal 500-yr FIRM in each county (Figure 2.9, Table 2.6). Orange's building tax density had the largest increase (622%) from the 100 to the marginal 500-yr floodplain. The high increase in Orange County is the result of the marginal 500-yr FIRM being only delineated in Chapel Hill, a relatively small area with high socioeconomic value. The smallest increase in building tax density was 180% in Buncombe. Concurrent with population density changes, building tax density significantly ($p = 0.024$) increased from inside to directly outside the 100-year FIRM boundary in the study area.

*2.7.4 FIRMS to DFIRMS: Changing Boundaries and Exposure*

The cumulative study area encompassed 6,132 $km^2$ (2,368 $mi^2$) of which 13.3% was located in the 100-yr FIRM and 12.0% in the DFIRM. Examining the cumulative socioeconomic value located in the DFIRM compared to the FIRM resulted in a 2.9% decrease in raw population (0.6% increase in density) and a 17.1% decrease in property value (12.1% decrease in density) contained by the DFIRM (Figure 2.10). The density of socioeconomic indicators was used to allow cross comparison between the different floodplains. Craven had the largest decrease in population, while Durham had the largest decrease in building tax from the 100-yr FIRM to DFIRM. Only Wake's 100-yr DFIRM contained a greater population density (Table 2.7).

The socioeconomic value located within the marginal 500-yr floodplain from FIRM to DFIRM also decreased by 15.4% for the population and 20.8% for the building tax value. Despite less socioeconomic value being located within the marginal 500-yr floodplain, the cumulative aereal extent has increased from 54 to 77 $km^2$.

At least 50% of the physical area, and 44 to 65% of the socioeconomic density, included in the 100-yr floodplain was in agreement by both the FIRM and DFIRM (Figure 2.11). In general, 25 to 50% more socioeconomic value was located only inside the FIRM and not the DFIRM 100-yr floodplain. Orange had the smallest overlap between FIRM and DFIRM for all indicators, which is perhaps indicative of its physiographic characteristics, with predominant headwater streams and less well-defined floodplains. The relative percentage of indicators in agreement between FIRM and DFIRM increased farther downstream to Durham and Wake County, where topography is less diverse and streams are generally larger and better defined.

There was a different pattern of floodplain agreement in the marginal 500-yr floodplain between FIRM and DFIRM coverage, with less than 18% overlap in socioeconomic value and physical areas. The lack of agreement partially resulted from using the marginal 500-yr floodplain boundary; whereby, some DFIRM and FIRM 500-yr floodplains were located within each other's 100-yr floodplain (Figure 2.12). The vertical difference in flood inundation is on the order of decimeters, and since topographic uncertainty is greater than a decimeter, it was not surprising that the 100 and marginal 500-yr boundaries overlap between iterations of flood maps. The overlapping floodplain boundaries support the use of the marginal 500-yr floodplain as a proxy for uncertainty in the 100-yr floodplain boundary. Despite increasing aereal coverage by DFIRMs, the majority of socioeconomic value in the Piedmont was located within the FIRM boundaries. Craven had up to 8% more socioeconomic value within the marginal 500-yr DFIRM (Figure 2.11).

**2.8 Discussion:**

The county level exploratory analysis does not allow for a conclusive explanation of why floodplain exposure changed through time. (T) FLEM was designed to be run by local floodplain managers with the assumption that county officials have the contextual background to understand the "why" behind model output.

By comparing changes in floodplain to county population densities, the effectiveness of 'moving people out of the floodplain' can be assessed in relation to overall county development patterns. Theoretically, there are three alternatives for floodplain population changes through time. First, floodplain density increased; thereby, suggesting floodplain management efforts were not successful. If the relative floodplain increase was greater than the county increase, then the floodplains were more attractive to develop than the rest of the county, and management efforts had no effect. If the relative floodplain population density increase was less than the county increase, then floodplain management was partially effective. Lastly, floodplain density decreased, despite increasing county population trends; thereby, indicating successful floodplain management. Piekle & Downton (2000) found the average U.S. population increased between 1990 and 2000 at a rate of 1.26% per year, and if the floodplain population increased at the same rate, it would account for 43% of the increase in flood damage. North Carolina's 21.4% population increase in the last decade was two times greater than the national average (NCNHM, 2001), and could account for increasing flood damage if the floodplain population increased at the same rate.

(T)FLEM's calculation of floodplain change through time in the original FIRMs showed a decrease in population for Wake and Craven, while Orange, Buncombe and Durham populations increased within the 100-yr floodplain at a rate of 0.7, 6.0 and 12.8%, respectively (Figure 2.7). From this general analysis, it can be concluded that floodplain management was effective in reducing exposure for Wake and Craven. Nevertheless, population growth in Orange County could theoretically be responsible for 2.6% of increased flood losses, Buncombe for 21%, and Durham's growth could account for 44% the increase in flood losses (Piekle & Downton, 2000). Burby (2002) found a 53% increase in structures located on floodplains throughout the U.S. since 1968. The findings from this study suggest that these North Carolina counties have managed their floodplain more effectively over the last decade than the national average.

Flood risk (equation 2.1) was calculated for the study area using the frequency of the 100 and marginal 500-yr floodplain for the *Hazard* and the population counts as the *Exposure* variable (Table 2.8). Based on the flood risk analysis, it is evident that the 100-yr floodplain is at much higher risk than the marginal 500-yr floodplain due to its frequency and the number of people located in the 100-yr floodplain. In addition it can be seen that risk decreased in Wake and Craven, while increasing in the remainder of the study area. Furthermore, despite Craven County having the smallest socioeconomic value of the study area, it has the second largerst risk for losses from the 100-yr flood. It should be noted that the calculation of risk inherently is associated with large uncertainty from a) FIRM boundaries and b) FLEM's socioeconomic distribution model.

The representation of the 100-yr FIRM as a well defined boundary, within which flood mitigation occurs and without which no regulations are required, could lead to development directly outside the floodplain.  Therefore, when flooding occurs outside the 100-yr FIRM, the level of impact may be catastrophic for those adjacent to the floodplain (Dorman & Bakolia, 2002).  In this analysis, the marginal 500-yr FIRM boundary was used as a proxy for uncertainty in the 100-yr floodplain.  The marginal 500-yr floodplain might be a biased indicator of floodplain development because most 500-yr boundaries were delineated in urbanized areas.  However, it is the urbanized areas that contain the majority of socioeconomic value that flood policy strives to protect.

Socioeconomic density adjacent to the 100-yr FIRM significantly increased (Figure 2.8, 2.9, Table 2.6); thus, it is reasonable to conclude that vulnerability is increasing adjacent to the 100-yr floodplain.  James (2004) suggested that residential development is shifting to locations outside of the 100-yr floodplain; however, he also noted that “we experience floods larger than those designated as 1% events more often than expected.”  It is hypothesized that the increasing marginal 500-yr FIRM density is largely a product of the clear-cut representation of the 100-yr FIRM, and the lack of official flood policy legislation for the marginal 500-yr FIRM.  The increase in development density within the marginal 500-yr FIRM could potentially equate to significant future flood losses (Piekle & Downton, 2000; IFMRC, 1994).  Several state floodplain association managers would like to see the 500-yr boundary as the extent to which critical infrastructure cannot be developed (Robinson, 2004; Bourget & Baily, 2004).

The cumulative comparison between FIRM and DFIRM surprisingly resulted in less socioeconomic value located within DFIRMs (Figure 2.11, 2.12), as was found in Lulloff

(2004) and Maune (2004). The change between FIRM and DFIRM is either the result of better data quality or temporal changes in flood inundation depths. Assuming changes are predominantly attributed to the increasingly accurate elevation data, there was a contraction of the 100-yr floodplain for Craven, Durham and Wake. Only Orange had increasing aereal coverage (1.97 $km^2$ or 0.77 $mi^2$) with the DFIRMs, as was also found for Wilson County, NC whose 100-yr FIRM increased by 4.47 $km^2$ (1.73 $mi^2$) (Aycock & Wang, 2004). Decreasing the 100-yr floodplain extent, which serves as the basis for flood policy cannot help reduce future flood losses. Perhaps a better solution than recreating FIRMs with more accurate data would be to display uncertainty on FIRMs for the benefit of floodplain managers to understand the potential risk.

An examination of the socioeconomic exposure showed that only Durham (500-yr) and Wake (100-yr) increased in flood risk from FIRM to DFIRM (Figure 2.10), perhaps due to the rapid increase in urbanization. However, Durham was an outlier as the only completed portion of the marginal 500-yr DFIRM was in an urban area; thereby increasing floodplain density. The decrease in exposure (raw and density) was surprising considering the stimulus for creating DFIRMs resulted from the catastrophic flood losses suffered during Hurricane Floyd. It was assumed DFIRMs would be more precautionary and inclusive, to assist in mitigating floodplain development, since there are over 6 million households located within the 100-yr FIRM, leading to flood losses in 88% of US counties (Burby, 2002). The largest increase from FIRM and DFIRM was the aereal extent of the 500-yr floodplain; however, the inclusion of the 500-yr floodplain was not incredibly meaningful since no policies are associated with that boundary. Perhaps a better approach would be to use the marginal 500-yr floodplain as a proxy for the uncertainty extent of the 100-yr floodplain.

### 2.9 Conclusion:

This exploratory analysis utilized a GIS environment to analyze changes in socioeconomic value located within existing floodplain boundaries through time and between changing floodplain boundaries to assess the effectiveness of floodplain management. The underlying assumption was the greater the socioeconomic value removed from floodplain boundaries, the greater the impacts of mitigation efforts in reducing future flood losses. (T) FLEM was automated to allow consistent, rapid calculation of socioeconomic values based on their spatial relationship with the floodplain. The data and methodology were freely available and enable local policymakers to assess the effectiveness of floodplain management at the county scale. A higher resolution analysis examining the spatial relationship of socioeconomic variables by stream flow and location within urban and rural areas was done in Chapter 3. The higher resolution analysis enables policy-makers to discern where floodplain management is effective; thereby, enabling managers to focus resources on reducing risk in highly exposed areas.

This study found that floodplain development density decreased between 1990 and 2000; thereby, indicating that floodplain management did reduce the rate of floodplain development, and in some areas removed development from the 100-yr floodplain. Thus, floodplain management had a positive effect on reducing potential flood losses by reducing exposure to the hazard. Unfortunately, this same policy inadvertently assisted in increasing the potential for future flood losses in areas adjacent to the 100-yr floodplain. The negative effect resulted because there were: 1) no floodplain regulations enforced outside the 100-yr FIRM, and 2) no representations of uncertainty in the 100-yr boundary. Thus, development has occurred adjacent to the 100-yr floodplain with little concern for the flood hazard.

Lastly, the shift from FIRM to DFIRM decreased the socioeconomic value included in the 100-yr boundary, which could result in increased flood losses as previously included areas become open for unregulated development. It is recommended that new DFIRM maps a) illustrate the flood probability moving away from the river and b) err on the side of caution by not removing current areas covered by the FIRMs, as the difference in elevation is on the order of decimeters. Decimeter elevation differences are far smaller than the predicted increase in flood elevation of several meters in streams experiencing urbanization and increased precipitation from climate change (Lulloff, 2004; Burby, 2002).

## 2.10 Tables:

**Table 2.1**: Social, economic and physical characteristics of the study area.

| County | Major Watershed | 2000 Population | Population Change (1990) | Building Tax ($ Billion) | Annual Precipitation (mm) | Percent Area Floodplain |
|---|---|---|---|---|---|---|
| Buncombe | French Broad | 206,330 | 15.37% | 16 | 914 - 1270 | 3.57 |
| Orange | Neuse / Cape Fear | 118,227 | 20.95% | 8 | 1118 – 1220 | 3.60 |
| Durham | Neuse / Cape Fear | 223,314 | 18.58% | 14 | 1118 – 1220 | 14.40 |
| Wake | Neuse | 627,846 | 32.57% | 50 | 1118 - 1168 | 9.16 |
| Craven | Neuse | 91,436 | 10.50% | 6 | 1270 - 1575 | 22.89 |

**Table 2.2**: Socioeconomic flood losses by county from 1995 – 2005 (Source: NWS, 2007).

| County | Fatalities | Property Damage ($M) |
|---|---|---|
| **Buncombe** | 2 | 82 |
| **Orange** | 7 | 3008 |
| **Durham** | 8 | 3007 |
| **Wake** | 8 | 3013 |
| **Craven** | 19 | 1822 |
| **Total** | **44** | **11032** |

**Table 2.3:** Weighted coefficient files created for the NLCD classification categories to distribute socioeconomic data.

| NLCD Type | Building Tax | Population |
|---|---|---|
| **Water** | 0 | 0 |
| **Low Density Residential** | 1000 | 10 |
| **High Density Developed** | 10000 | 35 |
| **Commercial, Industrial** | 10000 | 65 |
| **High Density Residential** | 10000 | 90 |
| **Barren Land** | 1 | 0 |
| **Deciduous Forest** | 100 | 5 |
| **Evergreen Forest** | 100 | 5 |
| **Mixed Forest** | 100 | 5 |
| **Shrub** | 1 | 1 |
| **Grasslands** | 1 | 1 |
| **Pasture/Hay** | 100 | 1 |
| **Cultivated Crops** | 100 | 3 |
| **Woody Wetlands** | 1 | 0 |
| **Herbaceous Wetlands** | 1 | 0 |

**Table 2.4:** Population and building tax values are presented as densities ($km^2$). Vector methods often resulted in one method estimate being above FLEM while the other estimate was below FLEM. For simplicities sake, the average vector density was presented in this table. The poorest fit between FLEM and vector methods was in Buncombe & Orange.

| | 100-yr Population | | Marginal 500-yr Population | | 100-yr Building Tax | | Marginal 500-yr Building Tax | |
|---|---|---|---|---|---|---|---|---|
| **County** | **FLEM** | **Vector Average** | **FLEM** | **Vector Average** | **FLEM** | **Vector Average** | **FLEM** | **Vector Average** |
| **Buncombe** | 161 | 66 | 298 | 88 | 5.7 | 6.6 | 15.5 | 12.4 |
| **Orange** | 110 | 62 | 651 | 364 | 5.0 | 4.0 | 22.6 | 15.6 |
| **Durham** | 111 | 114 | 188 | 152 | 4.7 | 5.3 | 21.7 | 19.6 |
| **Wake** | 79 | 111 | 268 | 203 | 5.1 | 4.2 | 20.1 | 13.7 |
| **Craven** | 31 | 37 | 151 | 117 | 2.2 | 3.2 | 7.6 | 7.7 |

**Table 2.5**: Changes in population density between 1990 and 2000 for the county, 100 and 500-yr floodplain. Density is population/$km^2$, negative percent changes indicated a decrease in population from 1990 to 2000 while positive values indicated an increase.

| | Total County Population Density | | | 100-yr FIRM Population Density | | | Marginal 500 Yr FIRM Population Density | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2000** | **Percent Change** | **P-Value** | **2000** | **Percent Change** | **P-Value** | **2000** | **Percent Change** | **P-Value** |
| **Buncombe** | 121 | 15.6 | **0.276** | 160 | 6.00 | **0.450** | 298 | 10.5 | **0.440** |
| **Orange** | 104 | 21.0 | | 111 | 0.7 | | 651 | -0.2 | |
| **Durham** | 290 | 18.6 | | 111 | 12.8 | | 188 | 15.7 | |
| **Wake** | 283 | 32.6 | | 76 | -8.2 | | 241 | 15.1 | |
| **Craven** | 46 | 10.5 | | 31 | -3.5 | | 153 | 3.6 | |

**Table 2.6**: Changes in the population and building tax densities between the county, 100 and marginal 500-yr floodplain. Changes between the 100 and 500-yr densities were significant for both the population and building tax indicators.

| | 2000 Population Density (Population/km$^2$) | | | | Building Tax Density ($M/km$^2$) | | | |
|---|---|---|---|---|---|---|---|---|
| | Total County | 100-yr FIRM | 500-yr Marginal FIRM | P-Value | Total County | 100-yr FIRM | 500-yr Marginal FIRM | P-Value |
| **Buncombe** | 121 | 160 | 298 | **0.027** | 9.4 | 5.7 | 15.8 | **0.024** |
| **Orange** | 104 | 111 | 651 | | 6.8 | 5.3 | 38.4 | |
| **Durham** | 290 | 111 | 188 | | 18.4 | 5.1 | 14.7 | |
| **Wake** | 283 | 76 | 241 | | 22.8 | 5.2 | 16.6 | |
| **Craven** | 46 | 31 | 153 | | 3.1 | 2.2 | 9.3 | |

**Table 2.7**: The percent change in raw population, building tax, and area between FIRM and DFIRM. Changes are relative to FIRM values, so positive values indicate an increase in DFIRM coverage and negative values indicate a decrease in DFIRM coverage.

| | Craven | Orange | Durham | Wake |
|---|---|---|---|---|
| **Population** | % | % | % | % |
| **100-yr Floodplain** | -26.3 | -7.5 | -17.6 | **19.5** |
| **500-yr Floodplain** | **16.2** | -108.0 | -246.0 | -3.4 |
| **Parcel** | % | % | % | % |
| **100-yr Floodplain** | -20.7 | -6.9 | -36.9 | -16.4 |
| **500-yr Floodplain** | **2.8** | -157.9 | -198.8 | **1.1** |
| **Area** | % | % | % | % |
| **100-yr Floodplain** | -14.8 | -12.1 | **4.7** | -4.1 |
| **500-yr Floodplain** | **37.8** | -484.9 | **53.7** | **54.3** |

**Table 2.8:** Changes in flood risk (exposure * hazard probability) between 1990 and 2000 and between the 100-yr and marginal 500-yr FIRM. The lower frequency and cumulative value in the marginal 500-yr FIRM resulted in much lower risk.

| 100-yr FIRM | Buncombe | Orange | Durham | Wake | Craven |
|---|---|---|---|---|---|
| **1990 Population** | **91.7** | **45.2** | **107.8** | **167.5** | **145.2** |
| **2000 Population** | **97.7** | **45.5** | **123.6** | **154.8** | **140.3** |
| **Risk Change** | **+6.0** | **+.3** | **+15.9** | **-12.7** | **-4.9** |
| **500-yr FIRM** | | | | | |
| **1990 Population** | **2.1** | **6.8** | **4.2** | **6.5** | **6.8** |
| **2000 Population** | **2.4** | **7.1** | **5.0** | **7.7** | **7.1** |
| **Risk Change** | **+0.3** | **+0.3** | **+0.8** | **+1.2** | **+0.3** |

## 2.11 Figures:

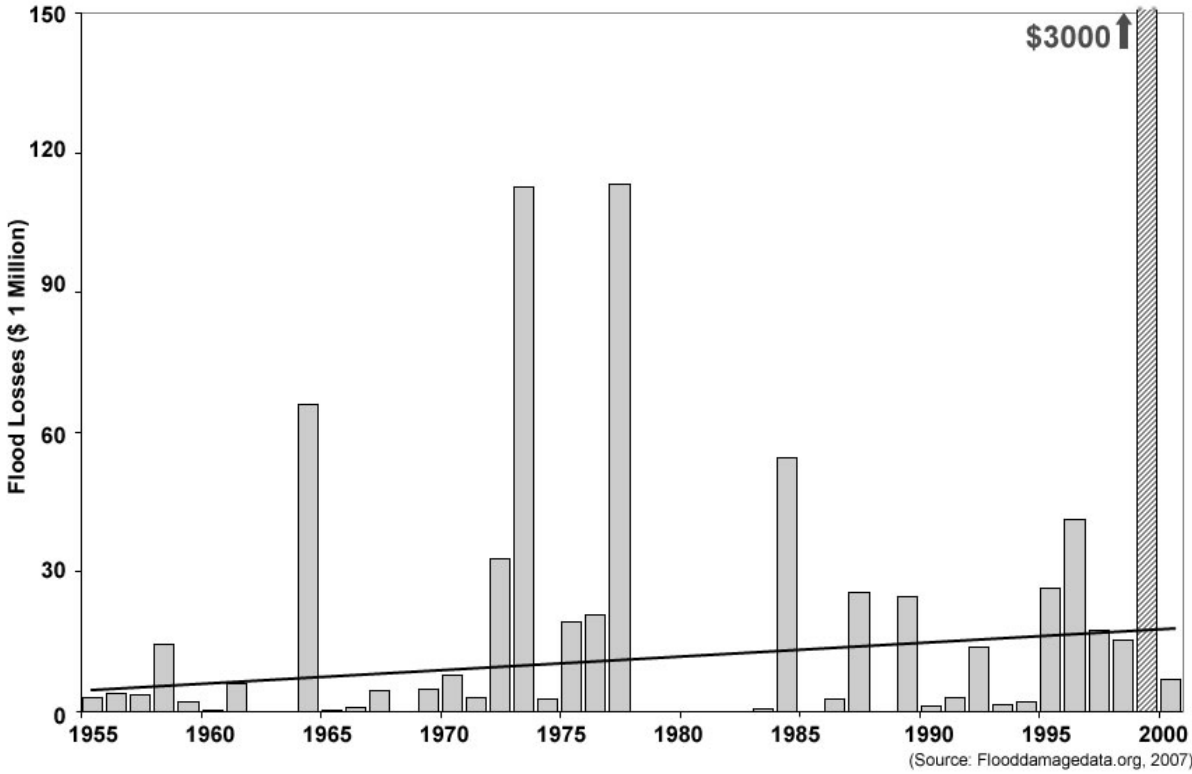


**Figure 2.1:** Flood damage trends in North Carolina from 1955 to 2003. Note the catastrophic impact of Hurricane Floyd as a focusing event for flood policy changes.

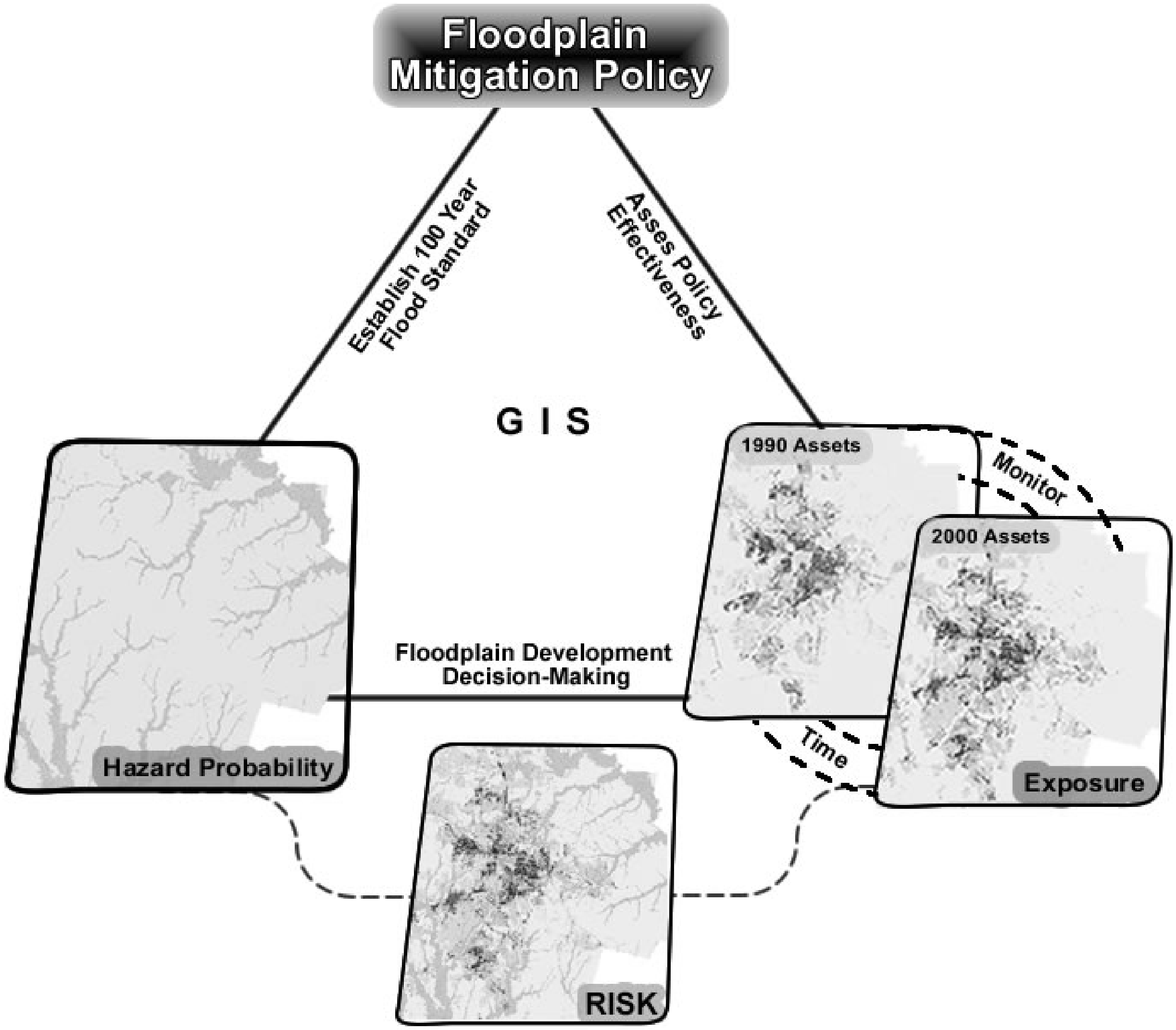


**Figure 2.2:** Theoretical framework for this thesis using a GIS and hazards paradigm to assess the effect of using the 100-yr floodplain boundary as the standard for flood policy. The spatiotemporal intersection of the 100-yr floodplain (Hazard Probability) and socioeconomic assets (Exposure) culminate flood risk. Monitoring changes in exposure relative to the 100-yr floodplain enables decision-makers to adjust their management strategies to become more effective.

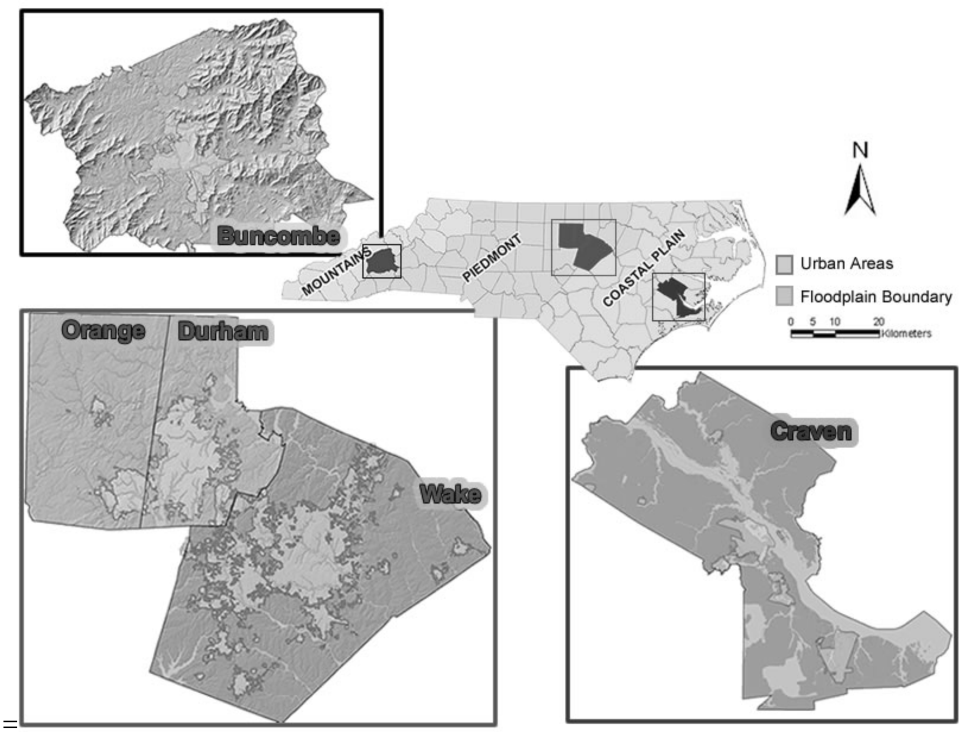


**Figure 2.3:** The physiographic characteristics of the study area, which spans from the flat coastal plains to the mountain range. Topographic variation and floodplain extents are illustrated in relationship to major urban areas.

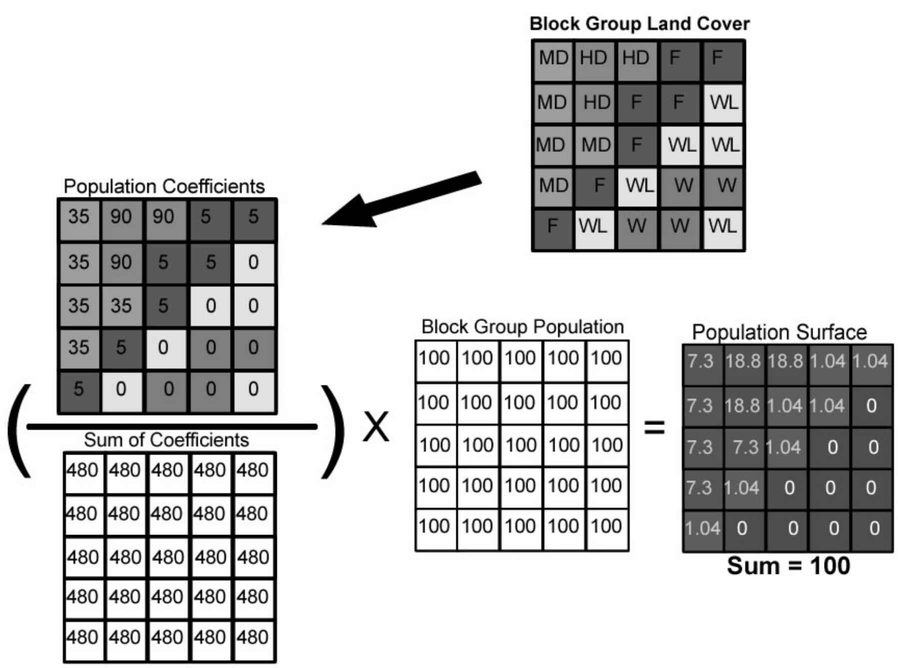


**Figure 2.4:** Schematic illustrates the process of creating a population surface for a block group with a population of 100. Coefficients are derived from table 2.3. MD = Medium Density Development, HD = High Density Development, F = Forest, WL = Wetlands, and W = Water. The population surface is rounded after the sum inside the floodplain is calculated to reduce rounding error.

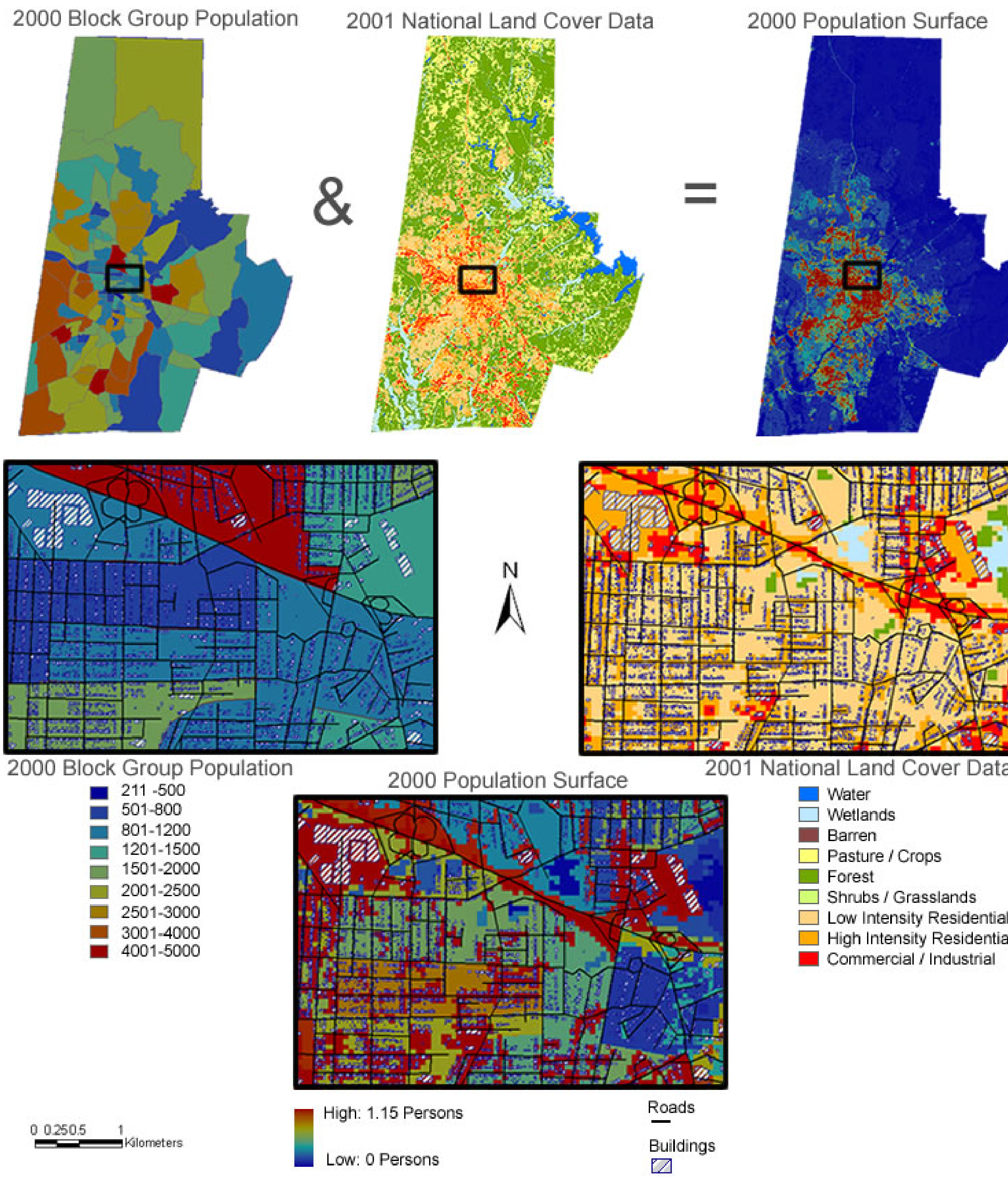


**Figure 2.5*:*** Illustrative methodology for distributing the population in Durham County using the ancillary 2001 NLCD. A building shapefile available for only Durham was overlayed to illustrate the effectiveness of distributing people in developed areas.

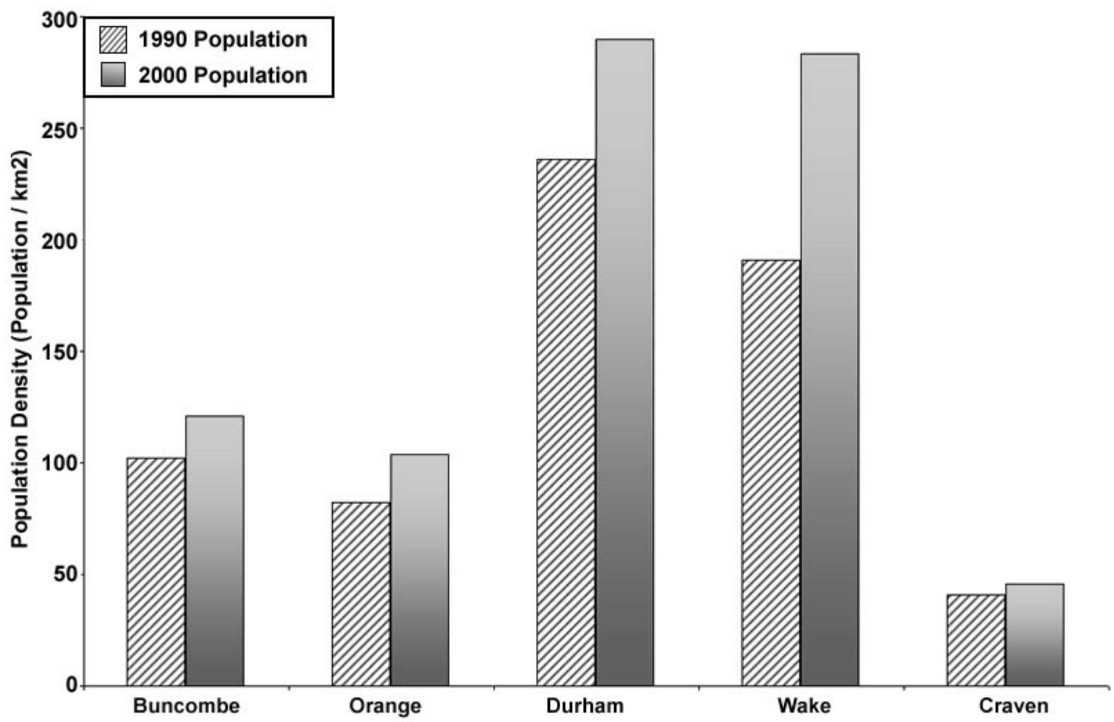


**Figure 2.6:** County level population density change from 1990 to 2000, showing an increase in population for all counties. If floodplain management does not effect development, it would be expected to see a similar increase in floodplain population density.

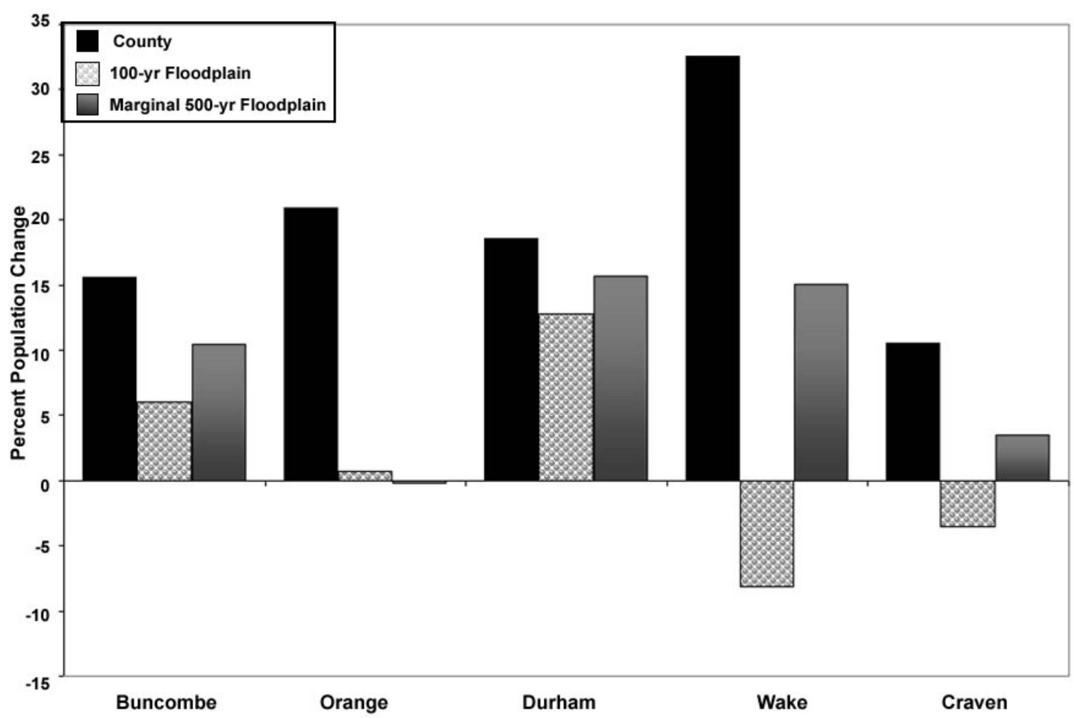


**Figure 2.7:** Percent population change in the FIRM floodplains from 1990 to 2000.

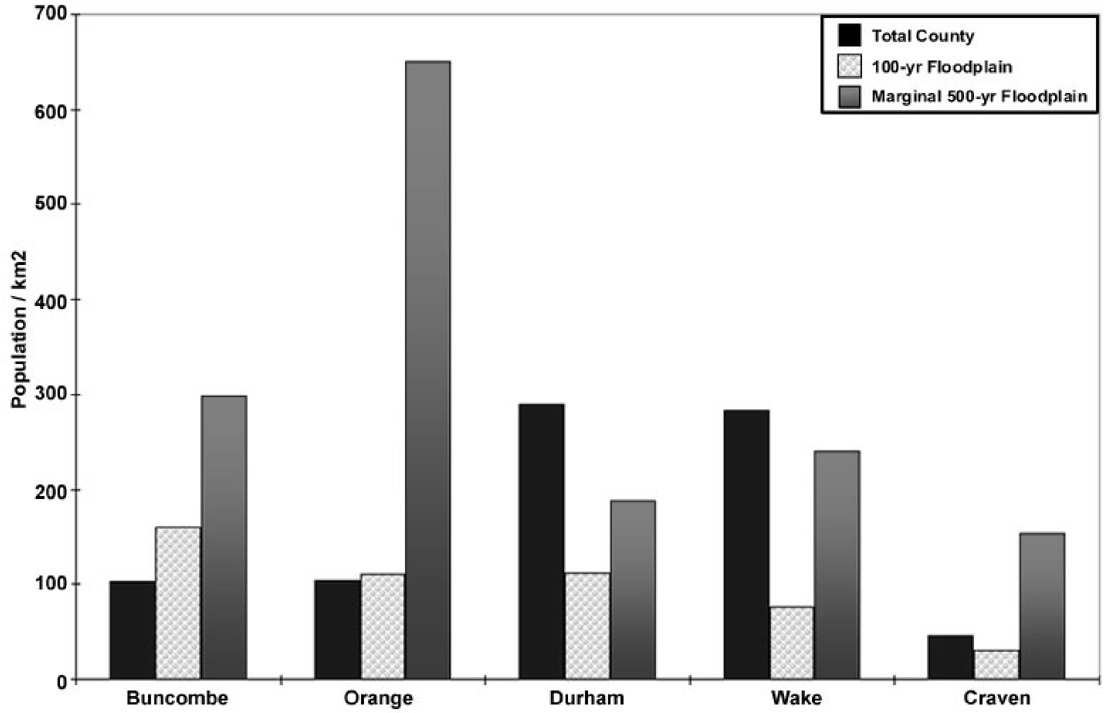


**Figure 2.8:** Population density inside the 100-y and marginal 500-yr FIRM. The county population density is displayed to gain a sense of how floodplain densities compare to the county density.

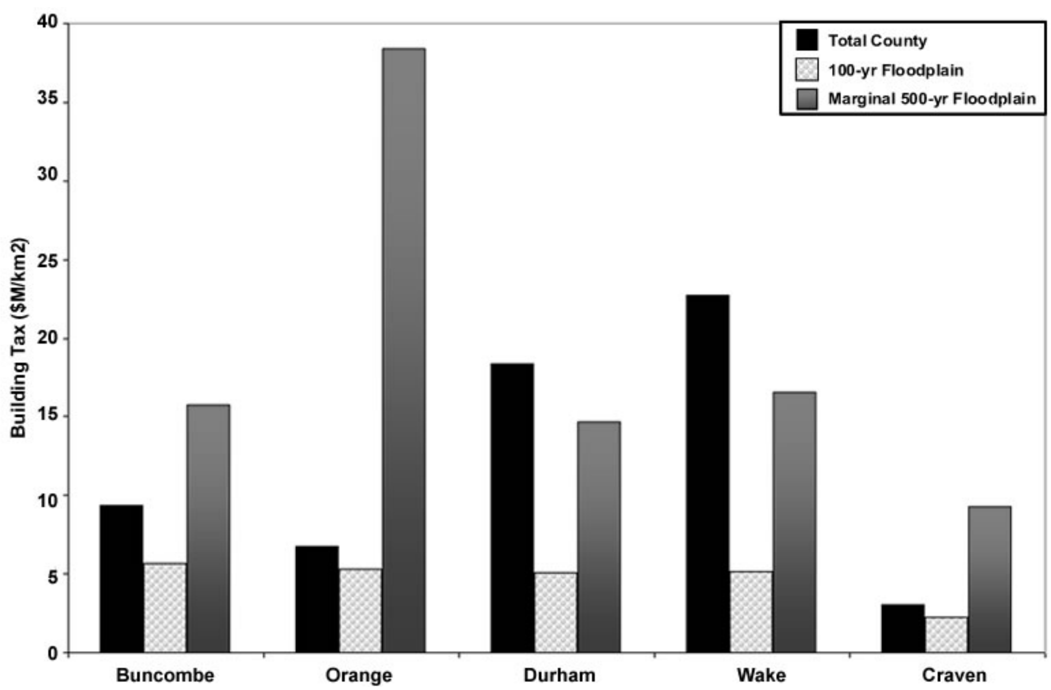


**Figure 2.9:** Building tax density (Millions) inside the 100 and marginal 500-yr FIRM. The county building tax density is displayed to gain a sense of how floodplain densities compare to the county densities.

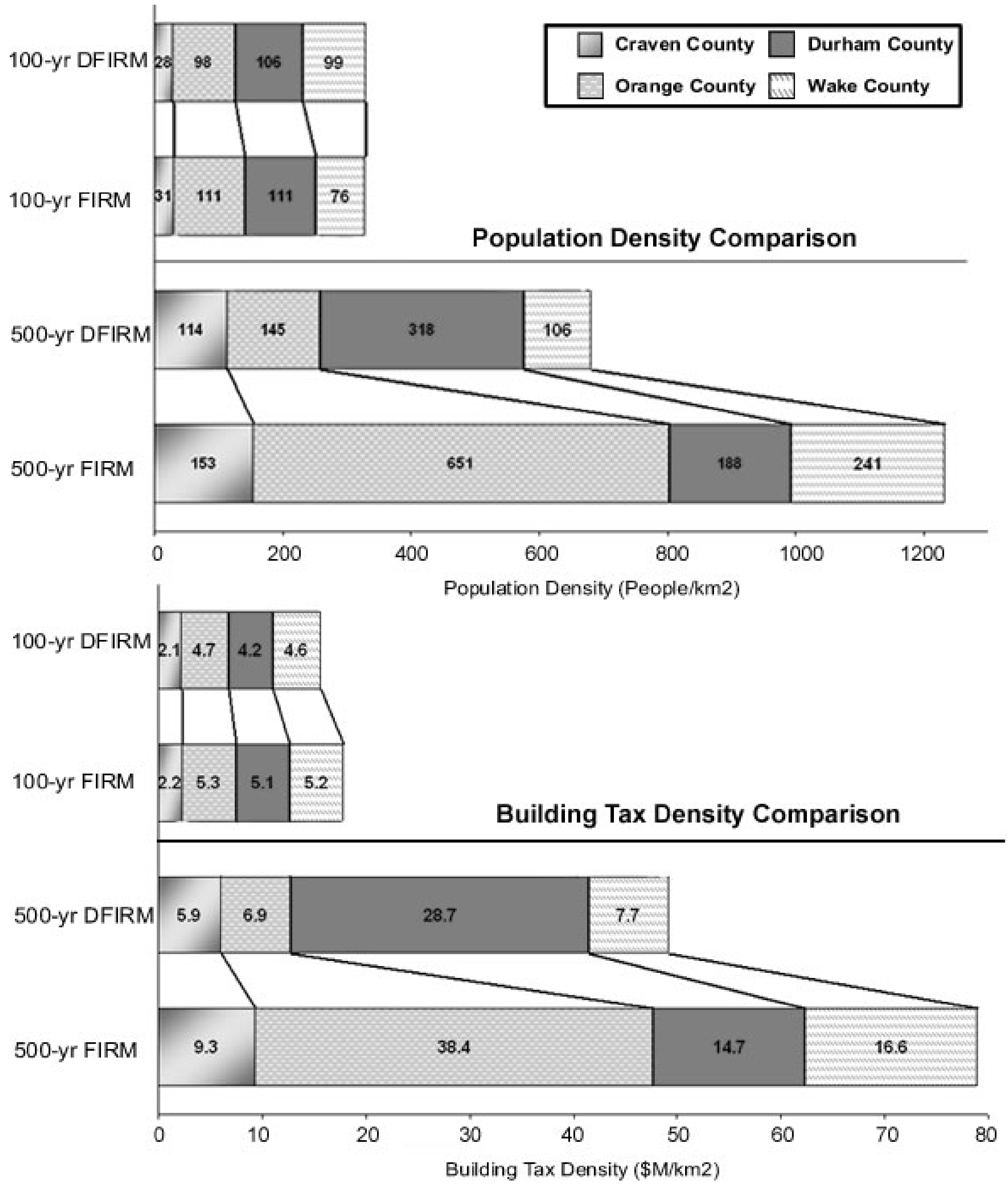


**Figure 2.10:** Cumulative change in socioeconomic density between the 100 and 500-yr floodplains for FIRM and DFIRM boundaries. Buncombe County is not presented because there were no available DFIRMs.

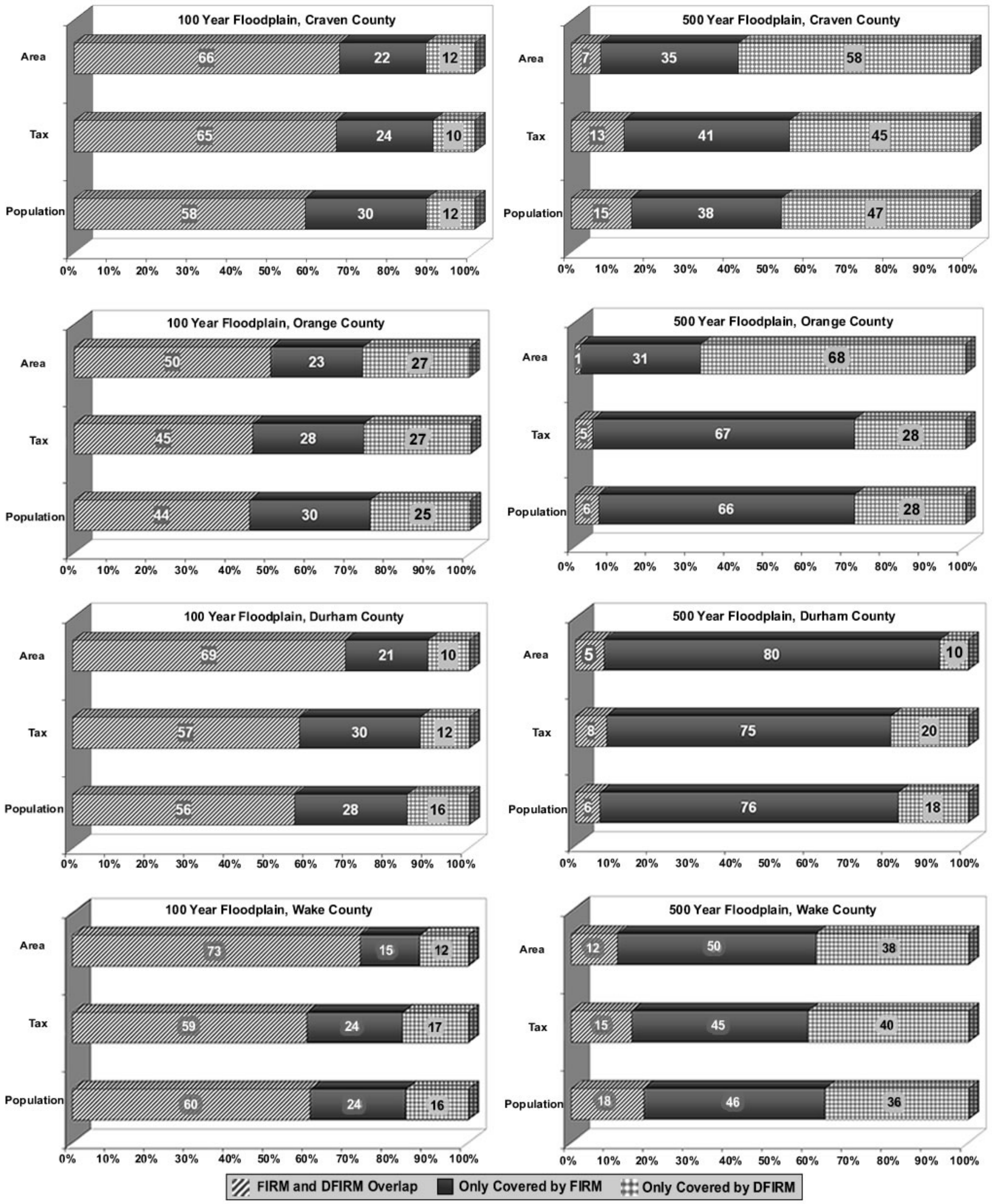


**Figure 2.11:** Comparison of normalized FIRM and DFIRM indicators showing the amount of area, population, and property value located where 1) the two floodplains overlap, 2) only the FIRM is located, and 3) only the new DFIRM is located. Values are normalized to the total value for each indicator among the three spatial boundaries.

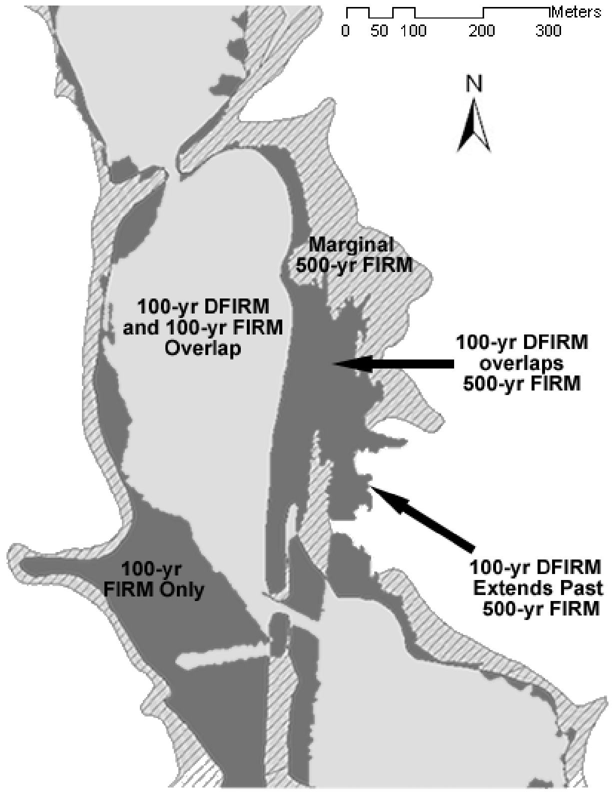


**Figure 2.12:** Example of 100-yr DFIRM extending into and beyond the 500-yr FIRM in Orange County.

# CHAPTER 3

SPATIAL DISTRIBUTION OF SOCIOECONOMIC VALUE AS A FUNCTION OF PHYSIOGRAPHIC PARAMETERS, DEVELOPMENT AND POLICY

## 3.1 Introduction:

Billions have been spent trying to *decrease* flood losses in the United States, with over $122 billion invested on structural control methods alone (IFMRC, 1994), yet flood losses have steadily *increased* throughout each geographically unique region of the country (Munich Reinsurance Company, 2006; Cartwright, 2005). Riverine floods are generally initiated through extreme precipitation events, whose severity is measured by the frequency of occurrence. The impact of floods does not become significant until it coincides with human development. Rising flood losses suggest that floods and humans are more frequenty intersecting spatially. The increasing intersection of humans and floods can be attributed either to 1) increasing frequency of floods, 2) increasing population density in floodplains or 3) increasing spatial extents of floods due to climate and land use changes.

Burton et al (1993) found the environment is becoming more hazardous simply as a result of where human development is occurring, implying current economic and political structures are increasing the risk of natural events. Additionally, developed countries have experienced a significant shift in the last 15 years from disasters occurring in rural to urban localities (Mitchell, 2006; Cohen & Werker 2004). Over the past 40 years the growth rate of large cities is shifting the dominant human habitat from rural to urban environments (Small, 2004). Floodplains account for an estimated 7% of the total area in the U.S. (IFMRC, 1994) and continue to be developed because their adjacency to waterways provides an ideal environment for both commerce and agriculture, which inevitably attracts residential development via job opportunities. Furthermore, as population size continues to increase, safe land available for development becomes limited and results in the transformation of hazardous areas, such as floodplains, from predominately rural to urban environments (Burby, 2002; Small, 2004).

Natural hazards research has traditionally focused on examining floods as a geophysical process (Haque & Etkin, 2007); thereby, implying the root cause of flood losses is due to the nature of floods rather than human-environment interactions. This duality is partially the result of the Western cultural heritage in viewing humans as separate from the natural environment. This view allows responsibility for flood losses to shift from human decision-making in settling the floodplain to forces of nature. However, in lieu of flood losses annually increasing by 3.45 % (Cartwright, 2005), natural hazards research has shifted to include the human component as a factor in increasing flood losses (Haque & Etkin, 2007; Mileti, 1999).

Natural hazards research has expanded its perceptions on how flood losses can continue to increase by including: climate change, population growth, land use change, increased vulnerability of structures, increased personal wealth, construction in flood prone areas, failure of flood protection systems, federal policies, and violation of floodplain management. The current trend of increasing flood losses is not sustainable, nor are the resources required to maintain a failing policy limitless. Mitchell (2006) noted that natural hazards are “constructed by human interactions with the physical environments and that their importance is likely to grow – not diminish – as societies develop." Thus, it is essential to understand the underlying causes of increasing flood loss prior to spending billions on management policies that might not address the most critical factors.

The consequences of natural hazards are deeply rooted into the larger issue of sustainable development (White et al, 2001), which refers to "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Report, 1987). The interdependence of the core element of sustainability: social, economic and environmental must all be addressed in hazard policies.

One of the key factors in creating a sustainable environment in hazardous locations revolves around how policies handle system uncertainty. Sources of uncertainty in decision-making can arise from a lack of data, deficiencies in models, and stochastic environments (Mitchell, 2002). It has been recommended by the Rio Declaration Principle 15 (Johnson, 1993) that the precautionary principle is utilized when dealing with uncertainty; whereby, activities are managed to minimize both known and unknown risks by erring on the side of caution to reduce potential losses. With regards to floodplain management, all the sources of uncertainty outlined above are present in the floodplain; however, policies are not precautionary and have been criticized for not being restrictive enough (White, 2001).

### *3.1.1 Introduction to the 100-yr Floodplain and FIRM:*

U.S. flood policy is based on the delineation of the 100-yr floodplain, which is the horizontal extent of inundation for a flood that statistically occurs once every hundred years. The 100-yr floodplain was selected as a standard guideline for policy enforcement (Robinson, 2004 & Reuss, 2004). However, the process of delineating the 100-yr floodplain has high uncertainty due to missing and low resolution data, the stochastic nature of floods, and epistemic errors in model assumptions. The uncertainty in delineating floodplain boundaries has been estimated to result in as much as 1.5 m (5 ft) of vertical error (Smemoe et al, 2007; Lawlor, 2004; IFMRC, 1994) which, could result in a significant shift in the horizontal floodplain extent depending on the topographic profile. The topographic profile refers to the rate of change in floodplain elevation, for example a flat coastal plain or an entrenched canyon. Floodplain boundaries are displayed on Flood Insurance Rate Maps (FIRM), which are required by the Federal Emergency Management Agency (FEMA) to be created for a community prior to participation in flood mitigation and insurance programs. Inside the 100-yr floodplain there are requirements for 1) obtaining flood insurance, 2) development and building codes, and 3) mitigating homes by elevation or flood proofing. Outside the 100-yr FIRM, there are no requirements for living in a floodplain.

FIRMs display the 100-yr floodplain boundary as a distinct, well-defined line with no indication of the spatial uncertainty present. Furthermore, FIRMs can become temporally outdated as climate change leads to different precipitation regimes and changes the frequency and magnitude of flood events (O'Brien et al, 2006; Hirsh et al, 2004). Additionally, land use change, especially urbanization, has caused as much as a two-fold increase in the magnitude of the 100-yr flood (Hirsh et al, 2004; Bana E Costa et al, 2004; Tobin, 2004). The spatially and temporally dynamic nature of the 100-yr floodplain is problematic because these changes often occur faster than FIRMs are updated. The result is generally an underestimated prediction of the location of the 100-yr floodplain boundary and little confidence by floodplain managers in the accuracy of FIRMs (Lawlor, 2004). The lack of trust has resulted in decreased enforcement of flood policy and has contributed to increasing losses (IFMRC, 1994). The method for delineating, displaying, and implementing flood policy has not followed the precautionary principle.

*3.1.2 North Carolina, Sustainable Development and Monitoring Success:*

North Carolina has transformed its floodplain management strategies to include sustainable development as a core feature of its policy (NCNHM, 2001). North Carolina suffered a series of hurricanes, starting in 1996 with Fran and ending in 1999 with Floyd, which impacted over half the population and cost several billions in flood damages. Following these hurricanes, the state has focused on redevelopment of the area to create cities sustainable to floods by initiating a Hazard Mitigation Grant Program (HMGP) designed to minimize future impacts from natural hazards (NCDEM, 2007). The four elements that guide the process of creating a mitigation strategy are to: 1) identify performance based objectives for established goals, 2) create indicators to measure progress, 3) identify criteria for selecting mitigation options, and 4) incorporate the selected mitigation strategies into the local community's mitigation plan. (NCDEM, 2007).

A cornerstone feature of the HMGP is to quantify the success of the program to articulate its effectiveness at reducing costs and in meeting goals. Furthermore, the establishment of social, economic and environmental indicators is essential in creating sustainable communities by providing quantifiable goals that can be monitored and evaluated. The goal of this chapter was to establish indicators and a methodology to measure the successfulness of flood mitigation strategies for reducing flood exposure at different spatial scales and contexts in North Carolina.

### 3.2 Research Objectives:

To measure the successfulness of reducing the risk for flood losses, it is necessary to identify the hazard probability and exposure of the indicator variable. In this project, the hazard probability is spatially defined as the 100-yr floodplain, or the 1% chance flood, and exposure is measured using population counts for the social indicator and building tax value for the economic indicator. Quantifying hazard probability and exposed assets enables risk to be spatially quantified in a meaningful way for emergency management planners. While the procedure for delineating the 100-yr floodplain has been established in FIRMs, the IPPC (1996b) has concluded that "little information is currently available regarding the socioeconomic impact of changes in the frequency and intensity of river floods." Furthermore, Cutter et al (2003) noted that the risk potential is either moderated or enhanced via a geographic filter (e.g. proximity to the river) and the social fabric of the area (e.g. development density), which can be further filtered via flood policies. To determine where flood management is effectively reducing losses, it is necessary to examine exposure through a geographic, social and policy lens. The remainder of this paper will discuss the study area, methods, and results regarding the spatial distribution of socioeconomic variables through a geographic, social, and policy lens (Figure 3.1).

#### *3.2.1 Defining the Geographic Lens:*

The spatial distribution of human population changes through time and understanding what factors determine this distribution is fundamental to understanding the dynamic relationship between humans and the natural environment (Small & Cohen, 2001). The utilization of both geophysical and socioeconomic data has the capability of improving our understanding of hazard exposure at a range of spatial scales. This chapter focused on the quantitative assessment of socioeconomic exposure to floods as a function of distance from the stream (fluvial proximity). An additional lens through which socioeconomic distribution was examined used the mean annual flow discharge of streams, because some of the most important issues in flood loss estimation models include flow velocity and depth (Dutta et al, 2003). The mean annual flow of a stream is generally correlated with stream order and size to produce a stream hierarchy (Huang et al, 2007). Disaggregating the stream into a hierarchy by flow discharges to examine population distribution as a function of fluvial proximity will provide a baseline risk assessment for monitoring changes in exposure through time at the reach scale, as well as supporting the assessment of potential impacts and scenarios for floodplain management (Small & Nicholls, 2003).

*3.2.2 Defining the Social Lens:*

The spatial distribution of population with respect to fluvial proximity as a function of development density was divided into urban and rural categories. The relationship between urban development and its effects on stream flow characteristics has shown that increasing impervious surface indirectly increases flood heights (Huang et al, 2007). However, how do the distributions of development density change in relation to fluvial proximity in rural and urban areas? Furthermore, have urban densities increased faster than rural densities near streams as human populations migrate from the rural to the urban environment (Small & Nicholls, 2003)? Burby et al (2000) found that the cheaper, hazardous areas developed at a faster rate as human populations continue to increase and the amount of available land for development decreased, and White & Haas (1975) noted population shifts from rural to urban areas resulted in more people living in ‘unregulated’ floodplains. Assessing how the spatial population distribution changed through time in rural and urban areas can provide guidelines to floodplain managers regarding how to adapt policy efforts to most efficiently meet urban versus rural needs. Furthermore, if there was a large increase in development adjacent to the 100-yr floodplain boundary, perhaps it would be more prudent to extend flood policy guidelines to include those areas (Chapter 2; ASFPM, 2000).

### *3.2.3 Defining the Policy Lens:*

In the U.S., exposure to floods is largely influenced by the effectiveness of floodplain management, which has decreased, but not stopped floodplain development (Burby, 2002). Policies focused on reducing flood losses by removing people from the 100-yr floodplain have been in place since 1994 for the nation, but North Carolina has been an extremely progressive at removing and elevating homes of repetitively flooded structures since Hurricane Fran in 1996. Unfortunately, there are no direct measures of trends in floodplain occupancy (Pielke, 2002) and no evaluations on the effectiveness of flood policies on changing the spatial distribution of exposure in relation to fluvial proximity, stream hierarchy, and urbanization. Through exploratory analysis of spatiotemporal socioeconomic distributions, this chapter assessed whether development was reduced in the 100-yr floodplain, if exposure increased adjacent to the 100-yr floodplain, and where floodplain management has been the most and least effective.

## 3.3 Study Area:

North Carolina is both topographically (elevation ranges from 0 to 2,038 m or 0 to 6686 ft) and climatologically (annual precipitation ranges from 1067 to 2642 mm or 42 to 104 inches) diverse (Figure 3.2), yet the entire state is subject to significant hydrological and damaging flood events. North Carolina is divided into three regions for discussion when examining physical attributes: the Mountain Region, Piedmont and Coastal Plain.

The study area consisted of five North Carolina counties, each reflecting different physiographic areas. The county scale was selected because FIRMs are produced at that scale. The counties examined were Buncombe (Mountain Region), Orange, Durham, and Wake (Piedmont), and Craven (Coastal Plain). Three contiguous Piedmont counties were analyzed to examine the longitudinal change in risk as floodplain extents expand from the headwaters (Orange) to the larger rivers and floodplains of Durham and Wake County. Interestingly, population in these counties follows the same increasing trend moving downstream from Orange to Wake County (Table 4.1). The Piedmont receives a mixture of rain from large fronts, local convective storms, and tropical storms. Hurricanes Fran and Floyd were the most damaging storm the Piedmont experienced during the 1990's; however, compared to the coastal communities the damage was relatively small. Orange and Wake are both participating communities of the HMGP, while Durham is the only county in the study area that is not a member.

Buncombe County is predominantly forested and Asheville is the major urban area. The French Broad is the largest river in Buncombe and bisects Asheville. Figure 3.2 shows the effects of mountain topography, with the majority of the 100-yr floodplain located within 200 m for all stream flows. Several costly floods have occurred in Buncombe during the 1990s due to intense rains from orographic uplifting and the remnants of hurricanes from the Atlantic and Gulf Coast. As a result, Buncombe is one of the participating communities in the HMGP (NCNHM, 2001) that has been actively reducing development on the floodplain.

Craven County has an extensive floodplain and wetland system due to its flat topography and is the least populated county in the study area. The histograms for Craven represent the flat topography, with half of the 100-yr floodplain area in the larger streams located at a distance greater than 700 m from the stream. The Neuse River, draining from the Piedmont, empties into the Pamlico Sound near New Bern, Craven's largest city. Craven's population is dispersed among several small urban areas and a military base, which is the largest and most southern urban area (Figure 3.2). Craven, like Buncombe, experienced several catastrophic floods in the 1990's, including Hurricanes Fran and Floyd. As a result, Craven is one of the initial HMGP demonstration communities and has actively removed property from the floodplain.

## 3.4 Methodology:

### *3.4.1 Data Description:*

The process of assessing risk encompasses three aspects: hazard, exposure, and vulnerability (NCDEM, 2007; Grunthal et al, 2006). The flood hazard is represented by the 100 and 500-yr FIRM boundaries, which provide the spatial extent and frequency of the hazard. The 100 and 500-yr FIRMs were obtained from FEMA. The assessment of fluvial proximity required the use of two vector river shapefiles and a digital elevation model (DEM). BasinPro Version 3.1 is a stream network with at a 1:24,000 scale. The United States Geological Society's (USGS) National Hydrology Dataset (NHD) has a coarser spatial resolution at 1:100,000, but contained mean annual flow values (NHD, 2006). Thus, BasinPro was used to define the spatial location of the rivers, while the NHD was used to disaggregate the stream network by mean annual flow. Lastly, Light Detection and Ranging (LiDAR) DEMs were obtained from the Department of Transportation (NCDOT, 2006).

Assessment of exposure can be divided into indicators for the constructed (building tax value) and human system (population counts). Risk was quantified by combining the flood event (100-yr floodplain) with 1) spatiotemporal transformations (population change through time), 2) constructed vulnerability (building tax value) and 3) social vulnerability (population) (Merz et al, 2006). ESRI's Topological Integrated Geographic Encoding and Referencing (TIGER) data provided 1990 and 2000 population counts in spatial block group boundaries for the nation (TIGER, 2004). Population data are a "useful indicator of the changing human ecology of a hazard" (Mitchell, 2000). Parcel data have a higher spatial resolution than block groups and were used to extract building tax values for the economic indicator. The National Land Cover Dataset (NLCD) was freely available from the USGS seamless website (USGS, 2006), and was an ancillary variable used to distribute population and parcel values within their vector boundaries. Vulnerability was not assessed in this study as its meaning, ability to quantify, and overall usefulness is debatable (Handmer, 2003; Yohe & Tol, 2002); rather, exposure was used as a proxy to measure relative changes in risk.

The threshold dividing urban from rural areas was determined by including those areas inside the U.S. Metropolitan Statistical Zones as of 2001 into the urban category. The metropolitan statistical areas were defined by the U.S. Office of Management and Budget (OMB) and consist of a population core greater or equal to 50,000 (OMB, 2000).

*3.4.2 Creating Hazard and Socioeconomic Surfaces:*

Hazard and exposure surfaces were created in ArcGIS 9.1. The attributes of the FIRM shapefiles defined the geographic location of the 100-yr floodplain. The marginal 500-yr floodplain, which does not include area covered in the 100-yr floodplain, was also extracted to assess development adjacent to the 100-yr floodplain.

Population and tax values are formatted and displayed in a GIS as discrete variables within their spatial boundaries. This format does not allow the analyst to discern how much of the population or tax value are located within the floodplain when only a portion of the shapefile intersects the floodplain. There are two common approaches to address this problem. First, it is assumed that population/tax values (socioeconomic) are uniformly distributed, and the percent area contained in the floodplain is correlated to the percent of socioeconomic value in the floodplain. The second method is an all or nothing approach; whereby, if the center of the block is inside the floodplain, all socioeconomic value is included and if the center is outside the floodplain, nothing is included. Neither method is based on valid assumptions, so NLCD was used as an ancillary variable to logically distribute population and building tax by placing more value in developed pixels. The population and tax surfaces were created at the same spatial resolution as the LiDAR data (6.09 m or 20 ft) used to create FIRMs. The goal was not to create a perfect socioeconomic distribution, but to create a better distribution than national vector datasets provided.

Details regarding the creation of population and tax surfaces are found in Chapter 2. Briefly, the NLCD was weighted by land type to attract people and property to developed pixels and to minimize the value in uninhabitable areas. The error for population and parcel distribution was constrained by the spatial boundaries of the vector polygons; thus, because the parcel resolution is higher than the population block group, the uncertainty of the tax surface was less than the population surface.

The weights used to redistribute building tax were scaled logarithmically with the assumption that more buildings are located in developed areas (e.g. commercial, residential) than undeveloped areas (e.g. wetlands, barren). The parcel shapefile was converted into a raster using building tax as the pixel value. The reclassified NLCD for building tax value ($NLCD_{BuildReclass}$) was divided by the sum of $NLCD_{BuildReclass}$ per parcel to get the percentage of building tax value attributed to each pixel. The percent building tax attributed to each pixel was multiplied by the building tax value for each parcel (*BuildingParcelRaster*) to create the *BuildingTax Surface* (Equation 3.1).

$$BuildingTaxSurface = \frac{NLCD_{Build\,\mathrm{Re}class}}{\sum NLCD_{SumBuild\,\mathrm{Re}class}} \times BuildingParcelRaster \qquad (3.1)$$

The population coefficient file created an ambient population surface (Figure 3.3). The classification was modified from the percentage of development used to classify the NLCD from low to high density residential and commercial areas (Homer et al, 2004). Forest values were given weight because much of North Carolina is forested and populations located beneath tree canopies are not readily captured by satellite imagery. Values of zero were used for water, wetland, and barren land cover. The 1990 population surfaces were created using 1992 NLCD.

The creation of the population surface followed the steps outlined for the building tax surface (Equation 3.2). The 6.09 m (20 ft) spatial resolution resulted in pixel values less than one, which is reasonable as the surface was used as the probability of finding X number of people at any given time in a pixel. Both exposure surfaces were used to calculate the cumulative value by fluvial proximity to mediate the significance of distribution error.

$$PopSurface = \frac{NLCD_{\mathrm{Re}classPop}}{\sum NLCD_{PopBlockGroup}} \times Population \qquad (3.2)$$

The socioeconomic surfaces were compared to the two standard vector methods described above to calculate the value located inside the floodplain boundary (Chapter 2). Population blocks (higher spatial resolution than block groups) were used for the population vector method. The socioeconomic surface variation from vector methods was less than 25% for population and 18% for building tax, with a tendency to underestimate values.

*3.4.3 Limitations for the Socioeconomic Surface:*

The high resolution socioeconomic surfaces created to serve as indicators in this exploratory analysis have several limitations. First, the raw population and tax data have an unknown amount of spatial and attribute error. The NLCD accuracy is between 71 and 76%, with accuracy being regionally variable. The data errors were then propagated in the creation of the raster surfaces. Secondly, all data were disaggregated to match the LiDAR spatial resolution used to create the fluvial proximity surface, which added additional uncertainty. Uncertainty was constrained by parcel and population vector boundaries, with larger blocks having a higher degree of uncertainty; however, large blocks are often associated with smaller socioeconomic densities. Lastly, the assumptions used to weight the coefficient matrices do not uniformly apply in every locality and introduce another level of error. However, the purpose of this research was to do an exploratory and comparative analysis of exposure in relationship to geographic, social, and policy factors. Thus, while the actual numbers have some uncertainty (18 - 25% on average), the relative differences and trends are sufficiently accurate for this study.

*3.4.4 Calculating Fluvial Proximity by Stream Flow:*

Calculating distance from a stream required creating a raster stream network. LiDAR has a vertical accuracy of 0.20 m (0.66 ft) and a horizontal accuracy of 3 m (10 ft) (Sanders, 2007; Mitasova et al, 2005). The high spatial resolution has a relatively high signal to noise ratio, especially in floodplains, where changes in elevation are small (Raber, 2003). The presence of noise in the floodplains created tortuous flow paths for routing water and resulted in over-estimated flow distances. Prior to routing water, the LiDAR DEM was filtered twice using an 11x11 mean rectangular kernel to reduce noise and smooth artifacts that could encumber hydrologic analyses (Sanders, 2007). Buncombe was not filtered because LiDAR was not available for this county and used the USGS 30 m DEM.

ArcGIS 9.1 ArcHydro tool was used to imprint the BasinPro streams into the DEM to force water to route in the same pattern as the 1:24,000 scale raster stream network. The steps below are standard and follow the recommendations of ESRI's ArcHydro (Maidment, 2002). The command 'Agree DEM' created a 20 m (66 ft) pixel depression where the BasinPro streams were located, with a smoothed buffer of 50 m (164 ft) sloping to the stream. DEMs were filled to remove any depressions that would prevent water routing and create an incomplete stream network. After depressions were removed, the flow direction was calculated for every 45 degree angle in the direction of the pixel with the steepest slope. The flow accumulation function counted the number of pixels from the ridgeline to the stream for each pixel value. A threshold of 8,000 flow accumulation pixels was established as the cutoff for inclusion in the stream raster. This threshold was established by trial and error to match the BasinPro vector streams.

The NHD shapefile contained mean annual flow attributes that were used to disaggregate stream reaches on a logarithmic scale by flow. The NHD streams were divided into five different stream segments on a logarithmic scale in cubic feet per second (cfs) ranging from > 1000 to 0.1 cfs, which were converted into the metric system (>28.3 cms – 0.003 cms). The spatial difference between the NHD and stream raster was less than 50 m, so a 50 m buffer was created around the NHD streams and used to extract stream raster reaches by flow (Figure 3.4).

Fluvial proximity (distance from the stream) was calculated after disaggregating streams by flow. There were two options for calculating distance. Euclidean distance is the straight line distance between two points, while flow path distance forces water to flow in the direction of least resistance with respect to elevation. Flow path distance was the best option because it accounted for the modified movement of flood water due to floodplain structure (Peterson, 2007; Dutta, 2003). For example, houses situated on a bluff have a Euclidean distance of 20 m (66 ft) from the stream, while the flow path might be 50 m (154 ft) because it accounted for the extra length of the path needed to travel up the bluff. The Spatial Analyst Cost Distance tool used the disaggregated stream rasters as the input and the flow direction raster, which was created from the DEM, as the cost raster (ESRI, 2007). The Euclidean distance was calculated with the Spatial Analyst Euclidean Distance tool to provide policy users with a more intuitive representation of socioeconomic exposure by fluvial proximity.

The maximum flow distance calculated for streams with a flow > 2.8 cms was 3000 m (1.86 mi), 0.3 – 2.8 cms was 2000 m (1.24 mi), and < 0.3 cms was 1000 m (0.62 mi). The maximum flow distances for each stream extended far enough to completely contain the 500-yr floodplain. The large streams and waterbodies had a width greater than a single pixel, so the NLCD was reclassified to give water a value of 0, so the flow distance remained zero while located in the waterbody and increased outside the shore (Figure 3.4).

*3.4.5 Calculating Exposure by Fluvial Proximity for the Geographic, Social & Policy Lens*

Zonal statistics (ESRI, 2007) calculated the sum of population and building tax values and the average Euclidean distance as a function of fluvial proximity (Figure 3.4). To account for the social lens, zonal statistics were separately calculated for streams inside and outside of urban areas. The policy lens used zonal statistics to calculate values inside the 100 and marginal 500-yr floodplain. The flood policy analysis consisted of four objectives.

First, the total population in the 100-yr floodplain by stream flow was calculated and related to the total population at risk of flooding. Secondly, the change in the 100-yr floodplain through time was examined to determine if people were removed between 1990 and 2000 as mitigation became a staple of flood policy. Third, the socioeconomic density as a function of fluvial proximity between the 100 and marginal 500-yr floodplain was compared to determine if development density increased outside the 100-yr floodplain. Lastly, the total population located in the marginal 500-yr floodplain by stream size was calculated to determine the risk for different stream magnitudes given a flood exceeding the 100-yr event.

*3.4.6 Limitations for Fluvial Proximity Methods:*

The fluvial proximity raster calculated by stream flow has uncertainty introduced through raw data errors, as well as model assumptions in delineating stream rasters and calculating flow paths. In addition, the stream raster, BasinPro and NHD had a spatial disagreement rarely greater than 50 m (154 ft); thus, the socioeconomic values within 50 m (154 ft) of the stream should be considered with caution. While flow distance was the most accurate method for assessing socioeconomic exposure as a function of fluvial proximity (Dutta et al, 2003), Euclidean distance is intuitively easier to understand and more useful for policy makers. Therefore, the flow distance was transformed into Euclidean distances for the purposes of the graphs shown in this chapter. This introduced further spatial error, but was necessary to make this research beneficial for floodplain management.

Stream hierarchies are created as streams of different order intersect to form stream networks. The junction points of stream reaches form areas of overlap when calculating the flow distance and exposure values. This was considered acceptable as those areas are exposed to flooding from two different streams and is exposed to two different flood hazards.

*3.4.7 Trend Analyses:*

The data were imported into Excel and socioeconomic values were plotted as a function of Euclidean distance from the stream (although the values were originally calculated via Flow distance and later converted to Euclidean). The cumulative sum of population and building tax value were calculated using Equation 3.3, where *SE* is the socioeconomic variable, $C_{SE}$ is the cumulative sum of the socioeconomic variable, and *i* is the fluvial proximity. The cumulative value provides floodplain managers with an estimate of the actual number of people living X distance from the stream and where development is most rapidly changing.

$$C_{SE} = \sum_0^i SE_i \qquad \textit{Equation (3.3)}$$

Cumulative socioeconomic density ($CD_{SE}$) was calculated (Equation 3.4) to normalize the socioeconomic distribution by the land area (*A*) available for development. Small & Cohen (2001) coined this distribution function as the Integrated Population Density (IPD) and used it to provide comparative indications of how relative densities change by fluvial proximity. The actual density ($AD_{SE}$) was calculated (Equation 3.5) for trend analysis purposes to locate any sudden shifts in development density.

$$CD_{SE} = \frac{\sum_0^i SE_i}{\sum_0^i A_i} \qquad \textit{Equation (3.4)}$$

$$AD_{SE} = \frac{SE_i}{A_i} \qquad \textit{Equation (3.5)}$$

Socioeconomic data were then plotted with the null hypothesis, which uniformly distributes population and tax value with distance from the stream based on the area available for development. The null hypothesis was calculated by averaging the cumulative sum of the socioeconomic data and dividing that value by the total area to get a constant population or building tax density (*Equation 3.6*). The null socioeconomic ($NH_{SE}$) value at every distance from the stream was calculated by multiplying the null hypothesis density ($NHD_{SE}$) with the area at each distance (*Equation 3.7*). Comparing the difference between the socioeconomic values and the null hypothesis allows floodplain managers to see where development is below or above expected values considering no influence by fluvial proximity or floodplain policy.

$$NHD_{SE} = \frac{Average(1990\sum_0^n SEn, 2000\sum_0^n SE_n)}{\sum_0^n A_n} \qquad \text{Equation (3.6)}$$

Where n is the farthest distance calculated from the stream center, and

$$NH_{SE} = NHD_{SE} \times A_i \qquad \text{Equation (3.7)}$$

**3.5 Results:**

*3.5.1 Relationship between Building Tax Value and Population Counts:*

The only temporal data available was population data, and to infer overall development with an economic component, the relationship between social and economic values was established. The relationship between population and property value as a function of fluvial proximity was predominantly linear with a y-intercept set to zero (inside the waterbody) and an $r^2$ fit greater than 0.89 (Table 3.2). Using the equation, $y = mx$, with $y$ = population and $x$ = building tax, the slope (m) relating population to building tax was 0.082. The well-behaved linear relationship was important to establish for discussions focused on temporal changes in the spatial distribution of development on the floodplain; *ergo* underlying the assumption that changes in population correlated to changes in building tax, which are directly related to development.

The results are divided into three sections to address the spatiotemporal distributions of socioeconomic value in relation to geographic, social and policy lenses. The geographic lens is assessed by examining the spatial distribution of socioeconomic value in relation to fluvial proximity and stream flow. The social lens examined how these trends change in urban and rural environments, while the floodplain policy lens examined how the trends differed within the 100 and marginal 500-yr floodplain.

*3.5.2 Geographic Lens:*

The cumulative socioeconomic value as a function of fluvial proximity generally increased linearly away from the stream, with $r^2$ values greater than 0.91 for building tax value and 0.94 for population counts. The y-intercept value was zero since neither people nor buildings are located in streams. The linear rate increased exponentially as stream flow decreased (Table 3.3, Table 3.4) to 0.03 cms. Below 0.03 cms, the area and overall socioeconomic value decreased as many of these streams were not represented at the 1:24,000 vector stream scale and were not created in the stream raster.

*3.5.2.1 Cumulative Building Tax Value:*

In all counties except Craven, the rate of increase in cumulative building values was less than or equal to the null hypothesis (Figure 3.5). In Craven, the building tax in the largest stream was greater than the null hypothesis at all distances from the stream. Additionally, the smallest Craven stream had a rapid increase in building tax value 176 m (0.1 mi) from the stream, where it exceeded the null hypothesis. The greatest absolute difference between building tax value and the null hypothesis was located near the stream, with the actual and null values merging as distance increased. Craven had the smallest difference between the null hypothesis and actual values. The largest difference between the null and actual building tax value for the Piedmont were in streams with a mean annual flow between 0.03 – 0.3 cms. Throughout the study area, the building tax value increased at a faster rate in streams with flow less than 0.3 cms.

*3.5.2.2 Cumulative Population Counts:*

The population null hypothesis was averaged between 1990 and 2000; *ergo* the 1990 population value was always less than the null hypothesis, while the 2000 population always surpassed the null hypothesis (Figure 3.6). However, the fluvial proximity at which the 2000 population exceeded the null hypothesis was strongly influenced by stream size (Figure 3.7). Greater than 28.3 cms stream flows had the smallest variation between the null and actual population values, and the 2000 population was always below the null hypothesis within 1000 m (0.61 mi) from the stream. The largest difference between the 2000 and null populations occurred close to the streams, which could indicate the distance of the 100-yr floodplain. The 2000 minus the null population showed the relationship to be a fairly well-behaved concave up polynomial curve (Figure 3.7) that crossed the null value with increasing distance from the river as stream size increased (Table 3.5). Similar to the building tax value, the greatest rate of population increase by fluvial proximity was located in streams with a mean annual flow of 0.03 – 0.3 cms

The temporal change in population distribution for the Piedmont counties demonstrated a linear increase in population with distance, and the greatest increase occurred in streams with less than 2.8 cms mean annual flow (Figure 3.8). The largest increase in population for all counties occurred in streams with a mean annual flow less than 0.3 cms. Furthermore, as stream size decreased, the rate of change from 1990 to 2000 by fluvial proximity increased (Table 3.6). Craven followed the same trend, except for streams with a mean annual flow greater than 2.8 cms, which had a population decrease throughout the fluvial proximity. Buncombe had a small increase in population for the largest streams and a larger increase as stream size became smaller, with the population increasing with distance from the stream.

*3.5.2.3 Temporal Changes in Population Density:*

Controlling for the amount of area containing the cumulative socioeconomic value above is necessary to assess development density. Buncombe had a threshold for population density at the 2.8 cms stream flow. Stream flow above this threshold had a population density around 200 people/km$^2$, while the density in streams below this threshold decreased to around 95 people/km$^2$ (Figure 3.9). Craven had a similar threshold where streams less than 0.3 cms had a convex down curve that asymptotes 200 m (0.12 mi) from the stream at a density of about 40 people/km$^2$. The 2.8 to 28.3 cms stream had the highest density in Craven and increased linearly with distance from the stream. Both of these counties had the largest urban areas intersecting the largest streams. The three Piedmont counties had the highest population density in the study area, and density increased moving from the headwaters in Orange downstream to Wake. In the Piedmont, the urban areas were intersected by streams of different flow magnitudes, so the most densely developed streams in the Piedmont were more variable. In the Piedmont, population density, for all but the largest streams, increased convexly with distance.

Comparing the actual to the null population density showed where development was different than anticipated assuming an even population distribution (Table 3.7). All streams with a mean annual flow above 0.3 cms initially had a development density lower than the null hypothesis within the first 90 m (0.06 mi) of the stream (Table 3.8). Buncombe's development increased and shifted closer to the streams from 1990 to 2000. Craven surpassed the null population density closer to the stream in 2000 than 1990 for flows less than 2.8 cms. The largest Craven streams had a decrease in density near the stream from 1990 to 2000, and experienced only a small increase in population density in the smaller streams. All three Piedmont County's 2000 population densities exceeded the null hypothesis closer to the stream than the 1990 population; thereby, indicating increased development near streams. Moreover, all three counties increased in population density from 1990 to 2000, with the greatest change having occurred in the smaller streams.

*3.5.3 Social Lens:*

The social lens examined cumulative population density (CPD) by fluvial proximity for streams located inside versus outside a 'metropolitan statistical area.' The building tax value was not displayed here because it had the same trend as the population, which also has the temporal component. Density values were used to account for differences in land area between urban and rural localities (Figure 3.10). In general, the urban CPD had a convex curve, indicating an initial rapid increase in density near the stream which slowed moving farther from the stream, while the rural CPD remained constant with a near zero slope.

In Buncombe, the urban CPD was always greater than twice the rural CPD, with the largest difference occurring along the largest stream. The CPD between 1990 and 2000 decreased within the first several hundred meters for all stream flows, except the smallest stream, which had an increase in urban population throughout the fluvial proximity. Craven had a decrease in urban CPD for all streams greater than 0.3 cms (Table 3.9). Only the 0.03-0.3 cms urban streams experienced an increase in population density throughout the fluvial proximity. Furthermore, Craven was the only county that had a decrease in rural population density from 1990 to 2000, which occurred in the 2.8-28.3 cms streams (Table 3.10). The rural population density throughout the rest of the study area increased through time.

In Orange County the CPD in all but the smallest stream initially decreased between 1990 and 2000 for the first hundred meters in the urban areas, after which the 2000 exceeded the 1990 CPD. The 2000 exceeded the 1990 CPD throughout the fluvial proximity in the smallest stream. In Durham, the CPD for the largest stream had an initial decrease from 1990 to 2000 for the first 180 m (0.11 mi). The 0.03-2.8 cms streams had a greater 2000 than 1990 population density throughout the fluvial proximity, although the difference is small for the 0.03-0.3 cms streams. Wake County streams between 0.3-2.8 cms had a small decrease in CPD for the first 130 m (0.08 mi), after which the 2000 surpassed the 1990 CPD. Streams with flow less than 0.3 cms experienced an increase in CPD throughout the fluvial proximity.

*3.5.3 Flood Policy Lens:*

The total population at risk to flooding by stream flow is given in Table 3.11. In general, streams with smaller flows contained more socioeconomic value in the 100-yr floodplain than larger streams. Population decreased in the 100-yr floodplain of Craven for all magnitudes of stream flow (Table 3.12), with the greatest decrease in the largest streams and less change occurring in smaller streams. Population also decreased in the 100-yr floodplain for streams with flow between 0.3 – 2.8 cms in Orange County and a couple of the Buncombe streams. The remainder of the streams in the rapidly growing Piedmont had a population increase in the 100-yr floodplain, with the greatest increase in the smaller streams.

The population change in the marginal 500-yr was remarkably different from the 100-yr floodplain. First, the only decrease in population occurred in streams with flow greater than 2.8 cms in Durham and Craven (Table 3.13). Moreover, the maximum decrease in population was 105 people, compared to 616 in the 100-yr floodplain. Little change occurred in Orange County between 1990 and 2000. However, both Durham and Wake had an increase in population in the marginal 500-yr floodplain for the majority of streams; although the magnitude of increase was less than that experienced in the 100-yr floodplain.

While the temporal change in population within the marginal 500-yr floodplain was less than the 100-yr floodplain, it is important to consider the area available for development to determine if land adjacent to the 100-yr floodplain has developed more densely (Figure 3.11). Throughout the study area, both the cumulative population and building tax density were several times greater in the marginal 500 than in the 100-yr floodplain. Only streams with flow greater than 28.3 cms had less development in the marginal 500 than the 100-yr floodplain near the streams. Furthermore, the rapid increase in the marginal 500-yr development corresponded with the decreasing area contained inside the 100-yr floodplain moving away from the stream (Figure 3.1), which made more area available for development outside the 100-yr floodplain.

Lastly, it is important to understand the spatial distribution of the population exposed to a flood event exceeding the 100-yr FIRM (Figure 3.13, Table 3.14). The analysis showed that for all counties, the 0.03-0.3 cms streams had the fastest population increase in the marginal 500-yr floodplain by fluvial proximity, and generally contained the greatest number of people. Additionally, the Mountain and Piedmont counties had a convex increase in cumulative population at risk by fluvial proximity, with the greatest change occurring in the first 200 to 400 m (0.12-0.25 mi) from the stream. Craven displayed the opposite trend with a concave up relationship between cumulative population and fluvial distance from the stream for flows greater than 0.3 cms, and a linear trend for the smaller stream flows.

## 3.6 Discussion:

The reach-scale exploratory analyses of spatiotemporal changes in exposure as a function of fluvial distance from the stream does not allow for a conclusive explanation of the cause and effect behind these changes. However, examining exposure distributions in relation to stream flow, urbanization and the flood policy makes it possible to hypothesize on the effects of these factors on socioeconomic distribution. Regardless, the distribution of exposure can spatially guide local officials to effectively concentrate flood mitigation efforts to reduce future flood losses.

### *3.6.1 Geographic Lens:*

The greatest amount of socioeconomic value was located around the smaller streams (Figure 3.5 & 3.6). This corresponds with stream hierarchy, where a typical county will have several smaller streams draining into one or two large streams. Each county had only one stream with the maximum flow, while there were over a dozen 0.03 – 0.3 cms stream reaches present, resulting in more land area available for development around the smaller streams. Furthermore, small streams tend to have more suburban development than larger streams (Syvirtski & Milliman, 2007); thereby resulting in greater socioeconomic exposure in stream with less than 0.3 cms flow. Cumulative socioeconomic values were compared to the null hypothesis, which assumed people were equally distributed. Building tax values were less than the null for all but two streams in Craven, and the maximum difference was located closest to the stream. The two stream reaches with a different trend were located near a military base with an airport that attracted building tax values when creating the socioeconomic rasters. The population value was also less than the null closer to the streams (Figure 3.7, Table 3.5), and only the larger streams surpassed the null with increasing distance. Thus, both fluvial proximity and stream size seemed to affect the socioeconomic distribution of exposure.

Socioeconomic density was calculated to account for unequal land area available for development by stream flow (Figure 3.9). Comparison of the population and null density (Table 3.7) showed that the population density was less than the null closer to the streams. From 1990 to 2000, the distance from the stream that the population surpassed the null hypothesis increased for stream flows greater than 2.8 cms in Craven (Table 3.8), indicating development was moving farther away from the stream. Craven experienced several flood disasters during the 1990s and has actively removed structures from the floodplain as part of the North Carolina Natural Hazard Mitigation Program (NCDEM, 2007; NCHMP, 2001). On the other hand, the Piedmont did not experience the level of flood impact that occurred in Craven, and from 1990 to 2000 the population density exceeded the null value closer to the streams. The Piedmont also has the fastest growing population in North Carolina and it is not surprising the population density increased throughout the fluvial proximity of the counties. Buncombe had experienced several large flood events in the 1990s, yet its exposure increased from 1990 to 2000, although the increase was much smaller than that experienced in the Piedmont.

It was not expected that socioeconomic value would be less than the null hypothesis closer to the streams, because property value in North Caroline increases by $300 for every 90 m (0.05 mi) closer to streams (Bin & Polaskly, 2006). However, this calculation did not account for floodplain effects (Bin & Polasky, 2006). Furthermore, throughout the study area, all streams had an increase in population density with distance from the stream; whereas Small & Cohen (2001) found an exponential decrease in population density moving away from rivers at the global scale. Thus, the spatial and temporal variations in exposure are different from what would be expected just examining geographic features.

*3.6.2 Social Lens:*

The dichotomous division between urban and rural areas enabled the effect of initial development density to be assessed regarding the effectiveness of flood policy on removing people from the floodplain. Floodplain management has not been applied equally in rural and urban areas as the NFIP was found to have less than a 10% penetration in rural, and 20 to 30% in urban, floodplains (Burby, 2002; IFMRC, 1994). The NFIP also does not allow flood insurance to be issued to a community without a FIRM; however, it has not yet developed a minimum standard defining which flooding sources (e.g. small urban streams or rural areas) warrant the costs of producing a FIRM (Lulloff, 2004). About 40% of the nation's communities are partially located in a floodplain, and given extreme hydrometeorological conditions, even a small stream in an urban area can cause significant flood damage (Riggs, 2004). State and local officials are also concerned that some rural counties with occupied floodplains have not been mapped by FEMA, and without FIRMs established in these areas, future development can occur without regulation and could result in an urbanized floodplain that has not been designed to sustain flood losses.

Urban areas contain higher socioeconomic densities than rural areas and are therefore prone to experiencing far greater flood losses for the same degree of inundation (Dutta et al, 2003). Furthermore, the 100-yr FIRM has not been established in many rural areas or streams with a small enough mean annual flow (Lulloff, 2004); yet the movement of populations from rural to urban areas has increased over the last decade (Small, 2004). According to Small (2004), the majority of the Earth's surface is sparsely populated at densities less than 10 people/km$^2$, matching the rural densities in this study area. However, despite rural migration to urban areas, rural population density increased uniformly, regardless of fluvial proximity, throughout the study area (Figure 3.10, Table 3.10). This indicated there has not been an impact by flood policy on development in rural areas; however, the socioeconomic exposure is relatively small when compared to urban areas.

In contrast, spatiotemporal changes in urban areas showed the effect of policy enforcement in the 100-yr floodplain. In all urban streams with flow greater than 0.3 cms, except Durham, the CPD decreased from 1990 to 2000 within at least the first 100 m (0.062 mi) from the stream (Figure 3.10, Table 3.9). However, the majority of streams with flow less than 0.3 cms, had an increase in urban CPD from1990 to 2000 throughout the fluvial proximity; thereby, indicating either a lack of 100-yr FIRMs for these streams or a lack of policy enforcement. Flood managers can look at Figure 3.10 and note the decrease in CPD from 1990 to 2000 in the large streams Craven, which indicates successful floodplain mitigation in these streams. In contrast, the smaller streams of these counties had greater densities closer to the stream in 2000 than in 1990. The Buncombe and Piedmont flood managers would note that flood policy had been successful within 200 m (0.12 mi) of urban streams, after which development increased. Furthermore, managers would see the constant increase in rural population densities through time, which should be addressed prior to development becoming firmly established around those streams. Once an area has placed a high level of investment in its development, there is a large inertia against relocation (Klein et al, 2003); thus, it is essential to control development early for areas with high flood risk.

*3.6.3 Flood Policy Lens:*

The spatial distribution of socioeconomic value located within hazardous areas is useful for emergency managers to know prior to a flood event. (Table 3.11). In almost all streams, the 100-yr floodplain had a density less than 100 people/km$^2$ and was less densely developed near the stream; thereby, indicating that floodplain policy had effectively been enforced. Holway & Burby (1993) found that effective floodplain management was the only significant variable decreasing the amount of flood losses experienced in the floodplain. Furthermore, socioeconomic exposure in the floodplain increased rapidly for short distances before it asymptotes in streams with flow greater than 0.3 cms (Figure 3.11). The fluvial proximity with rapid increases in socioeconomic density should be targeted by floodplain managers to reduce risk.

In 2006, Burby noted that the basic 100-yr standard of protection may be ill-advised, since 66 to 83% of flood losses in the U.S. were from events with recurrence intervals less frequent than the 100-year flood. Thus, while the 100-yr floodplain contains enforceable policies regulating development, none of these policies are applicable to the marginal 500-yr floodplain. To address the risk of flood losses for events exceeding the 100-yr flood, the development density in the marginal 500-yr floodplain was assessed and was found to be several times greater than the 100-yr floodplain (Figure 3.11). Furthermore, the density of exposure increased most rapidly near the streams, which indicated exposure is concentrated near the 100-yr flood boundary. The increase in socioeconomic density and exposure to events with recurrence intervals less than 100 years could explain why flood losses continue to increase despite policy efforts. Moreover, the population in the marginal 500-yr floodplain increased through time throughout the study area (Table 3.13)

Assessing the relative contribution of risk for a greater than 100-yr flood event in each county by stream flow allows floodplain managers to focus their resources and emergency management plans to reduce future flood impacts (Figure 3.12, 3.13, Table 3.14). The relative exposure by county indicated both Craven and Buncombe had the greatest socioeconomic risk from a catastrophic flood around the largest stream flows. It is therefore encouraging that floodplain density has decreased through time as structures were removed from the floodplain (Table 3.12). On the other hand, the more urbanized Piedmont generally had the greatest relative risk in the smaller streams. The presence of increased development adjacent to the 100-yr floodplain has been large enough that the Association of State Floodplain Managers (2000) recommended the 500-yr floodplain be used in regulating new urban development.

Since 1968, the NFIP has been criticized for using a uniform, minimum standard in areas subjected to very different flood conditions (IFMRC, 1994), yet the 100-yr floodplain has prevailed to be used in the 1994 mitigation policy as the boundary within which infrastructure should be reduced. According to Burby (2002) there was a 53% increase in floodplain development since 1968. Thus, despite flood losses and management policies, floodplains are continuing to develop. Graf (2001) found that for every $5 spent in public funds on flood protection, $6 are spent in the private sector in floodplain development. The trend of increasing development in the 100-yr floodplain was present in Buncombe and the Piedmont; however, Craven have reduced floodplain development since 1990, after experiencing several large flood events and actively participating in the HMGP (NCDEM, 2007, NCNHMP, 2001).

### 3.7 Conclusion:

Hazard losses are a product of the relationships between humans and the environment, their spatial interactions, and the resulting regional structures that have emerged on the earth' surface (Gober, 2000). The stream scale exploratory analysis of spatiotemporal changes in exposure as a function of fluvial proximity in relation to 1) stream hierarchy, 2) development density, and 3) floodplain policy. This study found socioeconomic value was generally less than the null hypothesis near the streams, with the greatest difference in streams larger than 2.8 cms. Below 2.8 cms, streams generally exceeded the null hypothesis for socioeconomic value with increasing distance from the stream. It was found that the most significant changes in density occurred in urban areas; while rural development increased by the same amount throughout the fluvial proximity from 1990 to 2000. Furthermore, from 1990 to 2000, socioeconomic value located closer to the largest streams decreased due to the effective management of the 100-yr floodplain. The largest change from 1990 to 2000 in reducing socioeconomic exposure occurred in Craven County, which had experienced major flood events and losses from several hurricanes including Fran (1996) and Floyd (1999) (NCDC, 2004; Dorman & Bakolia, 2002). Lastly, it was found that socioeconomic density increased significantly adjacent to the 100-yr floodplain, especially in the smaller streams of the rapidly urbanizing Piedmont.

The distribution of socioeconomic exposure variables can help to spatially guide local officials in concentrating flood mitigation efforts to reduce potential flood losses in the areas with greatest risk. There is a seemingly incompatible duality between land use planning to reduce flood risk and develope the land for residential housing (Chivers & Flores, 2002; Howe & White, 2004). The IFMRC (1994) concluded that urbanization will continue to occur in floodplains and there are two strategies that can be implemented to reduce flood losses: protection and removal. Historically, structural flood control measures and insurance have been used to 'protect' people from flood losses, yet flood losses have continued to increase. The 'mitigation era' (Godschalk et al. 1999) established after 1993 advocated not developing the land past the natural carrying capacity of the floodplain. The counties in North Carolina that experienced unsustainable flood losses are the counties that have actively and successfully reduced the risk for future flood losses by reducing exposure.

The impact of natural events on any given community is not random but determined by everyday patterns of social interaction (Morrow, 1999). Each community is inherently different in its flood history, local floodplain management agency, degree of urbanization and general attitude regarding flood losses. All of these factors have helped to create the spatial distribution of socioeconomic exposure in the study area. All floodplain managers, especially in urban areas, should know and store the spatial distribution of exposure variables for emergency use prior to an event (Dutta et al, 2003), and monitor the spatial changes in distribution through time to assess the effectiveness of flood policy in reducing exposure. Currently, flood management has been reactive; whereby, the increase in flood losses is driving flood policy changes. This thesis advocates monitoring exposure changes using measurable indicators to assess where floodplain policies have been effective, and more importantly where they have not worked. To reduce losses, we need to become actively engaged in monitoring, evaluating and adjusting floodplain policies before the next flood.

## 3.8 Tables:

**Table 3.1:** Physical, Social, and Economic Characteristics of the Study Area

| County | Major Watershed | 2000 Population | Population Change (1990) | Building Tax ($ Billion) | % Area Floodplain |
|---|---|---|---|---|---|
| Buncombe | French Broad | 206,3301 | 15.37% | 16 | 3.57 |
| Orange | Neuse / Cape Fear | 118,227 | 20.95% | 8 | 3.60 |
| Durham | Neuse / Cape Fear | 223,314 | 18.58% | 14 | 14.40 |
| Wake | Neuse | 627,846 | 32.57% | 50 | 9.16 |
| Craven | Neuse | 91,436 | 10.50% | 6 | 22.89 |

**Table 3.2**: Linear relationship between building tax and population by stream flow. The general relationship is: Building Tax = 0.082 * Population, with a standard deviation of 0.015 for the y = mx linear equation. The m value is shown below.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven | Average |
|---|---|---|---|---|---|---|
| **> 28.3 cms** | 0.044 | n/a | n/a | 0.114 | 0.106 | 0.088 |
| **2.8 – 28.3 cms** | 0.075 | 0.040 | 0.050 | 0.092 | 0.065 | 0.077 |
| **0.3 – 2.8 cms** | 0.075 | 0.070 | 0.068 | 0.084 | 0.102 | 0.087 |
| **0.03 – 0.3 cms** | 0.070 | 0.067 | 0.064 | 0.082 | 0.066 | 0.072 |
| **0.003 – 0.3 cms** | 0.092 | 0.058 | 0.064 | 0.081 | 0.160 | 0.111 |
| **Average** | 0.078 | 0.059 | 0.062 | 0.085 | 0.098 | **0.082** |

**Table 3.3**: Linear rate of cumulative building tax change by fluvial proximity, with the greatest change in the Piedmont and in streams with less than 0.3 cms flow.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven | Average |
|---|---|---|---|---|---|---|
| **> 28.3 cms** | 0.9 | n/a | n/a | 0.2 | 1.3 | **0.8** |
| **2.8 – 28.3 cms** | 1.9 | 0.0 | 0.6 | 3.4 | 0.6 | **1.3** |
| **0.3 – 2.8 cms** | 4.5 | 2.5 | 1.7 | 6.3 | 1.8 | **3.4** |
| **0.03 – 0.3 cms** | 13.2 | 4.9 | 8.9 | 29.1 | 2.9 | **11.8** |
| **0.003 – 0.3 cms** | 1.0 | 3.3 | 9.4 | 28.5 | 2.6 | **8.9** |
| **Average** | **4.3** | **2.7** | **5.2** | **13.5** | **1.8** | **5.4** |

***n/a: No mean annual stream flow of that magnitude was present**

**Table 3.4**: Linear rate of cumulative population counts by fluvial proximity, with the greatest rate of change in the Piedmont and in streams with less than 0.3 cms flow.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven | Average |
|---|---|---|---|---|---|---|
| **> 28.3 cms** | 19.9 | n/a | n/a | 1.7 | 12.1 | **11.2** |
| **2.8 – 28.3 cms** | 24.6 | 0.9 | 11.9 | 37.4 | 9.0 | **16.8** |
| **0.3 – 2.8 cms** | 59.7 | 32.7 | 25.6 | 75.3 | 17.4 | **42.1** |
| **0.03 – 0.3 cms** | 189.0 | 72.0 | 139.5 | 354.3 | 44.1 | **159.8** |
| **0.003 – 0.3 cms** | 9.8 | 56.3 | 146.8 | 353.6 | 16.3 | **116.5** |
| **Average** | **60.6** | **40.5** | **80.9** | **164.5** | **19.8** | **71.3** |

***n/a: No mean annual stream flow of that magnitude was present**

**Table 3.5:** Fluvial proximity (m) at which the 2000 population surpassed the null hypothesis. Craven had an overall population decrease for some stream reaches (L).

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven |
|---|---|---|---|---|---|
| > 28.3 cms | 358 | n/a | n/a | 402 | L |
| 2.8 – 28.3 cms | 1032 | 624 | 1267 | 785 | 1232 |
| 0.3 – 2.8 cms | 198 | 771 | 749 | 578 | 711 |
| 0.03 – 0.3 cms | 45 | 77 | 290 | 221 | 219 |
| 0.003 – 0.3 cms | 113 | 160 | 213 | 195 | 233 |

* n/a = mean annual stream flow of that magnitude does not exist
** L = 2000 population was always less than the null hypothesis

**Table 3.6:** The fluvial proximity (m) at which the 2000 surpassed the 1990 population. Buncombe and Craven had an overall decrease in population (L) in some streams, while the Piedmont and Craven had several streams with an overall higher 2000 population (G).

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven |
|---|---|---|---|---|---|
| > 28.3 cms | 92 | n/a | n/a | 30 | L |
| 2.8 – 28.3 cms | 239 | G | 78 | 35 | L |
| 0.3 – 2.8 cms | G | 121 | 55 | 60 | 342 |
| 0.03 – 0.3 cms | G | G | 22 | G | G |
| 0.003 – 0.3 cms | G | G | 42 | G | G |

* n/a = mean annual stream flow of that magnitude does not exist
** L = 2000 population was always less than the 1990 population
*** G = 2000 population was always greater than the 1990 population

**Table 3.7**: The null hypothesis density (population/km$^2$) for each county by stream flow.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven |
|---|---|---|---|---|---|
| > 28.3 cms | 201 | n/a | n/a | 73 | 88 |
| 2.8 – 28.3 cms | 242 | 74 | 104 | 260 | 111 |
| 0.3 – 2.8 cms | 105 | 155 | 146 | 150 | 43 |
| 0.03 – 0.3 cms | 112 | 84 | 248 | 206 | 38 |
| 0.003 – 0.3 cms | 95 | 99 | 222 | 238 | 28 |

* n/a = mean annual stream flow of that magnitude does not exist

**Table 3.8**: Fluvial proximity (m) at which population density initially surpassed the null hypothesis.

| Stream Flow | Buncombe | | Orange | | Durham | | Wake | | Craven | |
|---|---|---|---|---|---|---|---|---|---|---|
| Distance (m) | 1990 | 2000 | 1990 | 2000 | 1990 | 2000 | 1990 | 2000 | 1990 | 2000 |
| > 28.3 cms | 920 | 66 | n/a | | n/a | | L | 103 | 34 | 84 |
| 2.8 – 28.3 cms | 930 | 83 | 613 | 249 | 595 | 244 | 683 | 178 | 507 | 634 |
| 0.3 – 2.8 cms | 893L | 219 | 871 | 380 | 509 | 271 | 659 | 160 | 249 | 242 |
| 0.03 – 0.3 cms | L | 30 | L | 41 | 407 | 98 | L | 214 | 190 | 99 |
| 0.003 – 0.3 cms | L | 59 | L | 49 | L | 109 | L | 249 | 386 | 129 |

* n/a = mean annual stream flow of that magnitude does not exist
**L = the population was always less than the null hypothesis

**Table 3.9:** Fluvial proximity (m) at which the 2000 exceeded the 1990 cumulative population density for urban areas. Craven had an overall decrease in population for some streams from 1990 to 2000 (L). All counties had streams where the 2000 exceeded the 1990 population (G) throughout the fluvial continuum.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven |
|---|---|---|---|---|---|
| > 28.3 cms | 168 | n/a | n/a | n/a | L |
| 2.8 – 28.3 cms | L | n/a | 179 | 77 | L |
| 0.3 – 2.8 cms | 121 | 257 | G | 129 | L |
| 0.03 – 0.3 cms | 94 | 61 | G | G | G |
| 0.003 – 0.3 cms | 24 | G | n/a | G | 351 |

*n/a = stream flow of that magnitude was not present
**G = the 2000 population was always greater than the 1990 population
***L = the 2000 population was always less than the 1990 population

**Table 3.10:** Fluvial proximity (m) at which the 2000 exceeded the 1990 cumulative population density for rural areas. Craven had an overall decrease in population for one stream from 1990 to 2000 (L). All counties had streams where the 2000 exceeded the 1990 population (G) throughout the fluvial continuum.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven |
|---|---|---|---|---|---|
| > 28.3 cms | 15 | n/a | n/a | n/a | 203 |
| 2.8 – 28.3 cms | G | n/a | G | G | L |
| 0.3 – 2.8 cms | G | G | G | G | 126 |
| 0.03 – 0.3 cms | G | G | G | G | G |
| 0.003 – 0.3 cms | G | G | n/a | G | 29 |

*n/a = stream flow of that magnitude was not present
**G = the 2000 population was always greater than the 1990 population
***L = the 2000 population was always less than the 1990 population

**Table 3.11**: Population located inside the 100-yr floodplain by stream flow.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven | Total |
|---|---|---|---|---|---|---|
| > 28.3 cms | 3143 | n/a | n/a | 306 | 5664 | 9113 |
| 2.8 – 28.3 cms | 3546 | 56 | 1987 | 6497 | 4123 | 16209 |
| 0.3 – 2.8 cms | 5645 | 2371 | 4128 | 8486 | 2752 | 23382 |
| 0.03 – 0.3 cms | 4308 | 2604 | 8931 | 14598 | 4366 | 34807 |
| 0.003 – 0.3 cms | n/a | 1137 | 4968 | 7264 | 955 | 14324 |
| Total | 16642 | 6112 | 20014 | 37151 | 17860 | 195558 |

*n/a = no streams of this magnitude were present

**Table 3.12**: Population change in the 100-yr floodplain from 1990 to 2000 (number of people). The total change by stream flow and county are examined. Only Craven County and the 0.3 to 2.8 cms streams in Orange had a decrease.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven | Total |
|---|---|---|---|---|---|---|
| > 28.3 cms | 248 | n/a | n/a | 84 | -252 | 80 |
| 2.8 – 28.3 cms | -43 | 7 | 331 | 1134 | -254 | 1175 |
| 0.3 – 2.8 cms | 681 | -138 | 876 | 1776 | -120 | 3075 |
| 0.03 – 0.3 cms | -71 | 149 | 1081 | 3082 | -40 | 4201 |
| 0.003 – 0.3 cms | n/a | 78 | 245 | 1188 | -64 | 1447 |
| Total | 815 | 89 | 2533 | 7264 | -730 | 19942 |
| *n/a = no streams of this magnitude were present | | | | | | |

**Table 3.13:** Population change in the marginal 500-yr floodplain from 1990 to 2000 (number of people). The total change by stream flow and county are examined. Only the largest stream flow had an overall decrease through time.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven | Total |
|---|---|---|---|---|---|---|
| > 28.3 cms | 35 | n/a | n/a | 5 | -105 | -65 |
| 2.8 – 28.3 cms | 95 | n/a | -16 | 283 | -103 | 259 |
| 0.3 – 2.8 cms | 60 | 4 | 297 | 543 | 78 | 982 |
| 0.03 – 0.3 cms | 16 | 5 | 220 | 691 | 230 | 1162 |
| 0.003 – 0.3 cms | n/a | 7 | 152 | 251 | 22 | 432 |
| Total | 206 | 16 | 653 | 1773 | 122 | 5540 |
| *n/a = no streams of this magnitude were present | | | | | | |

**Table 3.14**: Population located in the marginal 500-yr FIRM at risk for floods greater than the 100-yr flood.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven | Total |
|---|---|---|---|---|---|---|
| > 28.3 cms | 334 | n/a | n/a | 47 | 1301 | **1682** |
| 2.8 – 28.3 cms | 615 | n/a | 1987 | 1504 | 1091 | **5197** |
| 0.3 – 2.8 cms | 578 | 462 | 806 | 1881 | 767 | **4494** |
| 0.03 – 0.3 cms | 560 | 782 | 1650 | 2558 | 1124 | **6674** |
| 0.003 – 0.3 cms | n/a | 511 | 954 | 1397 | 96 | **2958** |
| Total | **2087** | **1755** | **5397** | **7387** | **4379** | **21005** |
| *n/a = no streams of this magnitude were present | | | | | | |

### 3.9 Figures:

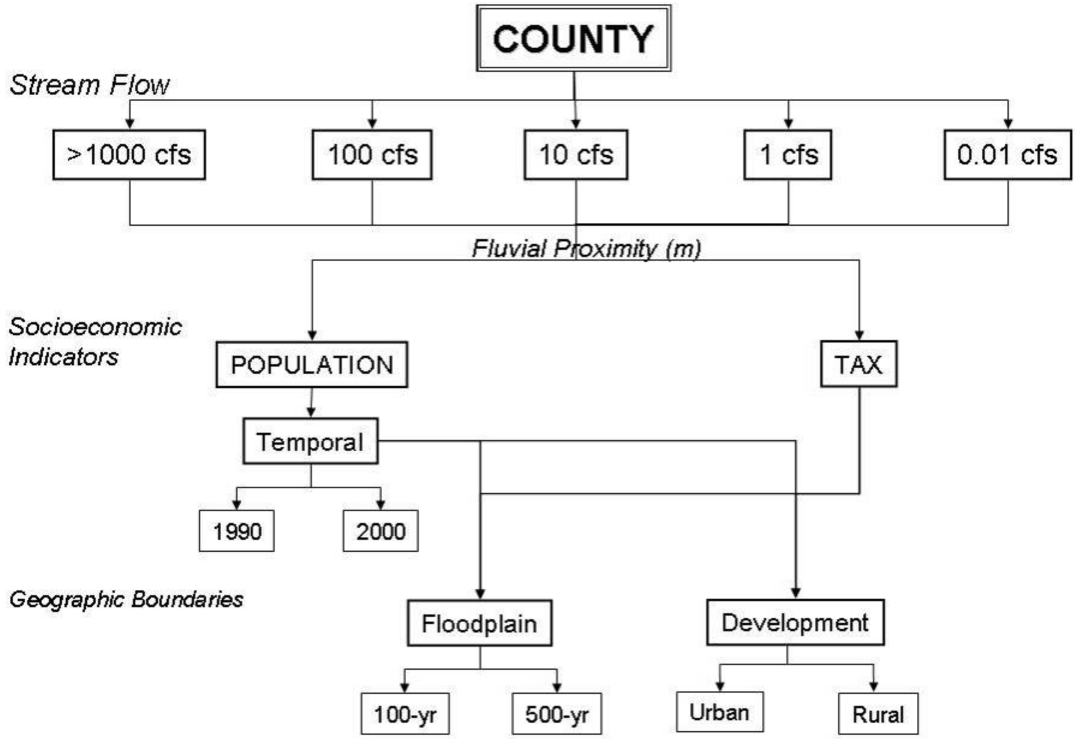


**Figure 3.1**: Framework for addressing the spatiotemporal socioeconomic distribution through geographic, social and policy lenses. Each county was subdivided by stream flow, from which the fluvial proximity of socioeconomic indicators were calculated. The calculations were repeated for urban versus rural and the 100 versus marginal 500-yr FIRM.

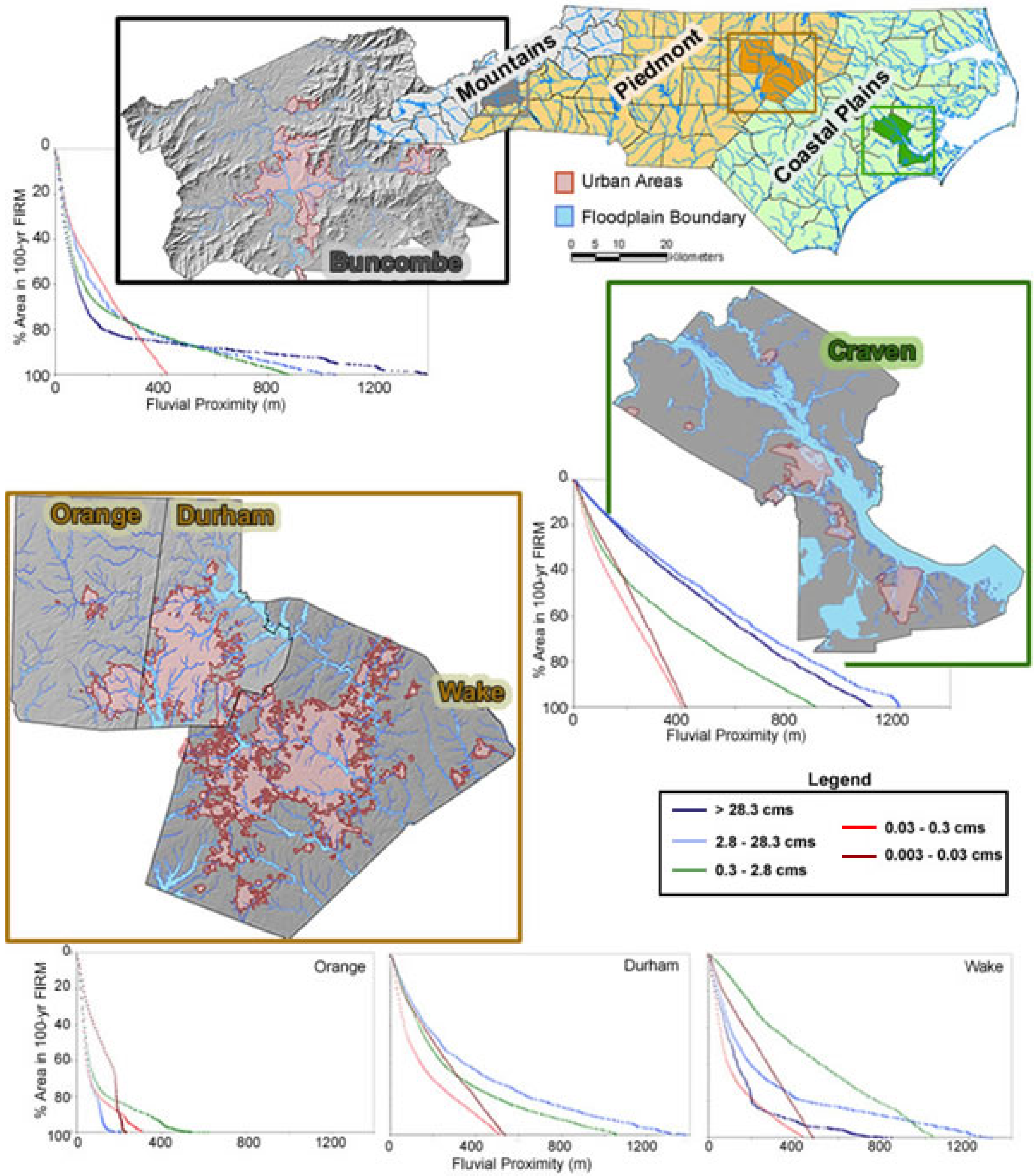


**Figure 3.2:** Study area illustrating topographic variation, urbanization and floodplain extent. The histograms were subdivided by mean annual flow magnitude. The graphs are read as the percent of the 100-yr floodplain located within X m of the stream. The topographic profile of Buncombe resulted in the majority of the FIRM located near the stream, while the flat topography of Craven resulted in a linear relationship between floodplain extent and aereal coverage.

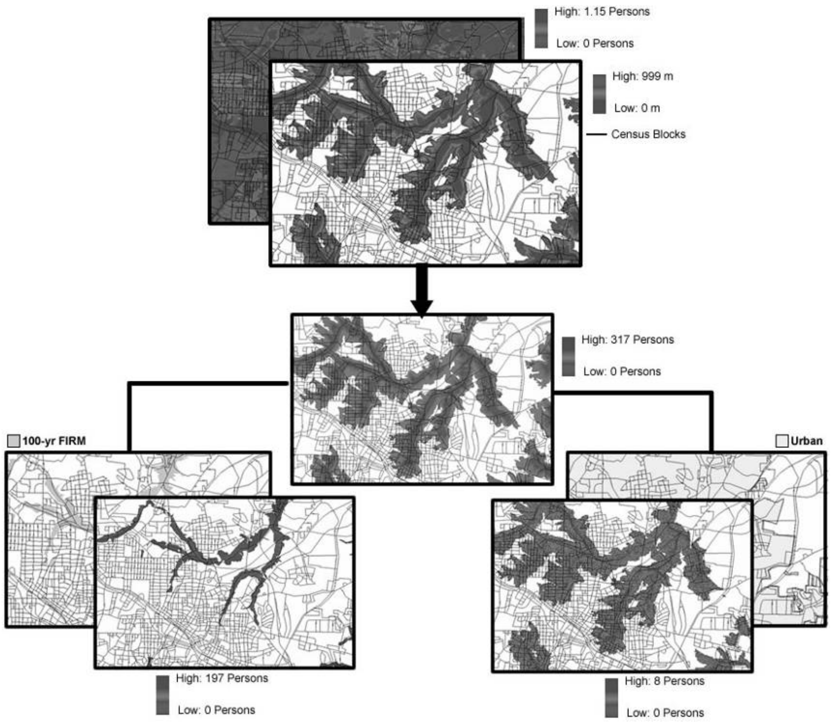


**Figure 3.3:** Calculating population exposure for 0.3 to 2.8 cms stream reaches in Durham by fluvial proximity, urban versus rural, and location inside FIRMs.

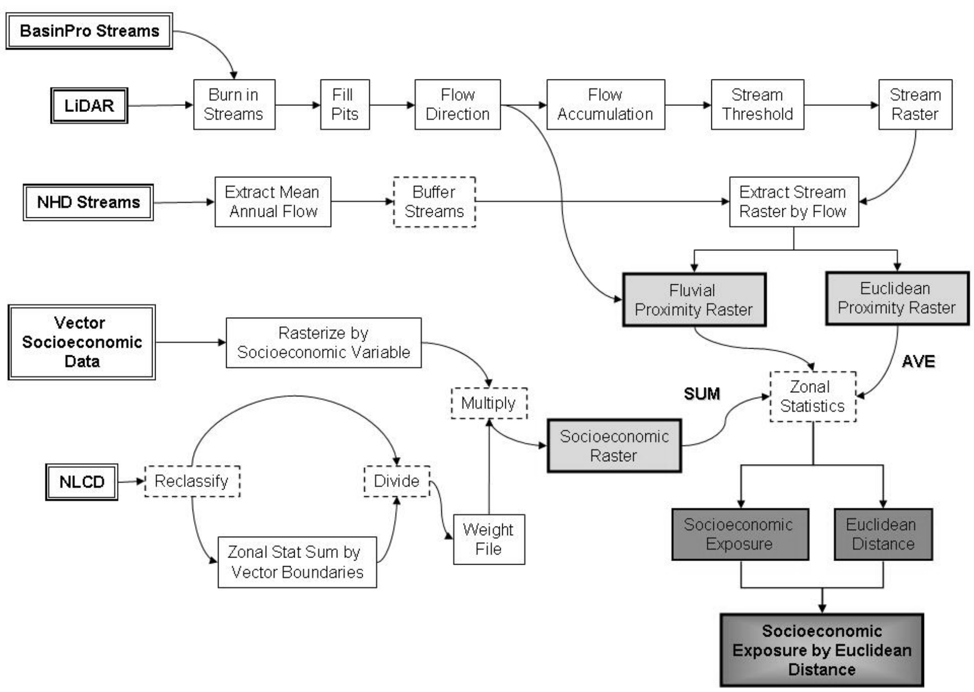


**Figure 3.4:** Methodology for creating raster streams of different flow magnitudes. Creation of the socioeconomic exposure was illustrated, as well as process of spatially intersecting exposure with fluvial proximity.

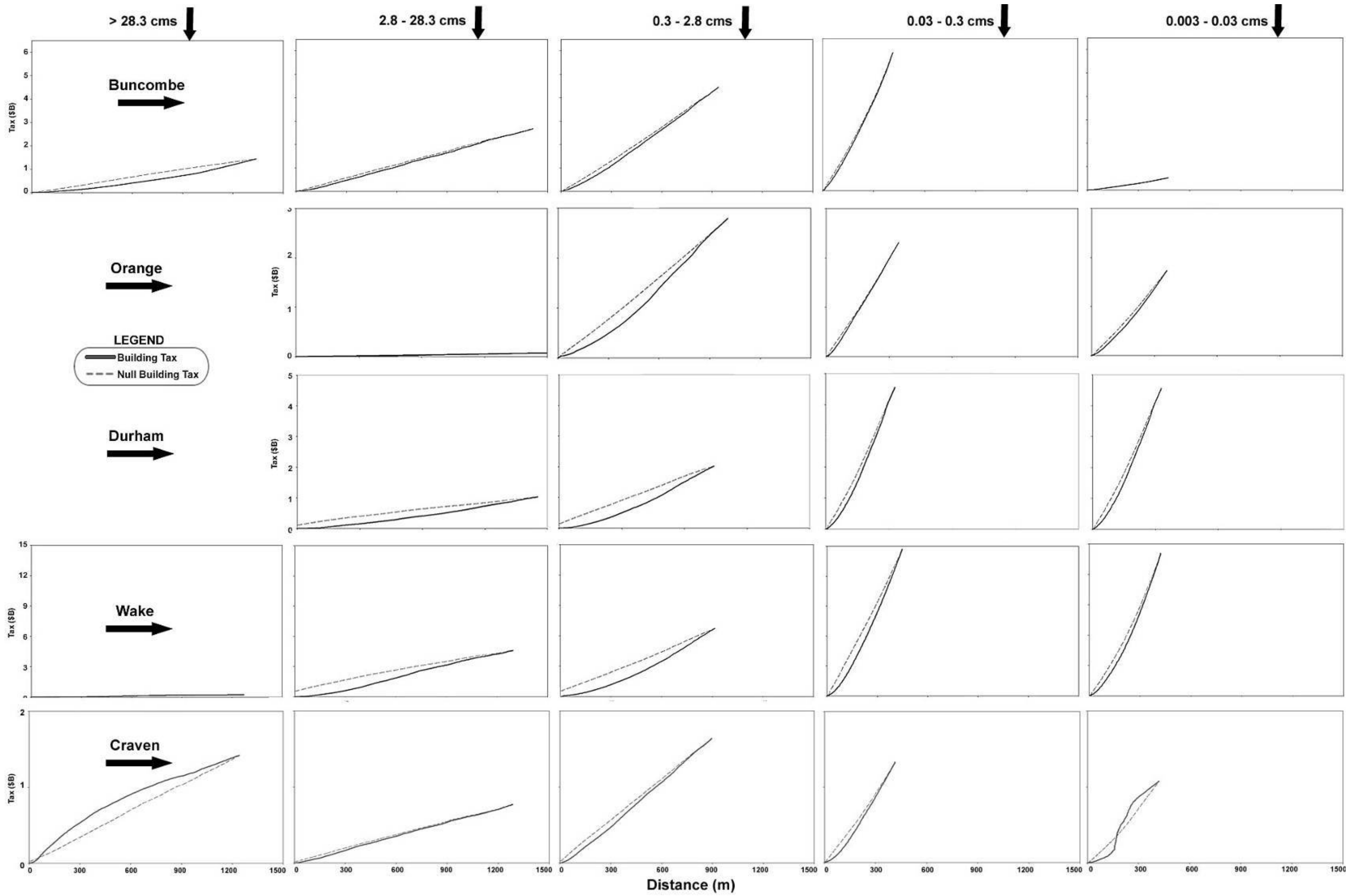


**Figure 3.5:** Cumulative building tax value as a function of fluvial proximity (m) by stream size and county. The y-axis values change by county and are represented by $ Billion.

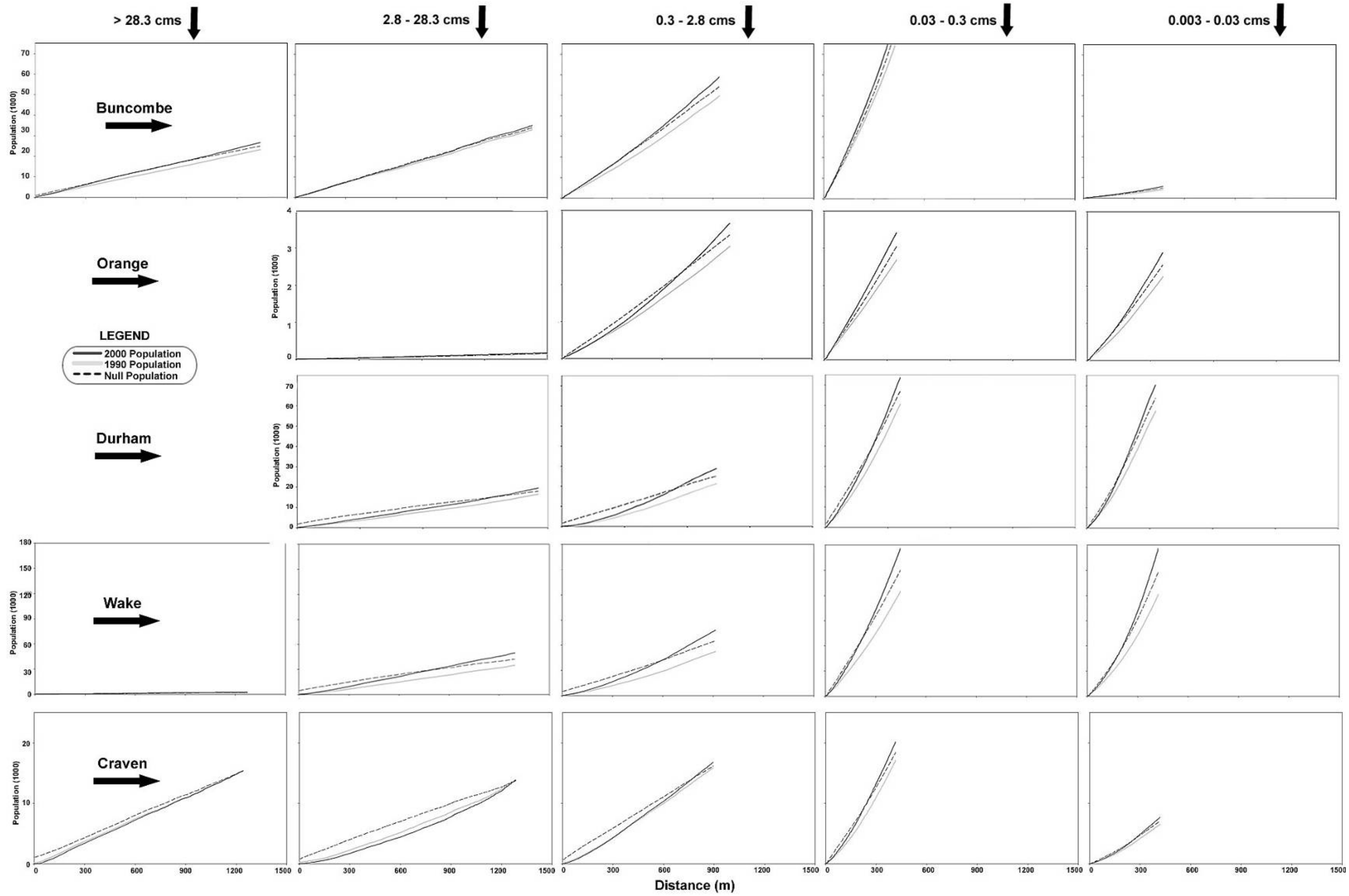


**Figure 3.6:** Cumulative population as a function of fluvial proximity (m) by stream size and county. The y-axis values change by county and values are in thousands.

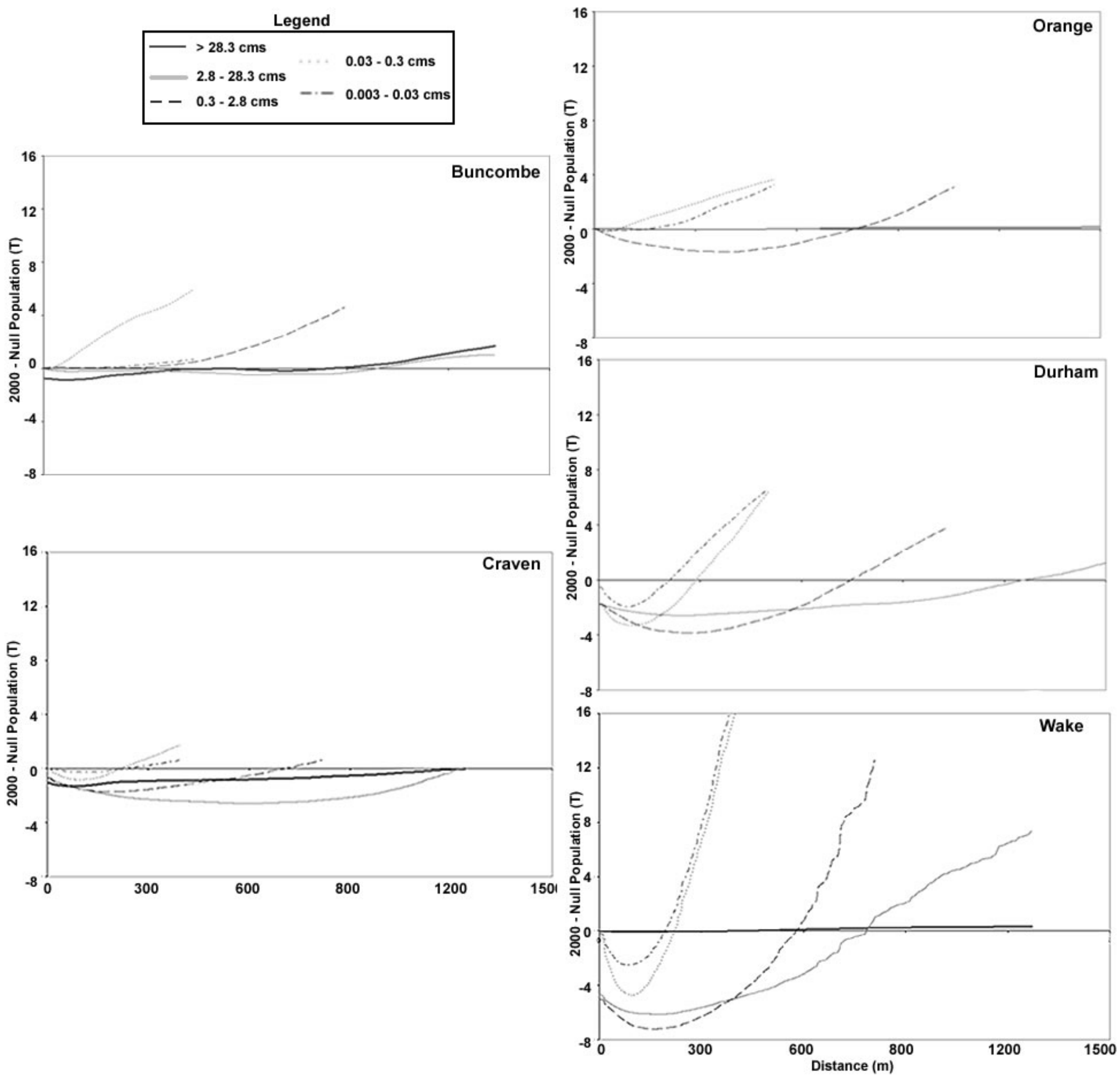


**Figure 3.7:** Difference between the null hypothesis and 2000 population by fluvial proximity. The y-axis is kept constant and is measured in thousands (T). The larger streams have the biggest negative difference within 300 m (0.19 mi) of the stream. Smaller streams exceed the null hypothesis values closer to stream.

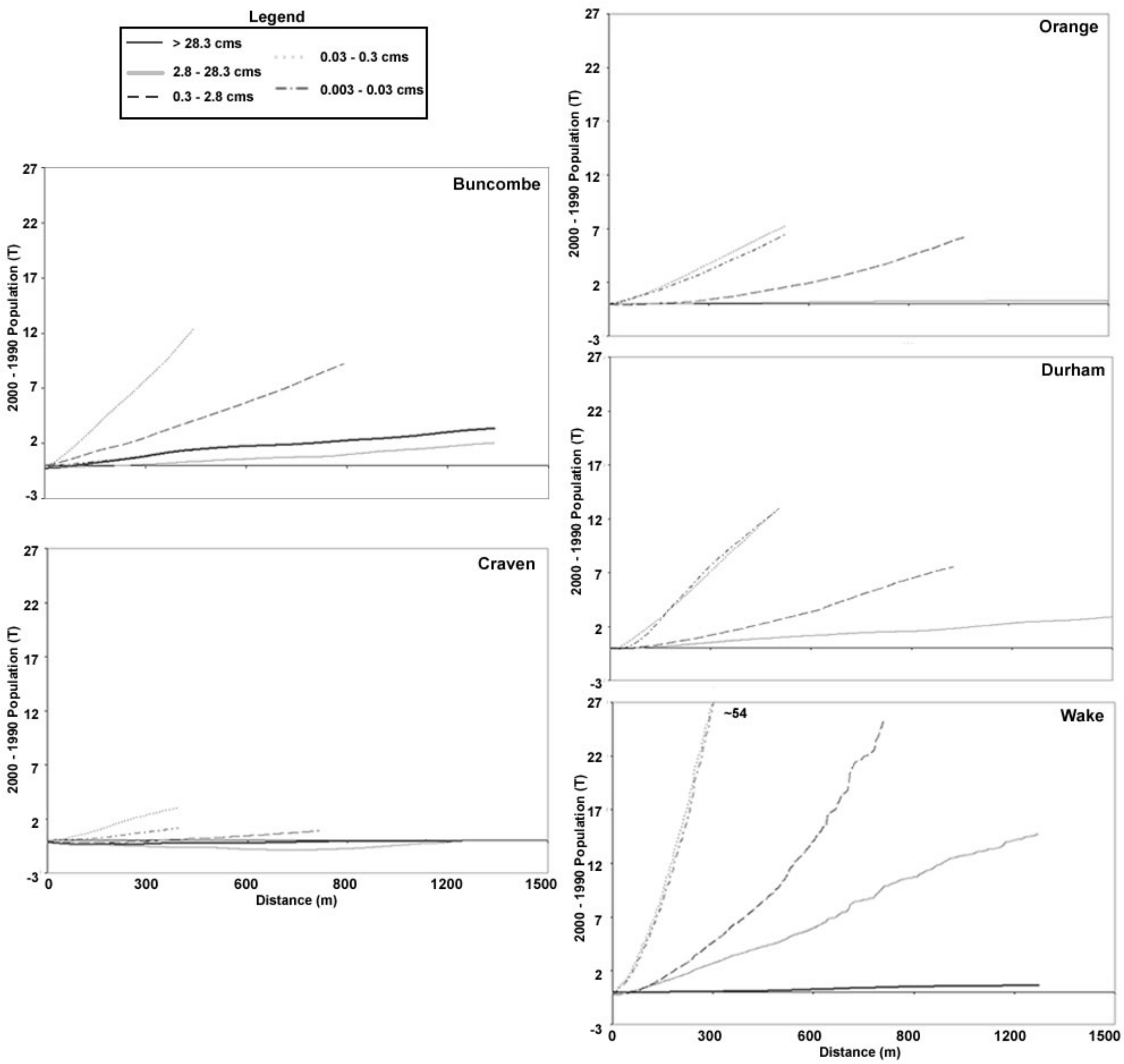


**Figure 3.8:** Difference between the 1990 and 2000 population by fluvial proximity. The y-axis is kept constant and is measured in thousands (T). Craven experienced a decrease in population from 1990 to 2000 in the majority of their streams. The Piedmont had a linear increase in growth, with the rate of increase becoming greater from Orange downstream to Wake County.

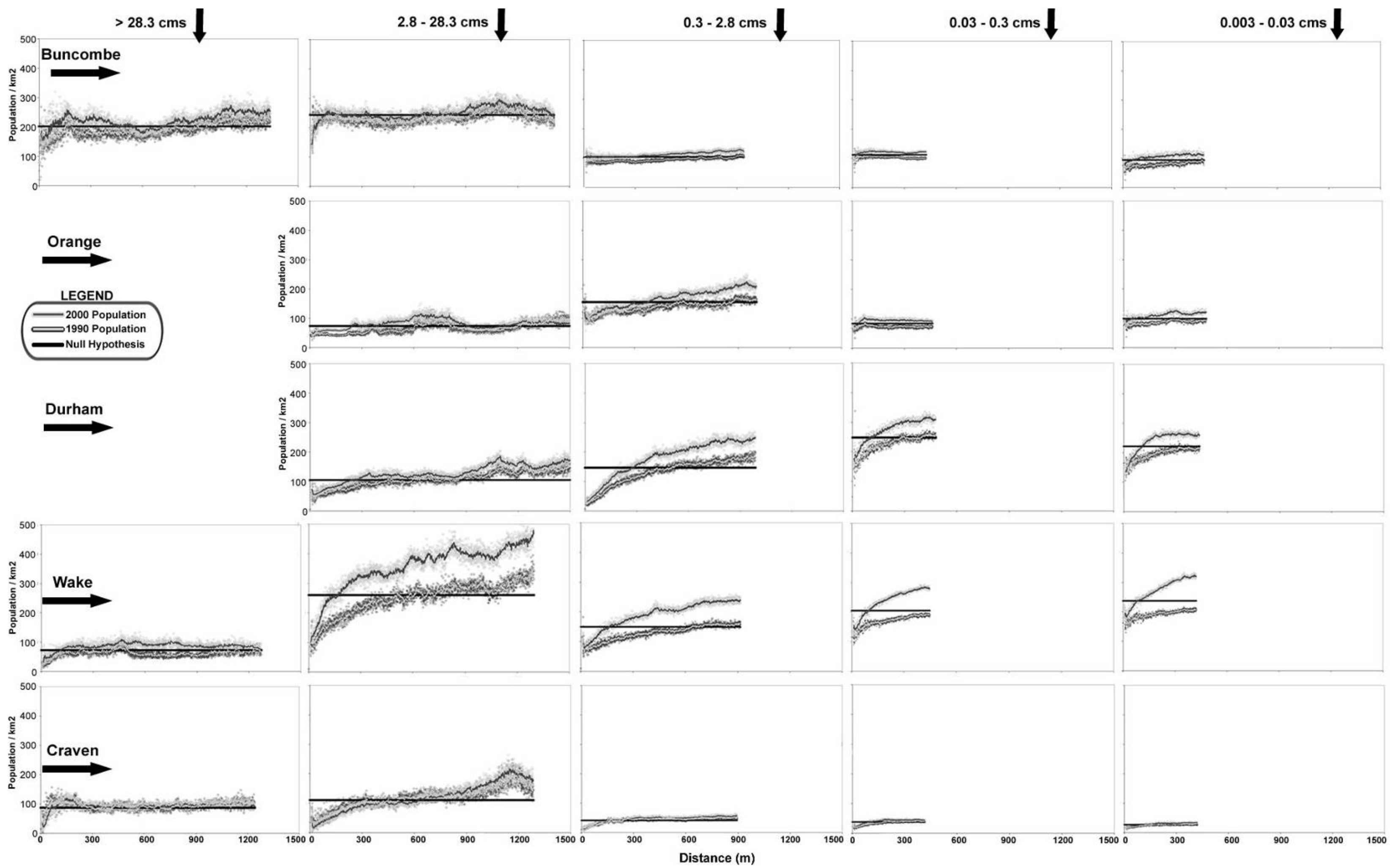


**Figure 3.9:** Population density through time as a function of fluvial proximity. The null hypothesis is shown to illustrate population density given an even distribution of people across the study area. Population density decreases with stream flows less than 0.3 cms in Craven, but increases in Buncombe and the Piedmont.

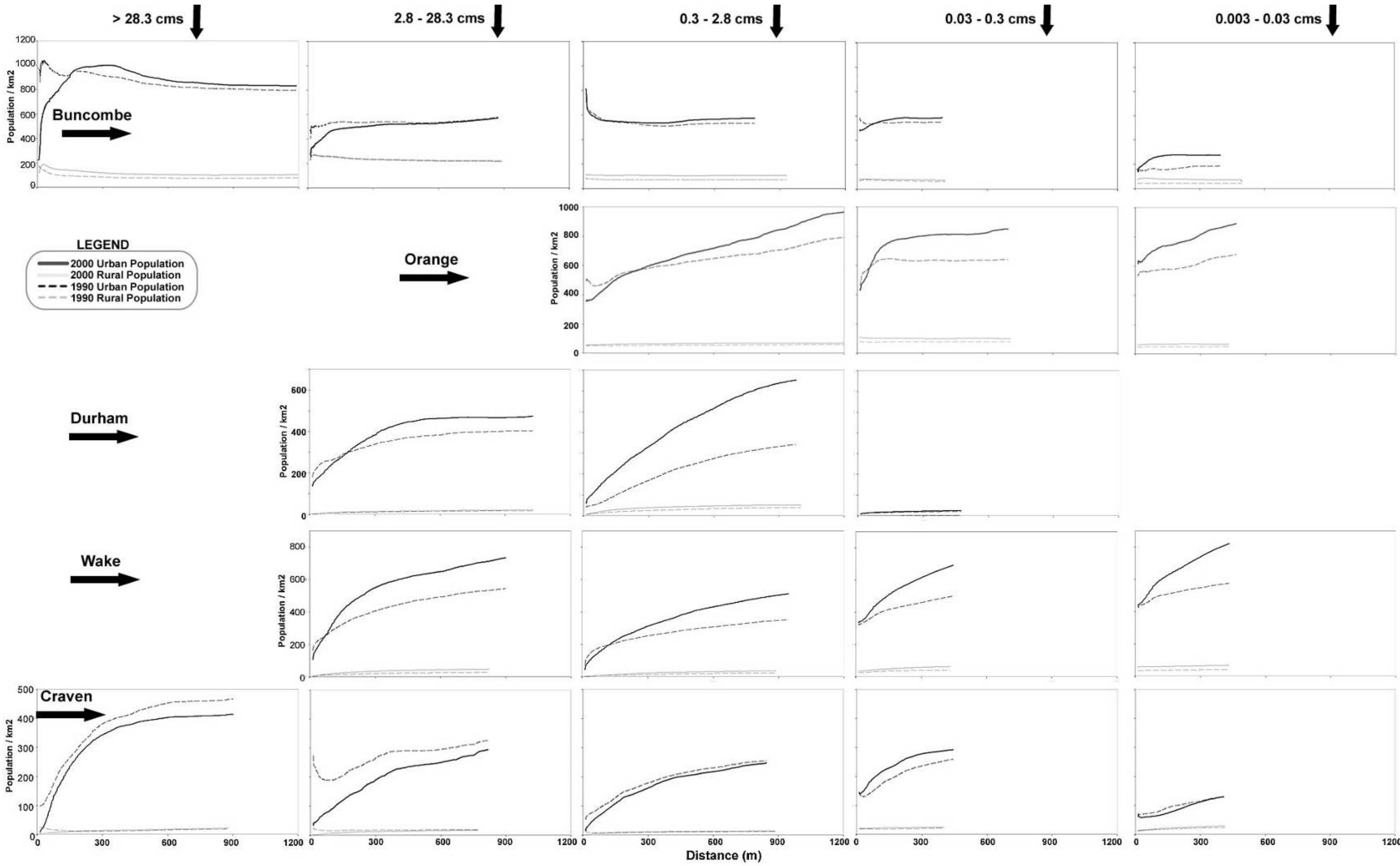


**Figure 3.10:** Cumulative population density change by fluvial proximity in rural and urban areas. Plots not shown on the map represent stream flows that did not intersect an urban area. Rural areas increased uniformly by fluvial proximity while urban areas increased at different rates. Y-axis scale changes for each county.

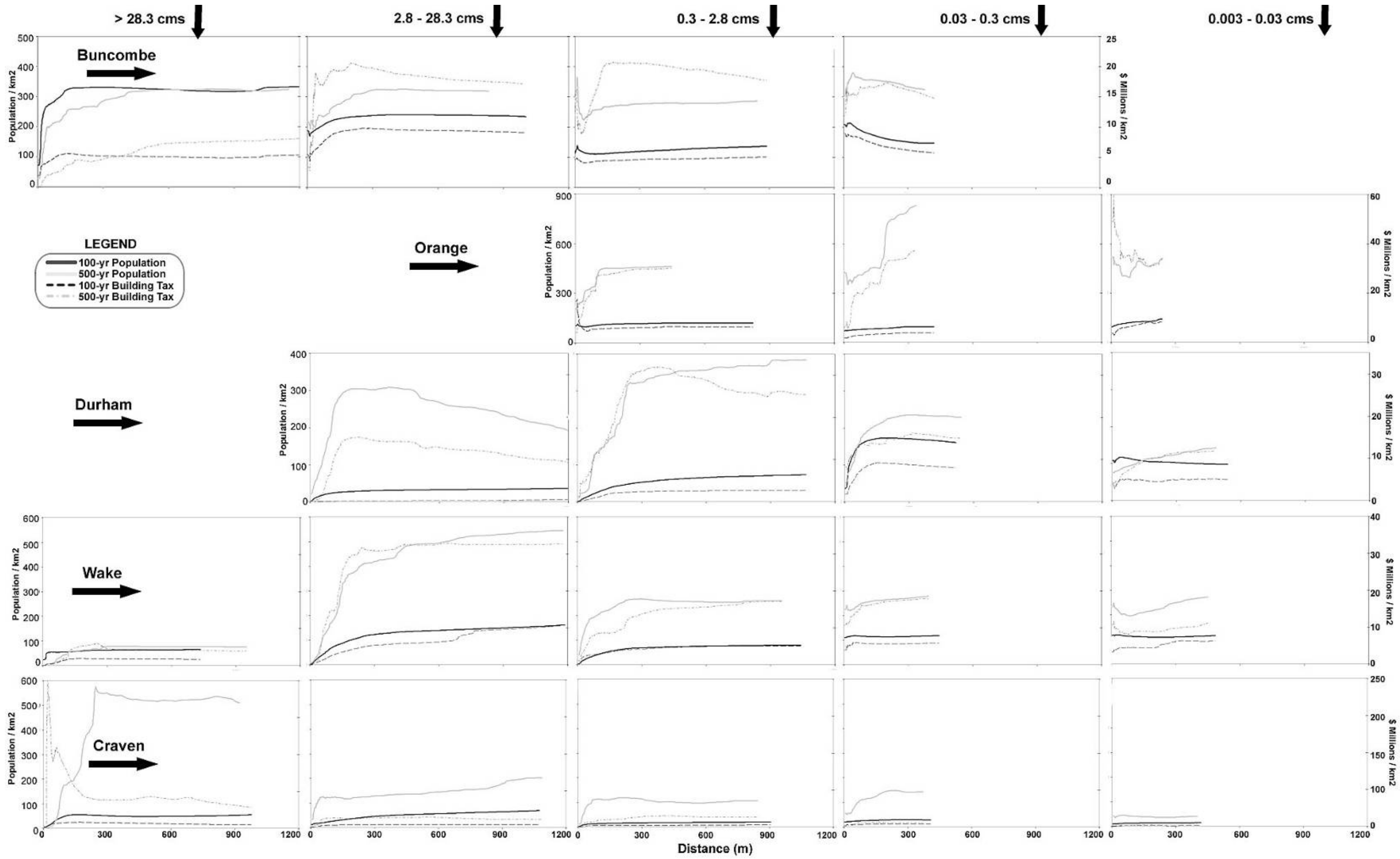


**Figure 3.11:** Cumulative socioeconomic density by fluvial proximity via the floodplain policy lens. Plots not shown on the map represent stream flows that did not have a FIRM. Notice the building tax and population values follow similar trends. Streams with a significant increase in density between the 100 and marginal 500-yr FIRM suggests increased exposure adjacent to the 100-yr floodplain. Y-axis variables change scale for each county.

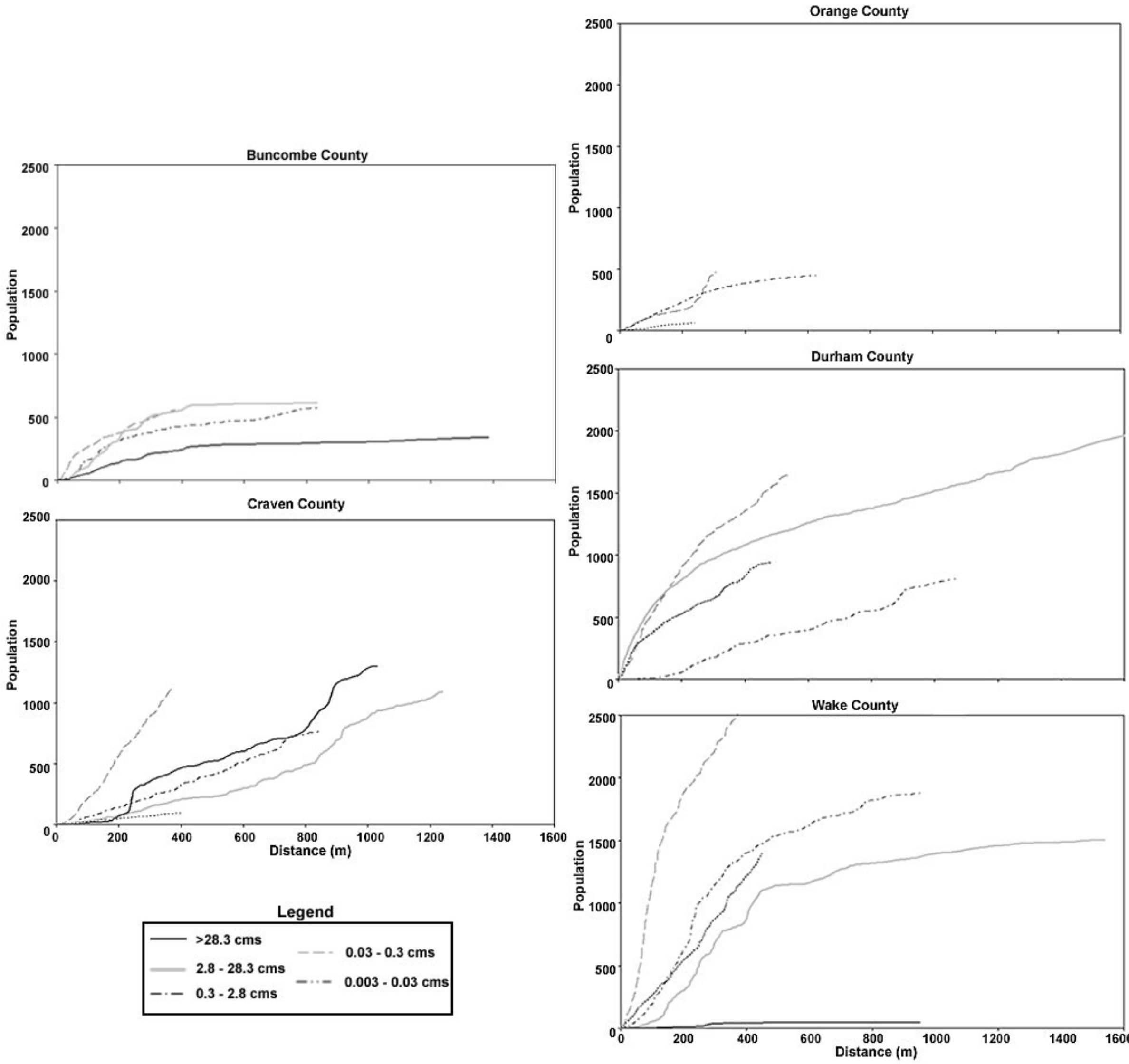


**Figure 3.12:** Cumulative population values located inside the marginal 500-yr FIRM by fluvial proximity. The y-axis is kept constant. Notice that the highest risk closest to stream was located in reaches with a flow of 0.03-0.3 cms.

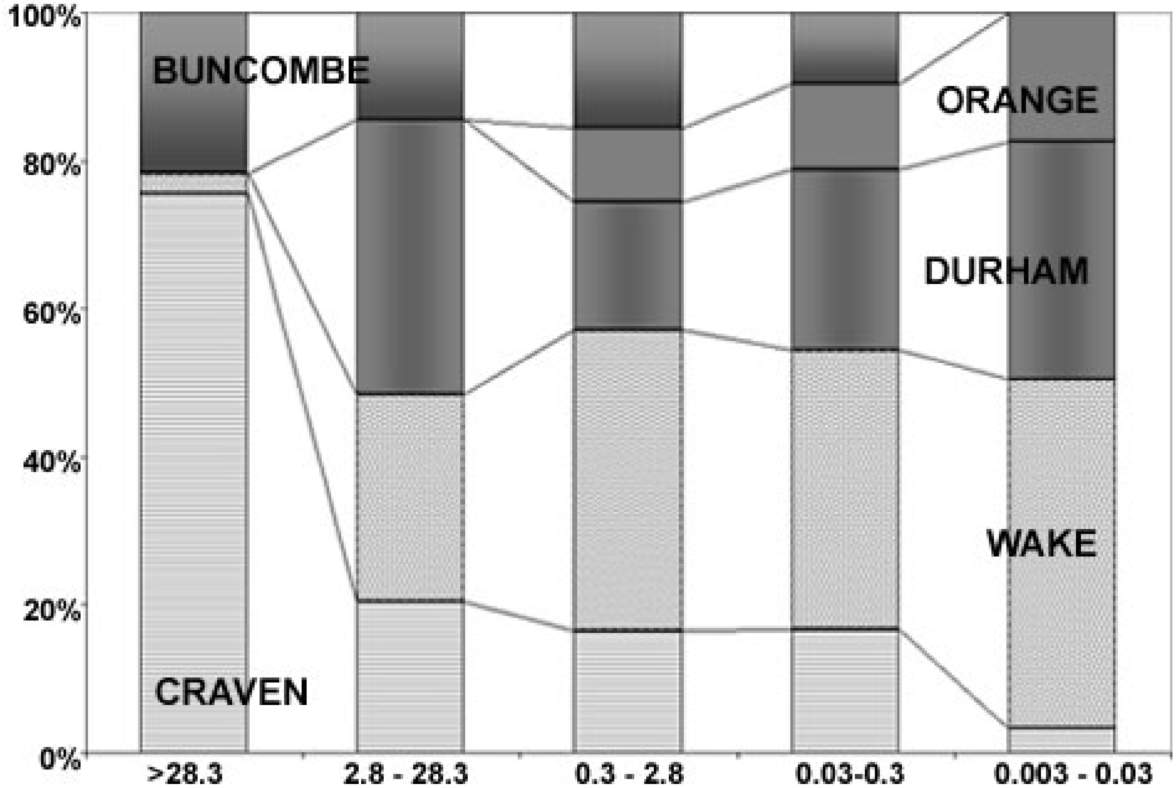


**Figure 3.13:** The relative contribution to the marginal 500-yr FIRM exposure by stream flow (cms). The greatest risk for Buncombe and Craven was located in the streams with the greatest flow, while the majority of the Piedmont risk was located in the smaller, urbanized streams.

# CHAPTER 4

HYPSOGRAPHIC DEMOGRAPHY AS THE HUMAN CATENA

## 4.1 Introduction:

The spatial distribution of human populations is influenced by the geographic, social and policy characteristics of an area at a point in time. Over the last 40 years the trend in urbanization has accelerated (Tobler, 1997; Small, 2004) and has increasingly altered the spatial population distribution. Concurrent with increasing urbanization, natural hazard losses have risen, especially with respect to hurricanes and riverine floods in the United States. Klein et al (2003) noted that significant coastal development and urbanization had taken place on the east coast of the U.S. between 1966 and 1989; thereby, increasing socioeconomic exposure to coastal hazards during a period with little hurricane activity. The greatest impact from hurricanes and riverine floods are on those located closest to the water body (fluvial proximity) and in low-lying areas. The distribution of human populations is influenced by proximity to water, altitude, and topographic profile of the area, which directly affects human exposures to flood hazards (Small et al, 2000; Small & Nicholls, 2000).

The underlying concept of sustainable development with relationship to natural hazards requires finding a balance between the benefits of occupying an area and the potential costs of a hazard event (Mitchell, 2000). This chapter focuses on riverine flooding and the exposure of populations in relation to the geophysical parameter of elevation and the topographic profile of the area. Chapter 3 examined the exposure of populations in terms of fluvial proximity to different flow magnitudes. This chapter continues by examining population exposure as a function of elevation via the 'human catena.' A catena is a profile that measures changes in two continuous variables. The human catena developed here compares the continuous variables of elevation, area, and population to examine the distribution of people through time at multiple spatial scales.

**4.2 Background:**

Riverine floods are a product of the location, intensity, volume, timing and duration of precipitation events. A flood does not become a hazard until it spatially intersects with human populations. Models predicting the impacts of floods require input regarding the temporal frequency and spatial extent of the hazard coupled with the exposure of population and economic assets (Vatsa, 2004; Handmer, 2003; Cutter et al, 2000). Over the last half century, and the last decade in particular, U.S. flood policies have been focused on decreasing human populations in the floodplain to reduce the exposure variable.

The spatial extent of impact that U.S. flood policy has on development is based on the 100-yr floodplain as displayed in Flood Insurance Rate Maps (FIRM). The 100-yr FIRM is displayed as the maximum horizontal aereal extent that would be inundated in a flood that statistically occurs once every 100 years. The 100-yr floodplain was established in 1968 as a minimum, enforceable and uniform standard for managing floodplains (Robinson, 2004 & Reuss, 2004). FIRMs are created by the Federal Emergency Management Agency (FEMA) as the tool through which flood insurance and mitigation policies are implemented to remove people from the floodplain, provide insurance, and require stricter development standards.

The delineation of the 100-yr floodplain has several layers of inherent uncertainty present via model assumptions, data shortage and errors, and the stochastic nature of extreme precipitation. The estimated vertical error from the initial delineation of the 100-yr floodplain using 30 m (98 ft) digital elevation models (DEM) ranges between 0.15 to 1.5 m (0.5 - 4.9 ft) (Thomas & Baker, 2004; IFMRC, 1994). Furthermore, there has been an increase in flood heights and frequencies over the past few decades, resulting in changes in the spatial extent of the 100-yr flood. Changing flood stages and frequencies have been attributed to a combination of climate change, structural flood control and urbanization (Smemoe et al, 2007; Thomas & Baker, 2004; IFMRC, 1994). The importance of higher flood stages is that a vertical inaccuracy of a few decimeters in the 100-yr flood boundary can translate horizontally from a few decimeters to several hundred meters depending on the topographic profile of the floodplain (Smith, 2004; Davis, 2004).

Members of the Association of State Floodplain Managers (ASFPM) have emphasized the importance of either changing the 100-yr floodplain standard to a more precautionary 500-yr floodplain boundary (ASFPM, 2000) or using a vertical profile for floodplain maps rather than the further abstracted and error prone horizontal delineation shown on FIRM (Davis, 2004; James, 2004). The argument used by Smith (2004) revolves around the topographic profiles of different floodplains. For example, if area A had an increase in flood height of 6 m (20 ft) between the 20 and 100-yr event, while area B had a change of 1 m (3 ft), the damage experience by a flood greater than the 100-yr event in A would have far more catastrophic consequences than the same magnitude flood experienced at B. Therefore, it does not make sense to limit development in both places by the same standards when the costs of flooding are much different. It would make more sense to use a vertical profile to obtain an accurate representation of potential exposure as a function of the elevation located below the flood stage of a 100-yr event. Furthermore, the use of vertical profiles can eliminate up to 0.91 m (3 ft) of topographic uncertainty added to the delineation of the horizontal floodplain extents (IFMRC, 1994).

A geographic information system (GIS) was used in this analysis to assess the exposure of populations as a function of elevation in relation to the risk of experiencing a 100 and 500-yr flood event. Furthermore, the vertical change in population distributions between 1990 and 2000 were assessed to determine if flood policy had successfully removed people from the lower elevations of the floodplains. Fluvial proximity to streams as an indicator of floodplain policy was examined in Chapter 3, which found streams with greater than 2.8 cms flow had a decrease in floodplain occupancy, while smaller streams showed little evidence of an effective policy removing people from the 100-yr floodplain. Moreover, both Chapter 2 and 3 found increasing development densities directly adjacent to the 100-yr floodplain, resulting in an increased risk of catastrophic losses for the 101-yr or greater event. This chapter quantitatively assesses the potential exposure to floods as a function of elevation and the potential advantage of using a vertical profile to assess exposure. Furthermore, this type of study can provide a baseline for monitoring and scenario development (Small & Nicholls, 2003), and supports the assessment of potential flood hazard impacts under different development and land use planning scenarios.

**4.3 Study Area:**

Quantification of population distribution as a function of elevation through time was undertaken at the state scale, as well as the county and stream scale for five North Carolina counties (Figure 4.1). Exploring the spatial intersection of population and environment can provide some indication of what factors most heavily influence human settlement patterns. Environmental factors are often described in relation to climatic parameters of temperature and precipitation (Small, 2004). In North Carolina, the average temperature can range by as much as 6.67 degrees Celsius (44 Farenheit) between the mountains and the coast, and is largely driven by changes in elevation and proximity from the coast (NCNHM, 2001). The average precipitation is less variable throughout the state; however, the mountains have a wide range of precipitation due to orographic influences, while the coastal plains periodically experience intense hurricanes (NCNHM, 2001).

North Carolina has been divided into three distinct geographic regions based predominantly on physiographic characteristics: Mountain Region, Piedmont, and Coastal Plain. Buncombe County is in the Mountain Region, which is predominantly forested and has an elevation range from about 300 m (984 ft) in the valleys to 2,037 m (6683 ft) at Mount Mitchell. The Piedmont has the most diverse land use, including forested and agricultural areas surrounding the most heavily populated metropolitan areas. The Piedmont ranges in elevation from 60 m (197 ft) in the East to 460 m (1509 ft) at the foothills of the mountains. The counties of Orange, Durham, and Wake represent the Piedmont as a cross section from high elevations in the headwaters (Orange) to the lower elevations of the larger streams in Durham and Wake. The Coastal Plains is heavily cultivated and contains extensive wetland and estuarine systems. Elevations in the Coastal Plain range from below sea level in the estuarine and wetlands to 25 m (82 ft), and is represented by Craven County in this study.

North Carolina has a population of slightly over 8 million. One third of the population resides in the Coastal Plain, with the majority located on or near military reservations (NCNHM, 2001). North Carolina's population increased by 21.4% from 1990 to 2000, with rapid development occurring in the Piedmont. Wake was one of 13 counties that experienced 'explosive growth', with greater than a 30% increase in 10 years.

The physiographic parameters of fluvial proximity (Chapter 2) and elevation are expected to influence human habitation, which was quantified by a population surface created using census block groups for 1990 and 2000 that were distributed using land cover data. The exposure of populations to the flood hazard and the effectiveness of floodplain policies were quantified by monitoring population changes before and after the 1994 flood mitigation policy that advocates the reduction of populations on the floodplain. The difference between changing population distributions as a function of elevation indicated whether the lower elevation floodplains experienced a decrease in population amongst the overall trend of increasing population at the county scale.

**4.4 Methods:**

*4.4.1 Data Description:*

The process of assessing risk encompasses three aspects: the hazard, exposure, and vulnerability (Grunthal et al, 2006). The flood hazard is represented by the 100 and 500-yr floodplain boundaries, which provide the spatial extent and frequency of the hazard, and were provided in spatial format by FEMA. DEM's were obtained from the North Carolina Department of Transportation (NCDOT, 2006). The elevation data, except for Buncombe, have a horizontal resolution of 6.09 m (20 ft) and were derived from Light Detection and Ranging (LiDAR) technology. LiDAR models have a published vertical accuracy of 0.20 m (0.65 ft) and a horizontal accuracy of 3 m (10 ft) (Sanders, 2007; Mitasova et al, 2005). Buncombe County does not have LiDAR data available, and their DEM had a horizontal accuracy of 30 m (98 ft) and a vertical root mean squares error of 7 m (23 ft) (USGS, 2007). Statewide elevation used the same DEM as Buncombe for consistency and was analyzed at a 30 m (98 ft) resolution.

Exposure was assessed with population counts to represent the human system and changes in development patterns. ESRI's Topological Integrated Geographic Encoding and Referencing (TIGER) data provided census counts in spatial block group boundaries for the nation (TIGER, 2004). Population data are a "useful indicator of the changing human ecology of a hazard" (Mitchell, 2000). The National Land Cover Dataset (NLCD) was freely available from the USGS seamless website (USGS, 2006), and served as an ancillary variable to better distribute population spatial locations.

*4.4.2 Creating Socioeconomic Surfaces:*

All spatial analyses were done in ArcGIS 9.1. Populations form a continuous surface covering the Earth, but in a GIS they are often represented as discrete vector polygons; whereby the entire area covered by that vector contains a single population value. The creation of a catena requires the comparison of distribution changes along two continuous surfaces. Elevation data were already continuously represented in a raster with a 6.09 m (20 ft) resolution, making it desirable to create a continuous population surface at the same spatial resolution. The population raster was made by using the NLCD raster as an ancillary variable to logically distribute the vector populations. The goal was not to create a perfect population distribution model, but to create a better distribution than vector data provided.

Details regarding the creation of a population surface can be found in Chapter 2. Briefly, the NLCD was weighted by land cover type to attract more people inside a block group towards developed pixels, such as commercial and residential, and to reduce the number of people in less developed areas, such as wetlands and water. The absolute error for population distribution was constrained by the spatial boundaries of the vector block groups.

The population coefficient file was designed to create an ambient population surface. The weights were modified from the schema used to classify NLCD from low to high density residential and commercial areas based on the percent impervious surface in the pixel (Homer et al, 2004). Forest values were given additional weight because much of North Carolina is forested and populations located beneath tree canopies are not readily captured by satellite imagery. Values of zero were used for water, wetland, and barren land cover. The 1990 population surfaces were created using 1992 NLCD.

The population surface was created by dividing the reclassified NLCD ($NLCD_{ReclassPop}$) by the sum of reclassified pixels in each block group ($NLCD_{PopBlockGroup}$). The resulting value was the percentage of the population assigned to each pixel by block group (*Equation 4.1*). The 6.09 m (20 ft) spatial resolution resulted in population pixel values less than one, which is reasonable for such a fine resolution, as it is more the probability of finding X number of people at any given time in a pixel. The population surfaces were only utilized as the cumulative population located at each elevation; thereby, mediating the significance of distribution error. The statewide analysis maintained a 30 m (98 ft) resolution because LiDAR was not used.

$$PopSurface = \frac{NLCD_{ReclassPop}}{\sum NLCD_{PopBlockGroup}} \times Population \qquad (4.1)$$

There are a few limitations regarding the population surfaces that were created. First, there was an unknown degree of spatial and attribute error associated with the raw population data, and the regional variation of error in North Carolina for the elevation and land cover data was unknown. Raw data errors were propagated and increased during the creation of the raster surfaces. Secondly, the NLCD was disaggregated to match the spatial resolution of

LiDAR at the county and reach scale, which introduced further uncertainty. The uncertainty was constrained by the vector block group boundaries, with larger blocks having a higher degree of uncertainty. Fortunately, larger block groups are often associated with smaller population densities (TIGER, 2004). Lastly, the assumptions used to weight the coefficient matrices do not uniformly apply in every locality and introduce another level of error.

*4.4.3 Creating Hypsographic Profiles of the Human Catena:*

Zonal statistics (ESRI, 2007) calculated the sum of the population at each elevation (m) above sea level (Figure 4.2). Zonal statistics were done at the state, county and stream scale. The state and county scale calculated the cumulative population at each elevation. The stream scale was subdivided logarithmically by mean annual flow into five categories: > 28.3 cubic meters per second (cms), 2.8-28.3 cms, 0.28-2.8 cms, 0.03 0.28 cms and 0.003-0.03 cms (Chapter 3). Zonal statistics used the average elevation at each distance from the stream, resulting in the removal of elevation extremes that were present in the county and state analysis.

The univariate relationship between population and elevation were examined by creating a human catena. However, development is limited by the amount of land available at any given elevation. Therefore, population values were normalized by land area for comparative analyses. The population (*Pe*) is divided by the area (*Ae*) at any given elevation (e) to calculate the total population per square kilometer of available land (*Equation 4.2*). This function was coined the Integrated Population Density (*IPD*) by Small & Cohen (2001).

$$IPD = \frac{\sum Pe}{\sum Ae} \qquad \textit{Equation (4.2)}$$

The inherent problem of utilizing density functions to display population trends with relation to elevation is that it discounts the actual population value. Small & Cohen (2001) accounted for this by multiplying the cumulative population distribution with the IPD. The Normalized Population Density (NPD) was calculated for each elevation as shown in *Equation 4.3*. The square root compressed the range and kept the units simple as people/km (Small & Cohen, 2001).

$$NPDe = \sqrt{IPDe * Pe} \qquad \textit{Equation (4.3)}$$

The spatiotemporal change in population distribution was calculated by subtracting the 2000 IPD and NPD from the 1990 values at each elevation, respectively (*Equation 4.4*). The temporal changes in population distribution were examined with the assumption that a negative change through time in low elevation areas indicated successful mitigation.

$$\Delta NPDe = NPDe_{2000} - NPDe_{1990}$$
$$\Delta IPDe = IPDe_{2000} - IPDe_{1990} \qquad \textit{Equation (4.4)}$$

It should be reemphasized that the assessment of flood exposure as a function of elevation provides an estimate for the number of people at risk inside and adjacent to the 100-yr floodplain. FIRMs only provide the horizontal extent of the floodplain; however, examining the maximum elevation inside the 100-yr FIRM at different stream magnitudes provides a vertical nexus for estimating flood exposure and management effectiveness.

**4.5 Results:**

*4.5.1 County Scale Analysis:*

The trends in the univariate distributions of population and area at each elevation were similar (Figure 4.3). Craven has the smallest topographic range in elevation, resulting in the county's population being constrained to 40 vertical meters. In contrast, Buncombe had an elevation range of 670 m, resulting in population values being more spread out among the different elevations. Lastly, the Piedmont counties had an elevation range between 100 and 200 m.

The cumulative population by elevation catena for Craven County exponentially decreased as elevation increased. On the other hand, Buncombe had a bimodal distribution of population with a large peak at 670 m followed by a smaller peak at 1,730 m (Figure 4.3). Both Durham and Wake had a unimodal peak in their cumulative population distribution that coincided with the largest area available for development. Orange had the largest population value located at an elevation of 150 m, as well as two smaller population peaks at 90 and 200 m. The 150 and 200 m peaks coincided with the most area by elevation, while the 90 m peak seemed to be a densely populated area. The temporal change in population distribution had the same distribution by elevation, but with a greater population in 2000 than 1990.

The IPD showed the elevations at which population preferred to develop regardless of the amount of land available (Figure 4.3). The IPD for Craven had a single peak for the 2000 population density of 80-100 people/km$^2$ at elevations between 2 to 7 m. The 1990 population had the same peak, as well as a second, smaller increase in population density between 20-35 m above sea level. Furthermore, the change in IPD from 1990 to 2000 decreased slightly below 3 m and above 18 m altitude (Figure 4.4). The NPD had a bimodal peak in population distribution at elevations of 3 and 7 m (Figure 4.4). Above 7 m the NPD decreased exponentially with increasing elevation. The NPD for Craven in 1990 and 2000 had a similar distribution pattern with a large decrease in population from 0 to 2 m above sea level, followed by an increase between 3-10 m above sea level. This is an instance where the IPD indicated high population density for 1990 at the higher elevations, but the NPD showed this to be a false signal because there were few people at those elevations. The IPD simply had a high value because so little land area is located above 20 m in Craven.

The IPD in Buncombe rapidly increased to peak at 220 people/km$^2$ around an elevation of 670 m, before exponentially decreasing to a fairly constant population density of 30 people/km$^2$ at higher elevations (Figure 4.3). There was a small increase in the IPD from 1990 to 2000 at all elevations, except between 600 to 750 m, where the population density decreased. Buncombe's NPD was a well-defined unimodal peak in population distribution at elevations between 580 and 760 m. Those elevations also had a decrease in the NPD and IPD values from 1990 to 2000 (Figure 4.4). Furthermore, the NPD showed the IPD peak at 1,730 m to be an insignificant peak when looking at the total population and density together.

In the Piedmont, Orange County's IPD had population densities greater than 300 people/km$^2$ from 78 to 146 m in elevation. Above an elevation of 170 m, the IPD was constant at 50 people/km$^2$ (Figure 4.3). The IPD from 1990 to 2000 decreased at elevations between 72 to 87 m, followed by a large increase between 90 to 170 m and a smaller increase at higher elevations (Figure 4.4). The NPD for Orange followed the same trends as the IPD; thereby, indicating the largest populations were also located in the more densely urban areas.

The IPD and NPD in Durham had a similar trend with a single unimodal peak in population distribution between 75 to 140 m above sea level, with the density reaching 590 people/km$^2$. The IPD for Durham increased at all elevations from 1990 to 2000, with the largest increase coinciding with the most densely populated elevations. There was no change in NPD from 1990 to 2000 at elevations less than 65 m, but from 75 to 100 m above sea level, there was a rapid, linear increase in the NPD (Figure 4.4).

The IDP for Wake had a constant density of 37 people/km$^2$ below 40 m in elevation. The IPD increased to 270 people/km$^2$ at 60 m above sea level and remained constant until an elevation of 110 m. Above 110 m, the IPD rapidly increased to a maximum density of 845 people/km$^2$ at an elevation of 150 m, above which the IPD exponentially decreased. The NPD for Wake followed the same pattern, except the population distribution peaked 20 m below the IPD. The IPD from 1990 to 2000 had an increasing rate of change as elevation increased (Figure 4.4). At the highest elevation, the IPD increased by 350 people/km$^2$. The NPD had a slightly different trend as the population change was near zero below 45 m, before increasing rapidly to a maximum change at an elevation of 130 m, above which the NPD steadily decreased.

*4.5.2 Stream Reach Analysis:*

Several important trends were evident when the cumulative population was calculated by elevation at the stream scale (Figure 4.5). First, streams with the largest mean annual flow were located in broad alluvial valleys at the lowest elevations in the county. In contrast, streams with a lower mean annual flow are typically headwater streams located at higher elevations. The exception was the 2.8-28.3 cms stream reach in Orange and Durham, which coursed through the majority of the elevation range. Second, there was an exponential increase in population as elevation increased for all stream flows, except the 2.8 – 28.3 cms in Orange and Durham and the smallest streams in Buncombe. Third, the cumulative population for all counties was greatest in streams with a mean annual flow volume between 0.03 and 2.8 cms. The urbanized Piedmont also had a large population located around the smallest streams. Lastly, population had an overall increase from 1990 to 2000, with the greatest increase occurring at higher elevations. Only streams with flow greater than 0.3 cms in Craven decreased in population at the lower elevations.

The IPD displayed several important trends indicative of the importance of topographic profile and flood policy in determining the spatial distribution of populations

(Figure 4.6). The larger streams and floodplains in Buncombe, which represents the Mountain Region, had the greatest IPD, and the IPD increased with elevation. Streams with a mean annual flow of less than 2.8 cms had a smaller IPD of approximately 100 people/km$^2$, and the IPD remained fairly constant at all elevations. For the NPD, the 0.03 – 0.3 cms streams had the greatest population exposure to flooding when accounting for total population and density; whereas, the streams greater than 0.3 cms had similar exposure levels (Figure 4.7).

The IPD for Craven had a similar trend to Buncombe, with the densest populations located along the largest streams, which spanned an elevation gradient of 4 m. Streams below 2.8 cms had a linear increase in IPD with elevation. All streams in Craven were constrained by an elevation range of 10 m. Similar to Buncombe, the NPD at 0.03 to 0.3 cms had the greatest value.

The topography of the Piedmont is conducive to development at all elevations since slopes are not as steep as the Mountain Region, nor so gentle as to produce the extensive wetlands system as in the Coastal Plain. Therefore, the IPD by stream flow for the Piedmont was partially driven by which stream sizes intersected the most urbanized areas. The IPD in Orange slowly increased with elevation, with the 0.3–2.8 cms having the greatest population density (Figure 4.6 & 4.7). The NPD had the greatest exposure for streams less than 2.8 cms and increased with elevation. Both the IPD and NPD in Durham were largest for streams with flow less than 0.3 cms. Furthermore, the IPD for all but the largest stream increased linearly with elevation. The IPD in Wake increased rapidly with higher elevations for all but the largest stream. The IPD ranged from 0 at the lowest elevation up to 337 people/km$^2$ for streams with flow > 2.8 cms; whereas, the IPD was never below 116 people/km$^2$ in the smaller streams. The NPD had a division of exposure by stream flow into three categories. Streams with flow > 28.3 cms had the smallest NPD by elevation, while streams with flow < 0.3 cms had the greatest exposure, and the exposure in 0.3- 2.8 cms streams were located in between the large and small streams.

Both IPD and NPD had a similar transition from 1990 to 2000 for all counties and stream flows; therefore, only the IPD will be discussed. Buncombe's IPD (Figure 4.8) decreased by 63 people/km$^2$ at elevations lower than 620 m for the largest stream. The IPD also decreased below an elevation of 650 m for the 2.8 – 28.3 cms streams. Craven also had a decrease in the IPD from 1990 to 2000 at all elevations for streams with flow > 2.8 cms and below 4.7 m in elevation. Only streams with flow less than 0.3 cms increased in IPD, with the greatest increase being less than 10 people/km$^2$.

The Piedmont had a large increase in population from 1990 to 2000, which was evident by the increase in IPD for Orange, Durham and Wake. The IPD in Orange County increased for all streams, with a maximum increase of 29 people/km$^2$ in the 0.3-2.8 cms stream, which was also the only stream to have a decrease in IPD for the lowest 15 m in the stream reach (Figure 4.8). In Durham, the IPD also increased in all streams, with the greatest increase in the 0.03 – 0.3 cms streams of 52 people/km$^2$. However, each stream flow regime had a decrease in the IPD at the lowest elevation for each respective stream. The IPD in Wake County had the largest increase with elevation in all stream reaches for the Piedmont. Only streams with flow > 0.3 cms had an initial decrease in IPD at the lowest elevations of the stream. The 2.8-28.3 cms streams increased by 100 people/km$^2$ from 1990 to 2000, with the largest increase occurring at the highest elevations in the stream reach.

## 4.6 Discussion:

### *4.6.1 Multi-scalar Analysis:*

This chapter examined the spatiotemporal relationship of population as a function of elevation at the county and stream scale. The importance of examining hypsographic distributions at multiple scales was highlighted in Small (2004), who found that the distribution of population with respect to physiographic parameters was extremely localized in population clusters that occurred at smaller spatial scales, and were not apparent at larger scales. While the county scale showed broad trends in the human catena, the stream reach scale showed different trends that were not apparent at the county scale of analysis. This localized, spatial clustering of populations is common in North America (Small & Cohen, 2001), so it was essential to examine the human catena at multiple spatial scales prior to making assumptions regarding floodplain management and population distributions.

At the global scale, Small (2004) found population decreased monotonically with elevation, which was partially related to the availability of more land area at lower elevations. However, comparisons of the IPD show populations are denser at lower elevations and continue to decrease monotonically as elevation increases (Small, 2004; Small & Cohen, 2001). Furthermore, land area decreased linearly with elevations below 800 m, while population densities decreased faster than exponentially (Small & Cohen, 2001). A similar trend was found in our analysis at the state and county scales (Figure 4.3, 4.9) with the area available for development changing at a slower rate than population values with respect to elevation. At the global scale, the majority of people live at a population density of 262 persons/km$^2$; however, within 100 m above sea level, the global population's modal density was over 500 people/km$^2$ (Small & Cohen, 2001). North Carolina had a smaller median IPD of 56 people/$km^2$ below 100 m above sea level, while the Piedmont and Coastal Plain had a range of median densities between 493 and 8 people/$km^2$, respectively. The range of IPD values at the county scale was reflective of urban densities in each county and illustrated the influence of localized, spatial clustering observed by Small & Cohen (2001).

Small (2004) found the NPD enabled a better representation of the population distribution at the global scale because it accounted for both density and the actual population value. Whereas, if only density was taken into account, a few people located in a small area could create the impression of a highly developed area with many people. Both state and county scale analyses had peak densities that were removed when calculating the NPD. The NPD was calculated at all scales in North Carolina (Figure 4.3, 4.6 & 4.9) and followed the same trends as the IPD; therefore, only the IPD will be discussed in this section.

Down-scaling from the global to the stream reach when creating the human catena revealed the localized, clustering nature of human populations (Figure 4.3, 4.6, & 4.9). At the state scale, the peaks in IPD were located at the elevations of major urban areas. To observe how the catena changed from the county to state scale, the human catena was calculated for North Carolina (Figure 4.9). The topographic profile for North Carolina begins at 0 m above sea level in the Coastal Plains and rises to above 2000 m in the Mountain Region (Figure 4.1). The land area available for development decreased exponentially moving from the flat coast to the higher elevations of the mountains, yet the population distribution did not follow the same trend. One third of North Carolina's population is located in the Coastal Plains, which was evident in the Cumulative Population graph (Figure 4.9); however, the much of the population is rural or dispersed among smaller, urban areas. The densely urbanized Piedmont populations form the peaks on the state catena, preventing a smooth monotonic decrease in population moving away from the coast and towards higher elevations (Figure 4.9, Table 4.1). Moreover, the boundary of the Piedmont is evident at around 400 m of elevation, after which only the large city of Asheville makes a significant impression on the population and density catena's. Thus, at the state scale population distribution by elevation was dominated by urban cities, while the county scale was dominated by a mixture of urban cities and fluvial proximity, as described below.

In Buncombe, the median county population density was 27 people/km$^2$ while the densities near the streams were several times greater. Furthermore, the majority of the population was concentrated at an elevation less than 720 m, which coincided with the major valley and floodplain of the French Broad (Figure 4.1 & 4.6). The French Broad bisects Asheville, which is the largest city in Buncombe, and resulted in the areas near the largest streams to dominate the IPD for elevations less than 650 m. The less populated headwater streams located at higher elevations contained a higher IPD than the county scale; thereby indicating preferential development around these streams.

Craven's median population density was 8 people/km$^2$, with areas around the streams containing densities 4 to 10 times greater (Table 4.2). The largest river is the Neuse, whose extensive floodplain contains portions of the two largest urban areas in the county (Figure 4.1). It is therefore not surprising that since Craven's, like Buncombe, largest streams intersect the major urban areas, the county IPD by elevation was dominated by the populations located around the largest streams (Figure 4.6). The stream IPD was less than the county scale; thereby, indicating development around streams is not preferred, as expected in a wetlands area with saturated grounds located near waterbodies.

Orange is in the headwaters of the Neuse and had the smallest and fewest streams of the study area. More importantly, the lowest elevations were located in the most urbanized area of the county (Chapel Hill and Carrboro), resulting in the county scale IPD being above 300 people/km$^2$ below 145 m, above which the IPD decreased to ~50 people/km$^2$. Above 150 m, the stream IPD again exceeded the county IPD values, indicating that population densities are greatest closest to streams.

Durham has larger streams and a greater portion of the county is urbanized than in Orange County. The multi-scalar IPD relationship (Figure 4.6) had the same trend of population density increasing at higher elevations. Once the elevation was higher than the stream reaches, the county IPD decreased by 200 people/km$^2$ within 5 m above the highest stream; thereby, indicating preferential development near streams in Durham. Lastly, Wake County had the highest overall IPD of 239 people/km$^2$ (Table 4.2), which occurred at elevations located above the fluvial proximity of the stream system (Figure 4.6). Wake was one of the fastest growing counties in North Carolina (NCNHM, 2001) and has a topography that enables development anywhere in the county. Only a few stream reaches had a greater IPD than the median county density; thereby, indicating that neither fluvial proximity nor elevation are the main drivers of population distribution.

*4.6.2 The Effectiveness of Floodplain Policy and the100 – yr FIRM:*

Lastly, changes in population exposure to the flood hazard from 1990 to 2000 were assessed by comparing the change in IPD by elevation to the maximum elevation in the 100-yr FIRMs for the different stream reaches (Table 4.3; Figure 4.8). FEMA's effort to reduce losses by removing people from the floodplain led to the assumption that elevations below the 100-yr floodplain should have experienced no change or a decrease in population.

The IPD in Buncombe decreased in the two largest streams at elevations below 670 m and had the greatest decrease in population density. During the 1990's, Buncombe experienced several flood disasters from intense precipitation produced by orographic uplift and tropical depressions (BCHM, 2004; FEMA, 2001). Buncombe has since "undertaken far-reaching steps to lesson the potential damage of future storms and floods" by participating in North Carolina's Project Impact and Hazard Mitigation Planning Initiative (HMPI) program (FEMA, 2001; NCNHMP, 2001). The purpose of these programs was to 1) identify and analyze all hazards, 2) assess vulnerable properties and populations, 3) assess the local capabilities to implement mitigation, and 4) prioritize feasible mitigation opportunities (NCNHM, 2001). In Buncombe, specific measurements that have been taken as a HMPI member include an aggressive program to buy-out properties that have been repetitively flooded and to enforce strict floodplain development regulations (FEMA, 2001). Our results suggest these efforts have been successful in terms of reducing populations in the 100-yr floodplain.

Craven had a significant decrease in the IPD at elevations below 5 m. Craven also participated in North Carolina's HMPI program following Hurricane Fran in 1996. Hurricanes Fran and Floyd (1999) affected most of North Carolina, especially the Coastal Plain. During Floyd, 40% of Craven's population was affected and 221 homes were damaged beyond repair (Baumbgardener, 2000). Largely in response to these hurricanes, the HMGP has removed 6,000 flood prone homes and elevate another 1,000 homes in the Coastal Plain. The only increase in IPD for Craven from 1990 to 2000 were located in streams with flow less than 0.03 cms or higher than 5 m above sea level.

In Orange, only the 0.3-2.8 cms streams had a decrease in IPD at elevations below 145 m, while the remaining streams had a small increase of less than 35 people/km$^2$. There was little differentiation in IPD changes by elevation for Orange (Figure 4.8). In Durham, the lowest 10 to 15 m of a stream reach had a decrease in density, while the IPD in the remaining streams increased linearly with elevation, and the most rapid change occurred in the smallest streams. Durham is the only county in the study area that was not a HMPI member. The IPD in Wake decreased for streams with flow > 0.3 cms at the lowest 5 m of the stream reach. The IPD in Wake increased at the fastest rate with elevation for all stream flows in the study area. The Piedmont did not experience the catastrophic flooding that impacted Craven and Buncombe in the 1990s, and it appears mitigation efforts have only reduced floodplain exposure at the lowest elevations of the stream reaches. Unfortunately, these counties are highly vulnerable to floods because of the high number of people living near the floodplain (NHMP, 2001), and it is important for floodplain management to actively reduce and limit floodplain development before a catastrophic flood occurs.

**4.7 Conclusion:**

This chapter quantified the extent to which the current spatial patterns of humans were influenced by the topographic profile of the area, the effect of scale on the distribution patterns, and the assessment of flood management effectiveness on reducing populations in the floodplains. The characteristics of a floodplain and its potential for catastrophic flood losses are shaped by two factors: 1) the topographic profile and 2) the level of exposure.

The ASFPM have emphasized the importance of either changing the 100-yr floodplain standard to a more precautionary 500-yr floodplain boundary (ASFPM, 2000) or using a vertical profile for floodplain maps to reduce the uncertainty of the floodplain boundary present in FIRMs by up to 0.91 m (3 ft) (Davis, 2004; James, 2004, IFMRC, 1994). The use of a catena to display exposure as a function of the elevation located below the flood stage of a 100-yr event also highlights the topographic profile as exposure is constrained to within a few meters (Coastal Plain) versus spread out over several hundred meters (Mountain Region). Clearly, a few decimeters will have a much larger impact on floodplain extents in Craven than in Buncombe; however, the flood depths will be greater in Buncombe as the horizontal extent of inundation is constrained by the topography. Not all floodplains were created equal and it is important to consider the topographic profile of the floodplain and the socioeconomic exposure along that profile to determine where flood policy should be upheld.

The multi-scalar exploration of population distribution by elevation is important to assess because distribution is influenced by different drivers at different scales. The state analysis showed population and changes in IPD were driven by the elevation of major urban areas. The county analysis showed population distribution to be a function of both the elevation of urban areas and the density of development around streams. Lastly, the stream reach analysis showed that the size and proximity to the streams, as well as the presence of floodplain management influenced population distribution. Thus, the state and county scale of analysis did not capture the influence of floodplain management on the spatial distribution of humans by elevation, while the stream flow scale did not provide input on the importance of urbanization in driving the hypsographic profile.

The importance of elevation in relating to flood hazards can be vertically quantified because streams are located at the lowest elevations in a watershed to enable routing of waters from the land to the stream and downstream. Furthermore, floodplains spatially surround rivers and therefore also occur at the lower elevations in a human catena. By monitoring the changing human catena in relationship to the 100-yr FIRM elevations, the effectiveness of floodplain management can be assessed for its ability in reducing population in the lowest portions of the floodplain. Maune (2004) even suggested that flood policy and FIRMs should be based on vertical rather than horizontal criteria. The 100-yr floodplain boundary is a function of elevation and the process for depicting flood risk from a planar perspective results in additional uncertainty (IFMRC, 1994). Furthermore, the relationship between humans, flood depths and elevation can be geospatially and temporally intersected to observe past, present, and future scenarios of floodplain development and potential flood losses. Monitoring flood exposure in relation to physiographic parameters and at multiple scales can assist policy makers in their prioritization of where mitigation is most needed to reduce exposure, where it has been effective, and where enforcement of development regulations is essential to reduce the potential for future flood losses.

**4.8 Tables:**

**Table 4.1:** Average elevation and population density for major urban areas in North Carolina. The elevation of these urban areas is the main driver behind the state scale human catena.

| Urban Areas | Elevation (m) | Density (pop/km$^2$) |
|---|---|---|
| New Bern | 5 | 166 |
| Wilmington | 15 | 714 |
| Durham | 120 | 763 |
| Raleigh | 132 | 930 |
| Chapel Hill | 146 | 952 |
| Charlotte | 242 | 971 |
| Greensboro | 250 | 826 |
| Winston-Salem | 278 | 659 |
| Asheville | 650 | 650 |

**Table 4.2:** Median population density (people/km$^2$) in the study area. The Piedmont has the highest overall population densities; however, there are several streams in Buncombe that surpass the piedmont densities. Craven has the lowest population density at every scale.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven |
|---|---|---|---|---|---|
| > 28.3 cms | 200 | n/a | n/a | 89 | 79 |
| 2.8 – 28.3 cms | 237 | 80 | 89 | 259 | 71 |
| 0.3 – 2.8 cms | 108 | 156 | 116 | 145 | 35 |
| 0.03 – 0.3 cms | 121 | 93 | 256 | 209 | 36 |
| 0.003 – 0.3 cms | 101 | 104 | 225 | 247 | 27 |
| Average | 153 | 108 | 172 | 190 | 50 |
| Total County | **27** | **86** | **79** | **239** | **8** |

**Table 4.3:** Maximum elevation (m) inside the 100-yr floodplain by stream flow. Stream flows without a maximum value either did not have a floodplain or was part of another floodplain.

| Stream Flow | Buncombe | Orange | Durham | Wake | Craven |
|---|---|---|---|---|---|
| > 28.3 cms | 631 | n/a | n/a | 61 | 2 |
| 2.8 – 28.3 cms | 639 | 132 | 94 | 76 | 2 |
| 0.3 – 2.8 cms | 680 | 154 | 94 | 95 | 5 |
| 0.03 – 0.3 cms | n/a | 178 | 101 | 89 | 7 |
| 0.003 – 0.3 cms | n/a | n/a | 108 | n/a | n/a |
| Average | **656** | **157** | **99** | **80** | **4** |

## 4.9 Figures:

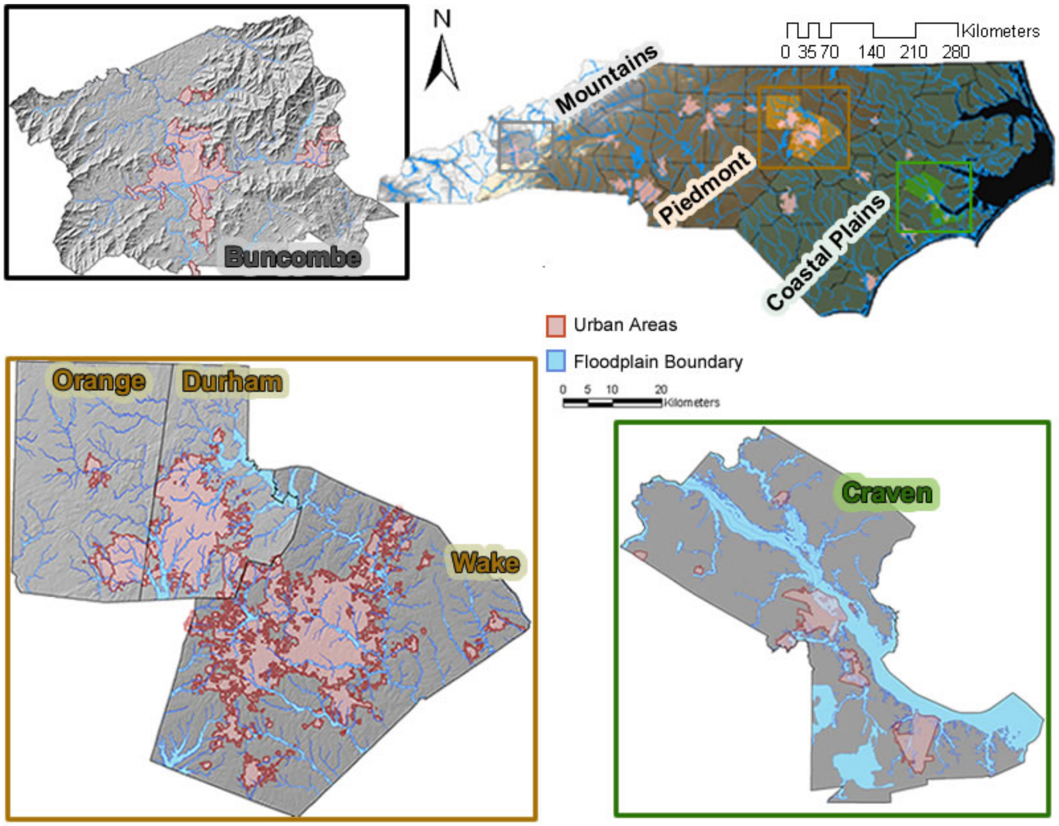


***Figure 4.1:*** Topographic and fluvial characteristics of the study areas by physiographic regions in North Carolina

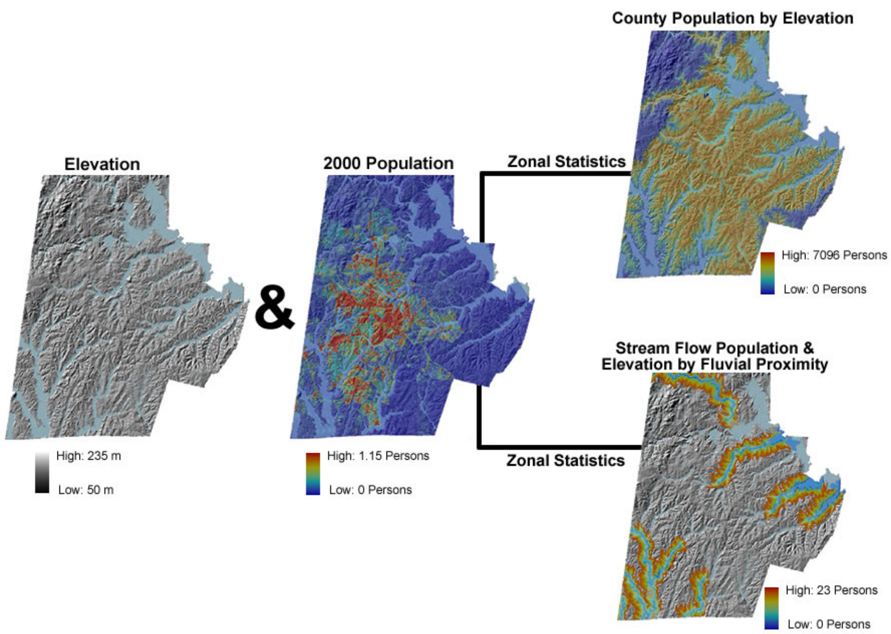


***Figure 4.2:*** Process of calculating population by elevation. The county scale used zonal statistics with the elevation as the zone and total population as the value. The stream scale used fluvial proximity as the zone and the average elevation and population sum as the value.

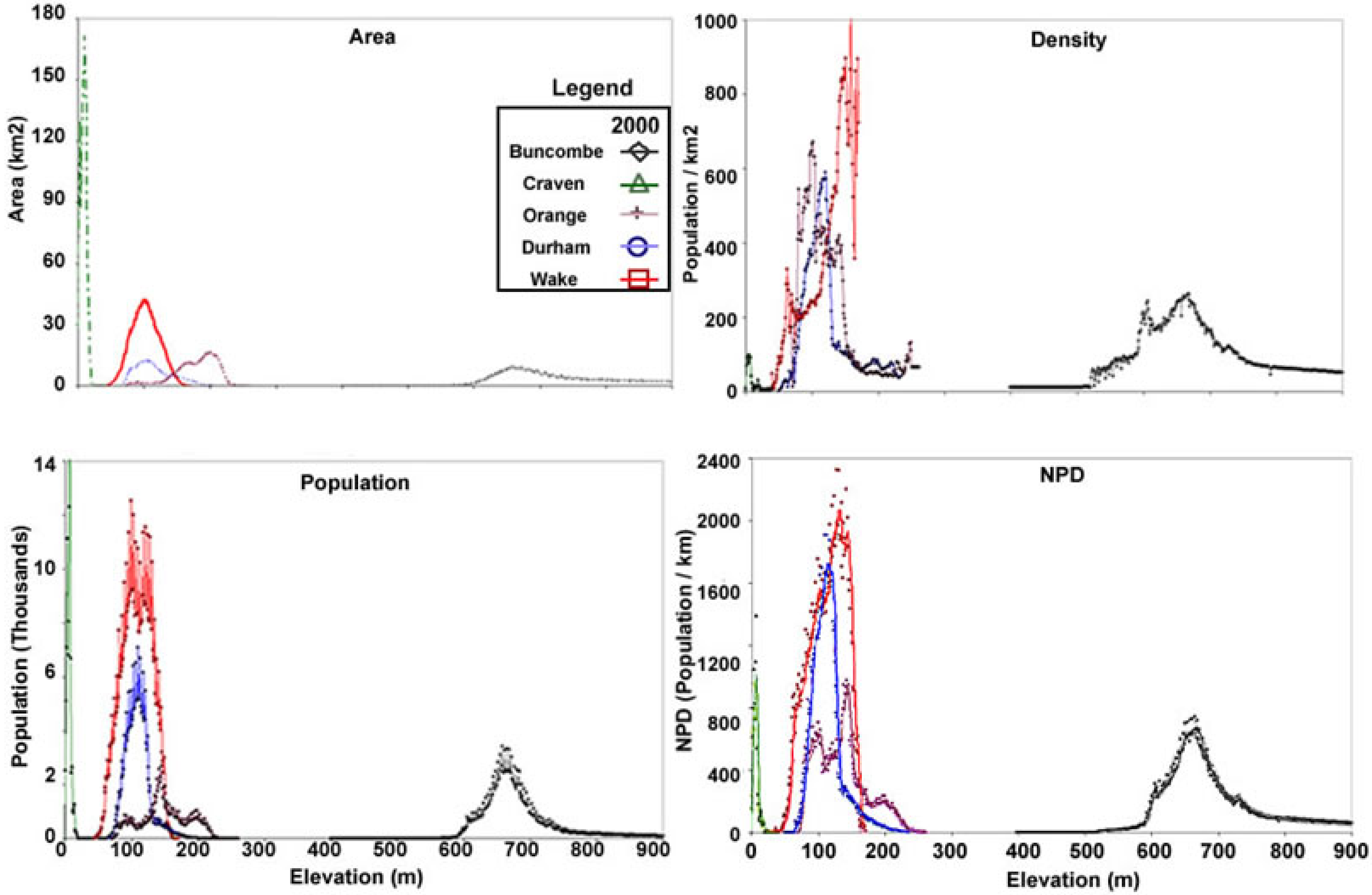


***Figure 4.3:*** County scale area, population and population density by elevation. Note that the balance between population and area provides a different trend when examining the densities of development. The NPD combines population and density to create a smoother curves.

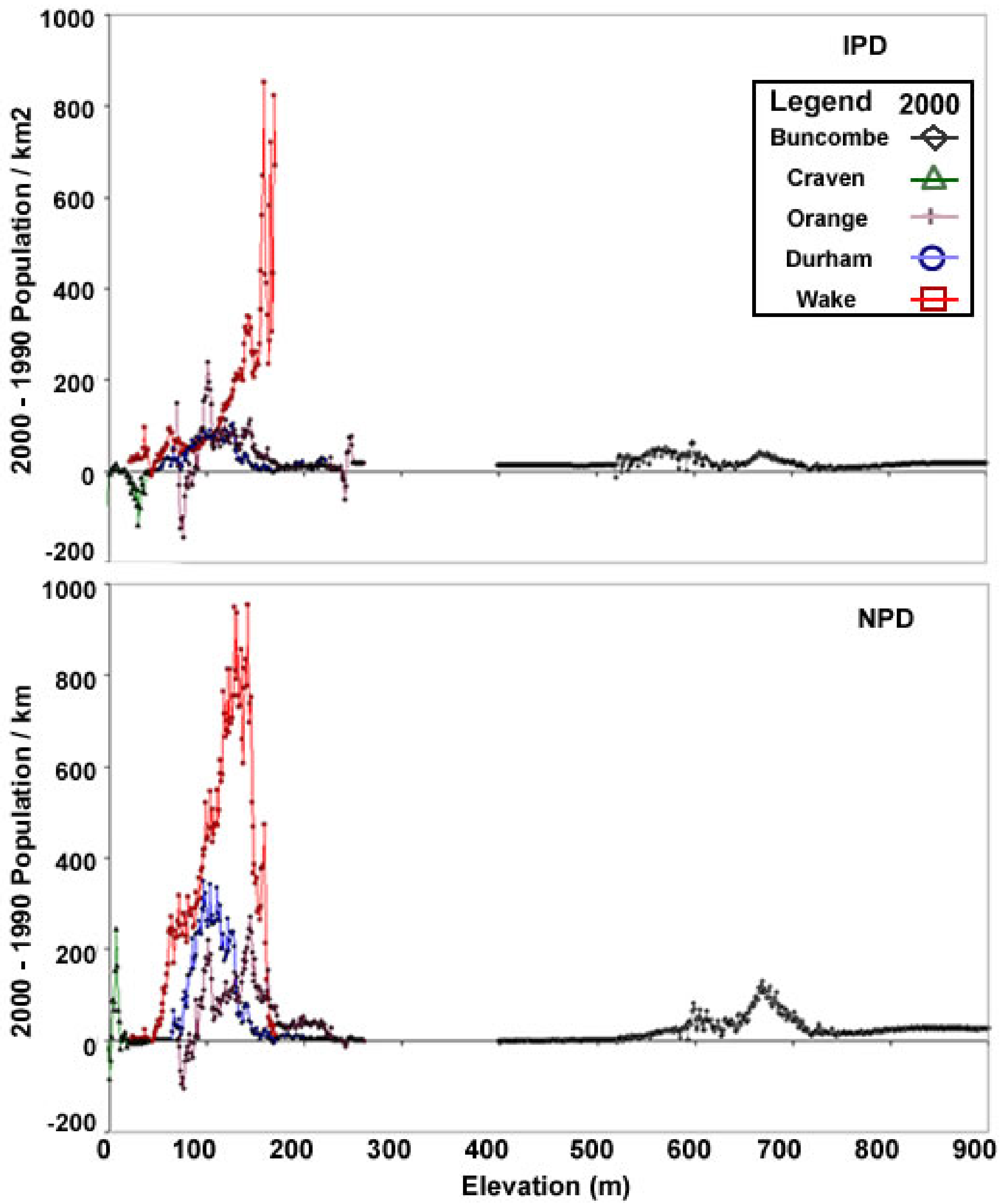


***Figure 4.4:*** County scale change in the IPD and NPD from 1990 to 2000 by elevation. Values located above zero indicate an increase in population, while those values less than zero indicate a decrease in population. The NPD provides a smoother figure as it takes into account both the actual population values and the density of development.

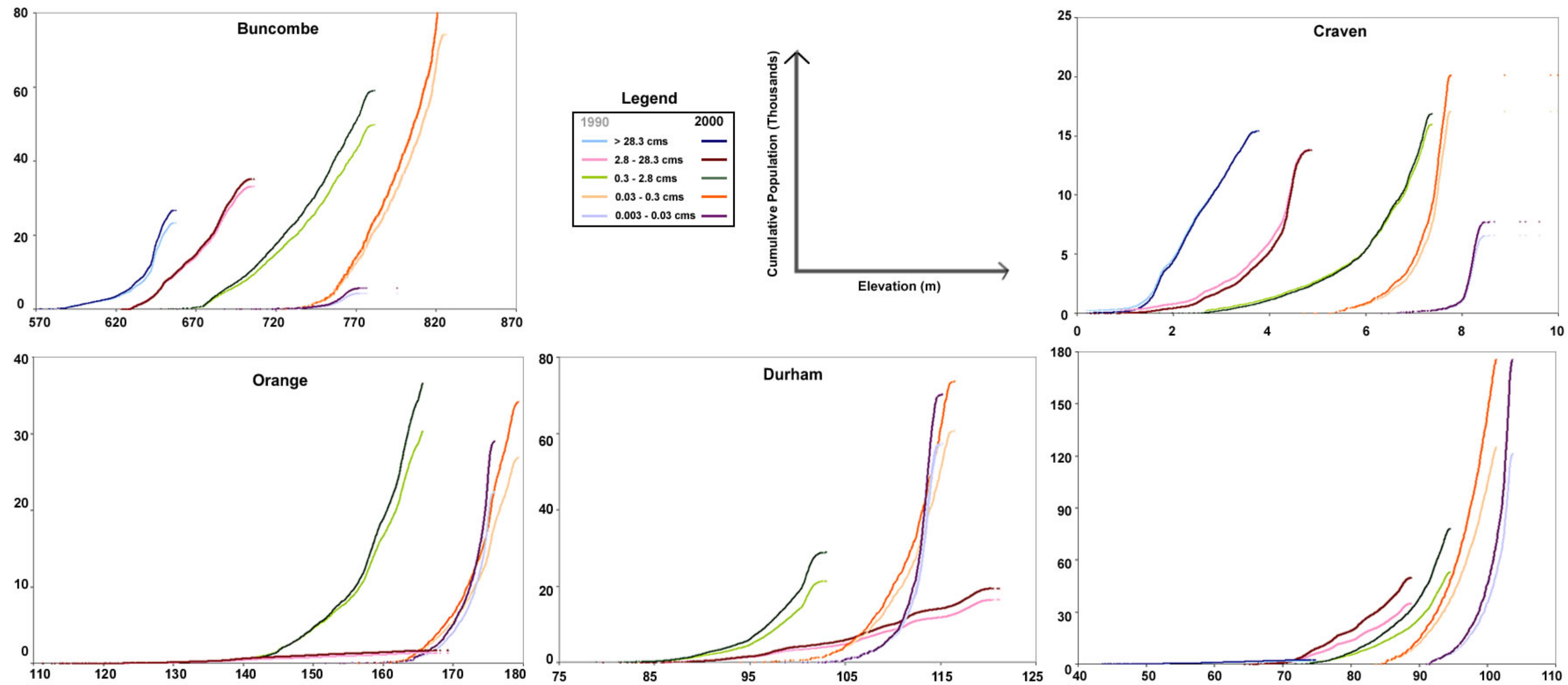


***Figure 4.5:*** The cumulative population values by stream flow and county. Note the different x (elevation) and y (cumulative population) axis scales. The cumulative population is the sum of the population at each elevation plus the population at a lower elevation.

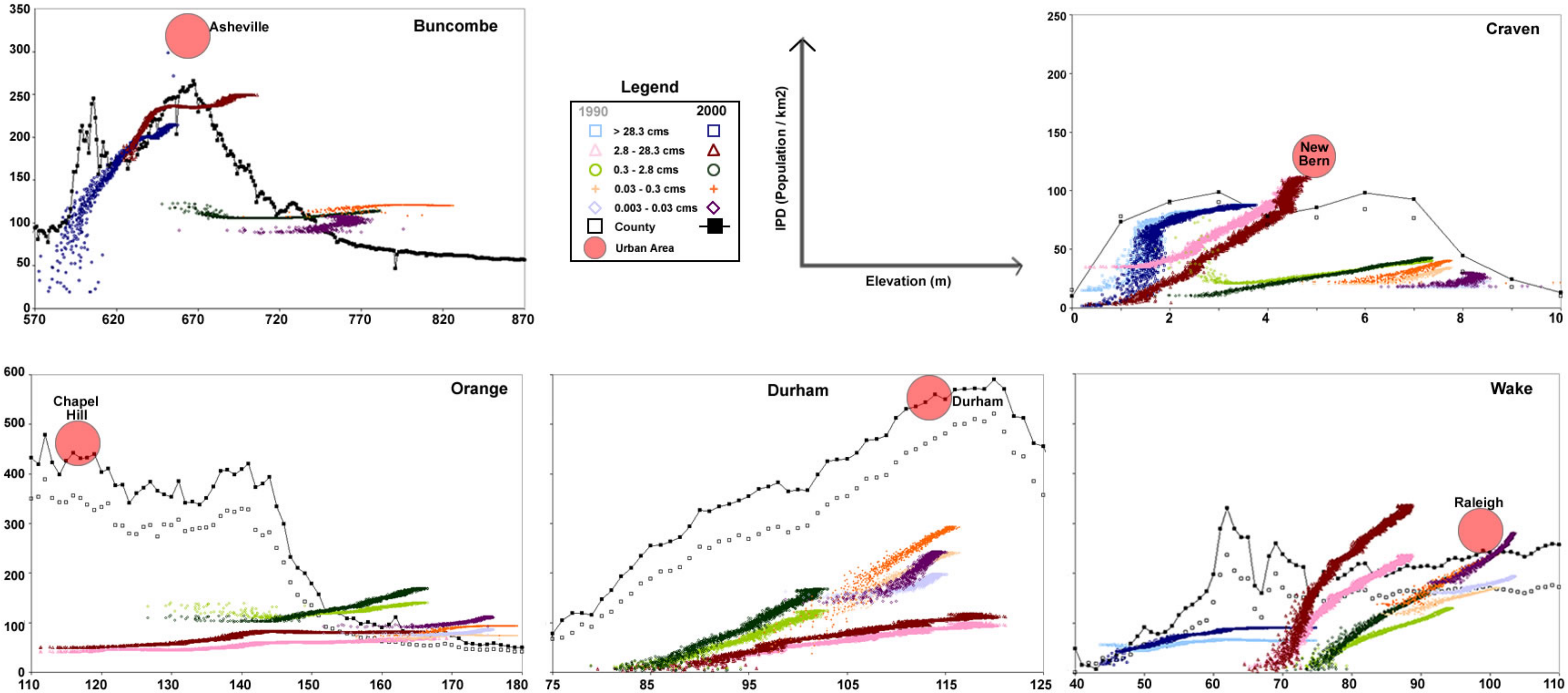


***Figure 4.6:*** Multi-scalar overlay of population density at the county and stream reach scale. The elevation (x-axis) changes for each graph. The top graph's y-axis remains constant from 0-250 population/km$^2$, while the lower graphs share the same y-axis at 0-600 population/km$^2$. The 1990 population is shown on the graphs and is the lighter shade. The most populated urban area for each county is shown on the map at the mean elevation for the urban area.

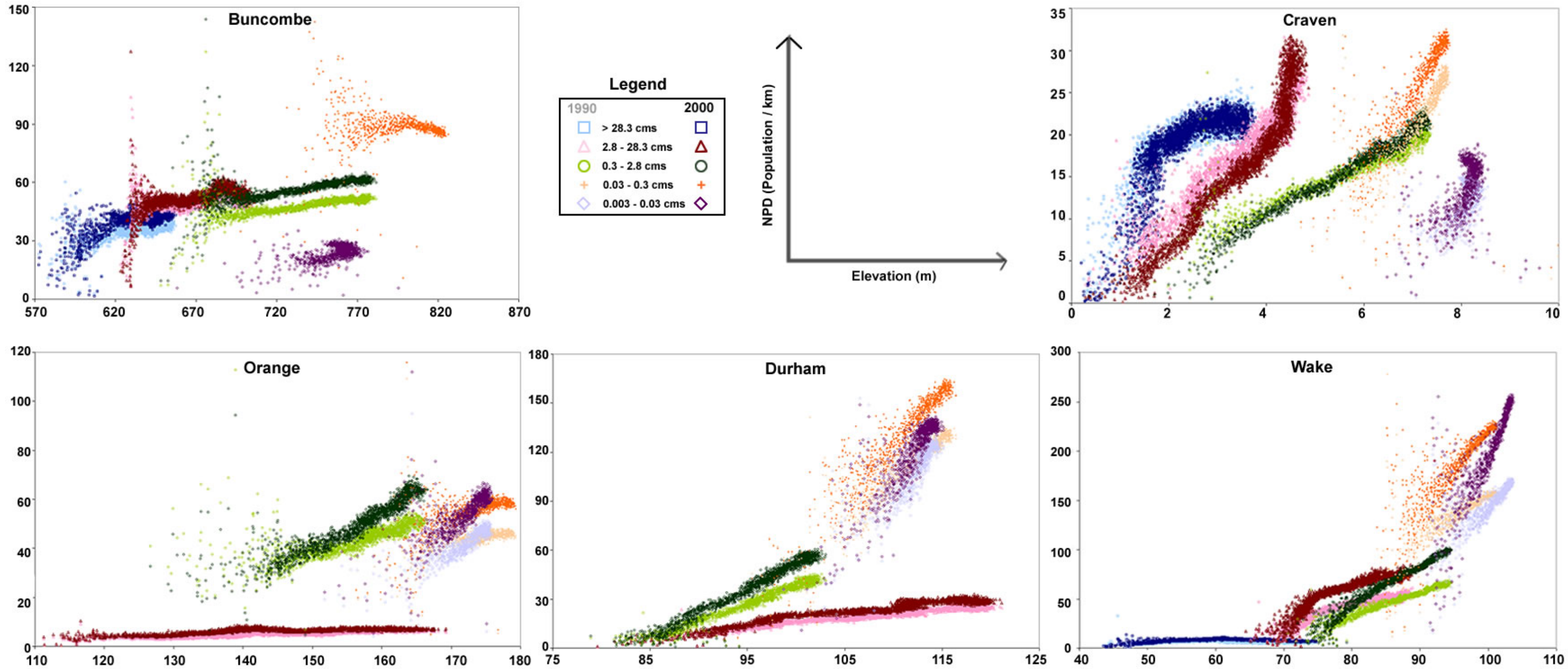


***Figure 4.7:*** Normalized Population Density as a function of elevation. Note the change in elevation (x-axis) and the y-axis (normalized population. The NPD takes into account the population density and actual population values when creating the catena. The 1990 population is shown on the graphs and is the lighter shade.

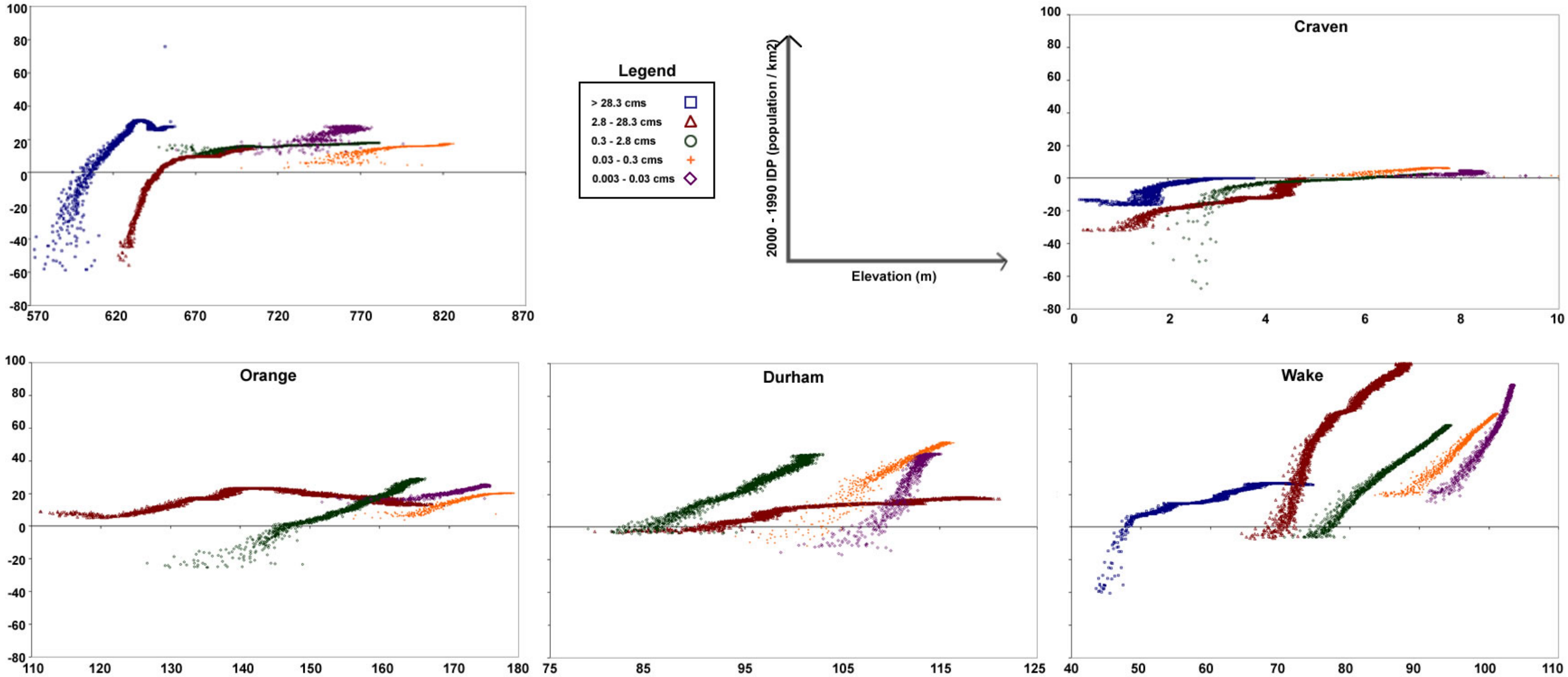


***Figure 4.8:*** Change in IPD from 1990 to 2000. The y-axis remains constant with a maximum density change of 100 persons/km$^2$ and a minimum density change of -80 persons/km$^2$. The elevation (x-axis) values change for each county.

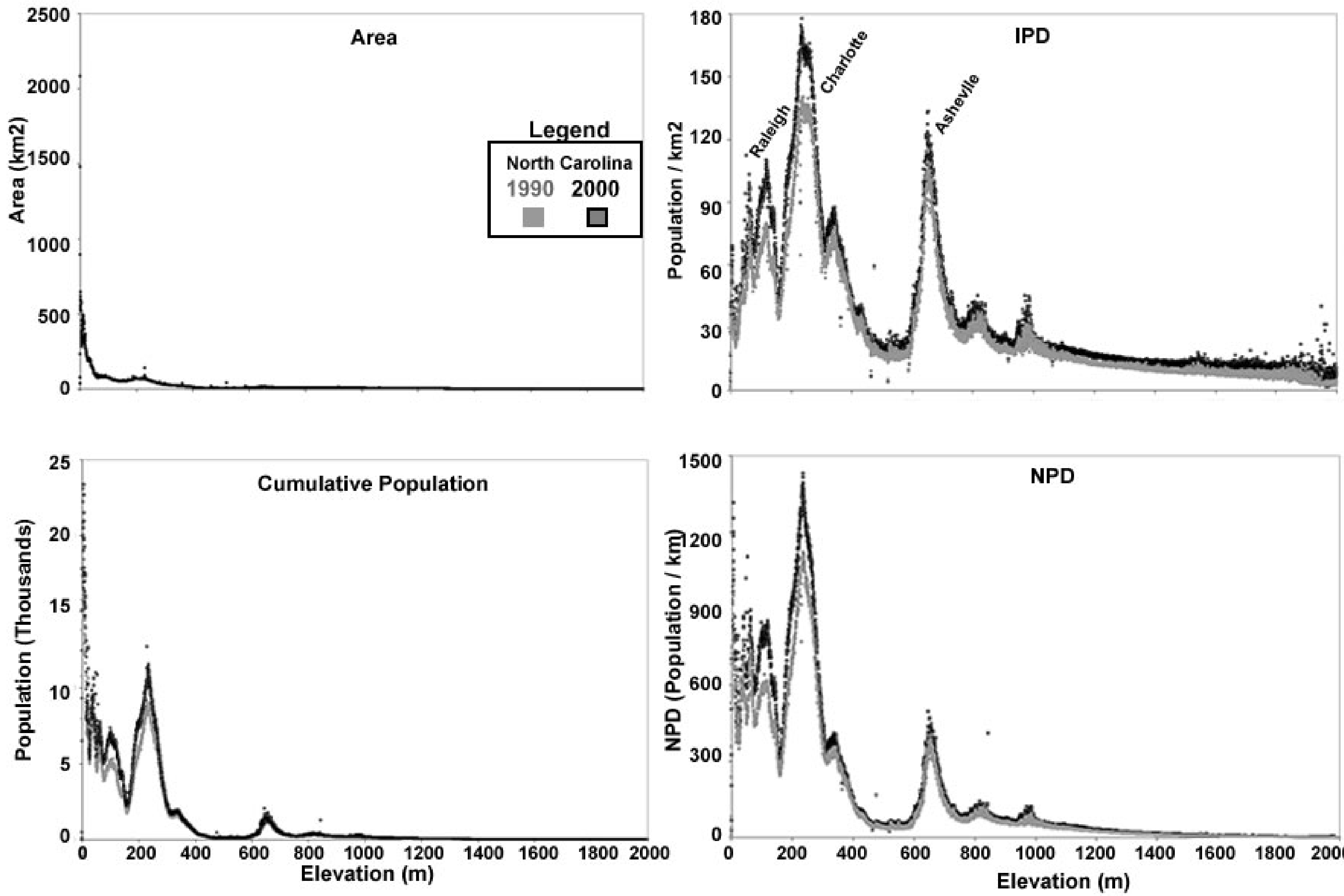


**Figure 4.9** State scale area, population, IPD and NPD catena. Note that the balance between population and area provides a different trend when examining the densities of development, and urban areas drive catena trends and areas of major increase from 1990 to 2000.

# CHAPTER 5

## CONCLUSION ON THE EXPLORATORY ANALYSIS OF FLOOD HAZARDS AND POLICY IMPLICATIONS

Flood losses have increased over the last century despite flood policies and management efforts. The increase in losses suggests that flood hazards and human development are spatially intersecting either due to increasing development of floodplain, increasing flood extents, or a combination of those factors (Mitchell, 2006). The persistent and insegrevious rate of increasing flood losses indicates that current floodplain development and policies are not sustainable.

The goal for developing sustainable floodplains is to both reduce socioeconomic losses and create resilient communities (Mileti, 1999). A cornerstone supporting the development and maintenance of sustainable communities in floodplains relies on a policy that takes a precautionary approach when dealing with system uncertainty (Mitchell, 2002). Floods are stochastic, data is missing or of poor quality, and assumptions must be made in models that delineate the 100-yr floodplain, which serves as the minimum standard for implementing flood policies. Currently, no uncertainty is displayed on maps guiding the management of our floodplain, nor has the 100-yr floodplain been fully accepted as being restrictive enough to reduce flood losses to a sustainable level.

North Carolina has embraced the concept of sustainable development for floodplains after several hurricanes in the 1990s impacted over 60% of the population and led both policy makers and the public to view natural hazards as an important component of developing communities that are resilient to flood events (NCDEM, 2007). Furthermore, North Carolina has recognized that managing floodplains for sustainability requires measuring the success of policies to reduce flood losses using quantifiable indicators (NCDEM, 2007). With respect to floodplain management, the broad goal is to reduce flood losses, which are increasing due to the increasing intersection of people and property to the flood hazard. Thus, people and property value are tangible measures that can be used as indicators for monitoring.

The objective of this thesis was to measure the success of five counties in North Carolina in reducing flood losses by quantifying changes in social and economic exposure at multiple scales. The methodology used only freely available data to enable consistent analysis of exposure and hazards throughout the study area. Furthermore, the North Carolina Department of Emergency Management has emphasized the conduction of hazard vulnerability assessments using GIS (NCDEM, 2007), which was done throughout this thesis. The effectiveness of mitigation policies was assessed by quantifying changes in exposure prior to the 1994 mitigation policy, as well as inside and adjacent to the 100-yr floodplain. The analysis was performed at multiple spatial scales for the benefit of policy decision-makers wanting to assess exposure at the state and local planning scale, in order to determine where funding should be focused to be most cost effective.

Chapter 2 focused on county scale changes in flood exposure. Socioeconomic exposure inside the 100-yr FIRM decreased from 1990 to 2000; thereby indicating flood policy was effective at removing development from the 100-yr floodplain and theoretically reducing future flood losses. On the other hand, exposure adjacent to the 100-yr floodplain increased during the same period. It was hypothesized that the increase in exposure adjacent to the 100-yr floodplain was a result of 1) no regulations required outside the 100-yr floodplain and 2) not indicating the level of uncertainty on the location of the floodplain boundary in FIRMs. The presence of increased exposure is significant because 66-82% of flood losses occur outside the 100-yr floodplain (Burby, 2002). Lastly, the production of DFIRMs, which are believed to be more accurate than FIRMs, did not cover as much socioeconomic value, and could result in increased flood losses as new areas become available for unregulated development.

The exploratory analysis in Chapter 3 was spatially more localized and considered the regional context by calculating exposure as it related to fluvial proximity, stream size, development density, and the presence of FIRMs. The study found streams with flow greater than 2.8 cms typically had less dense development than the smaller streams and development densities increased with increasing distance from the streams. Either flood policy or history has led communities to regard large floodplains as not being as safe for development as the smaller floodplains. The most significant change in population density from 1990 to 2000 occurred in urban areas as people moved out of the larger streams in Buncombe and Craven, while moving into the smaller streams throughout the entire study area. Furthermore, the greatest change in density was located near the stream when population decreased and farthest away from the stream when population increased. Floodplain management was most effective in the large, urban streams of Buncombe and Craven, while having little effect elsewhere. Both counties had experienced large flood losses from several hurricanes, such as Fran (1996) and Floyd (1999) (NCDC, 2004; Dorman & Bakolia, 2002) and have become active in mitigating their floodplains by removing structures and limiting development. In contrast, rural development throughout the study area increased by the same amount in all stream and at all fluvial proximities; thereby, indicating little effect from flood policies. Lastly, it was found that socioeconomic exposure density increased significantly adjacent to the 100-yr floodplain, especially in the smaller streams of the rapidly urbanizing Piedmont. Floodplain management officials should be aware that development adjacent to the 100-yr floodplain was most prominent in the smaller, urbanizing streams.

Chapter 4 examined socioeconomic exposure as a function of elevation at multiple spatial scales to assess the potential for establishing FIRMs using elevation criteria; thereby reducing some of the uncertainty in transforming vertical elevation to horizontal distances when delineating the 100-yr floodplain. Creating a human catena of population density to elevation by stream size from 1990 to 2000 showed changing human exposure along a vertical profile. Furthermore, because large streams are at lower elevations than the smaller headwater streams, this method of displaying exposure allowed the separation of population distributions by stream flow to be observed on the same plot. From this profile, it was evident that populations in Buncombe and Craven were reduced in the floodplains of larger rivers beneath a specific elevation. Above this elevation and in the smaller rivers, these same counties had an increase in population from 1990 to 2000. Furthermore, by considering the changes in elevation (120 m in Buncombe versus 5 m in Craven) from the location of the largest to the smallest river elevations would assist policy makers in understanding the potential impact of a few decimeters of uncertainty for the 100-yr flood on impacting populations. Lastly, the Piedmont had a small decrease in population at the lowest elevations of the stream reaches, with significant increases at higher elevations. This indicated floodplain management for the Piedmont was only successful at the lowest areas of the floodplain where floods are more frequent and losses more repetitive, and management needs to focus on the smaller, urbanizing streams to reduce future potential losses.

The spatial distribution of socioeconomic exposure variables can spatially guide local officials in concentrating floodplain mitigation efforts on reducing potential future flood losses in the areas with greatest risk. The impact of natural events on any given community is not random but determined by everyday patterns of social interaction (Morrow, 1999). Each community is inherently different in its flood history, local floodplain management agency, degree of urbanization and general attitude regarding flood losses. All these factors have influenced the spatial distribution of socioeconomic exposure in the study area. Since risk is a function of the intersection between the spatial location of a hazard and socioeconomic value, the risk of flood losses is greatest when people and property are highly concentrated on the floodplain. Floodplain management activities need to focus on reducing the exposure of urbanized areas to the most significant flood expected to occur at the current temporal point in space (IFMRC, 1994). The high density exposure in urban floodplains, requires managers to be especially vigilant in monitoring the spatial changes in distribution through time to assess the effectiveness of flood policy in reducing exposure.

Currently floodplain policy changes have been reactive; whereby, catastrophic flood losses are driving the changes in policy. This research project promoted a more passive approach by monitoring changes in floodplain exposure with quantifiable indicators to assess policy effectiveness and to reassess policy or management approaches if exposure was not reduced (Figure 5.1). The recognition that development in floodplains increases exposure to flooding and is culminating in increased flood losses suggests the potential for decreasing future flood impacts requires a refocusing of floodplain management. After Hurricane Fran in 1996, North Carolina refocused on hazard mitigation for sustainable development, which resulted in the decrease of exposure in the two sites most impacted by flooding in the 1990s for this study area (NCDEM, 2007). Furthermore, the reduction of exposure in the floodplains of these counties, especially for the larger streams, showed management has been effective at reducing floodplain development, while the national trend has been to increase floodplain development (Pinter, 2005 & Burby, 2002). Additionally, North Carolina has focused on increasing spatial data and accessibility for hazard vulnerability analyses (NCDEM, 2007; Dorman & Bakolia, 2002). The use of GIS technologies and spatial data to create higher resolution analyses will enable policy-makers to discern where how effective floodplain management has been; thereby, enabling managers to focus their resources on reducing risk in highly exposed areas.

The long arm of floodplain management is based on FIRMs, which are derived as an elevation and extrapolated into a horizontal boundary that adds additional uncertainty and removes the topographic profile of the floodplain. The human catena displayed exposure as a function of elevation, removing the horizontal uncertainty, and enabling policy makers to see the difference in exposure impact for a flood stage at the 100-yr versus 500-yr event on socioeconomic exposure. Furthermore, by subdividing exposure analysis by stream size, which relates the potential magnitude of the flood experienced, it would enable adaptive management for the magnitude of the flood that should be managed in relation to its potential effect on the socioeconomic assets within the floodplain (IFMRC, 1994). According to James (2004), an objective approach to floodplain management requires discontinuing the use of the 100-yr floodplain and instead uses the “fundamental principles from economic analysis, environmental quality, and social well-being” in delineating FIRMs. The risk based approach would also alleviate the problem of the 100-yr flood standard in not addressing the risk of larger floods to floodplain occupants located outside the 100-yr boundary (Davis, 2004). A potential solution would be to maintain the 100-yr floodplain standard as a bare minimum, and utilize the precautionary principle in those areas where risk-based analysis indicates a high potential for flood loss outside the 100-yr boundary. Regardless of the baseline standard used, now is the time for floodplain management to become actively adaptive in their management by monitoring, evaluating and adjusting floodplain policy before the next catastrophic event.

**5.1 Figures:**

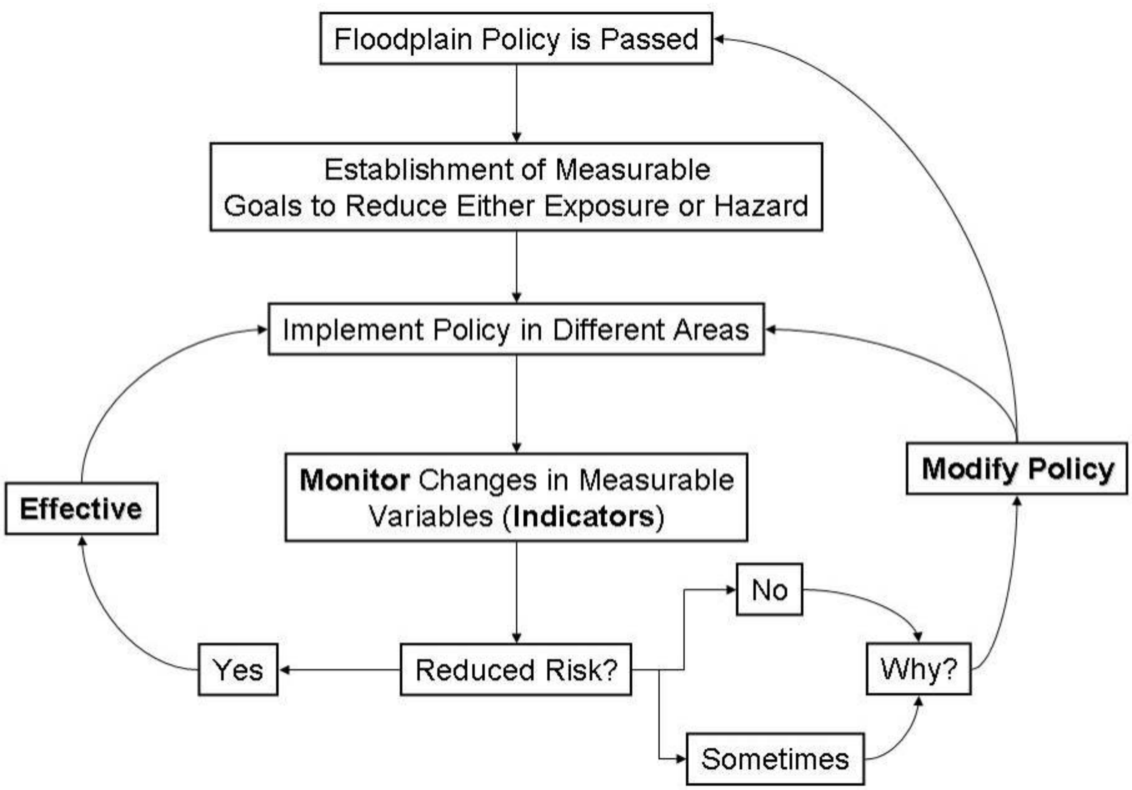


**Figure 5.1:** Use of indicators and monitoring to assess policy effectiveness. Modifications of policy are made to enhance successfulness of the policy.

# APPENDIX

## (TEMPORAL) FLOOD LOSS EXPOSURE MODEL PROGRAM FOR CHAPTER 2

**Data Preparation Form**

```
'Declare Variables:
Dim pMxDoc As IMxDocument
Dim pMap As IMap
Dim pSRFactory As ISpatialReferenceFactory
Dim pPrjCoordSys As IProjectedCoordinateSystem
Dim gp As Object
Dim Workspace As String
Dim InputFile As String
Dim OutputFile As String
Dim County As String
Dim pLayer As ILayer
Dim File As String

'Declarations for vector features
Dim pFactory As IWorkspaceFactory
Dim pFWorkspace As IWorkspace
Dim pFeatureWorkspace As IFeatureWorkspace
Dim pFClass As IFeatureClass
Dim pFLayer As IFeatureLayer

'Delcarations for raster features
Dim pRWorkspace As IRasterWorkspace
Dim pRasterDataset As IRasterDataset
Dim pRasterLayer As IRasterLayer
Dim pRaster As IRaster
Dim pRasterProps As IRasterProps
Dim pCell As IPoint
Dim pRGeoProcess As IRasterGeometryProc
Dim pSpatRefFac As ISpatialReferenceFactory2
Dim pSpatRef As ISpatialReference
Dim pRasterBandCollection As IRasterBandCollection
Dim pOutWS As IWorkspace
Dim pOutWSF As IWorkspaceFactory
Dim strOutType As String
Dim pRLayer1 As IRasterLayer

'Set up the workspace and GUI form
Private Sub cboCounty_Change()
  If cboCounty.Value = "Craven" Then
    'set gp workspace to Craven County
    Workspace = "C:\MyDocs\Masters\Craven"
    County = "Craven"
  ElseIf cboCounty.Value = "Buncombe" Then
    'set gp workspace to Buncombe County
    Workspace = "C:\MyDocs\Masters\Buncombe"
    County = "Bunco"
  ElseIf cboCounty.Value = "Durham" Then
    'set up gp workspace to Durham County
    Workspace = "C:\MyDocs\Masters\Durham"
    County = "Durham"
```

```
    ElseIf cboCounty.Value = "Orange" Then
        'set up gp workspace to Orange County
        Workspace = "C:\MyDocs\Masters\Orange"
        County = "Orange"
    ElseIf cboCounty.Value = "Wake" Then
        'set gp workspace to Wake County
        Workspace = "C:\MyDocs\Masters\Wake"
        County = "Wake"
    Else
        cmdProject.Enabled = False
        cmdAdd.Enabled = False
        cmdClip.Enabled = False
    End If
End Sub

'Add layers to the ArcMap
Public Sub cmdAdd_Click()
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap

    Call AddRaster(County & "DEM", Workspace & "\Projected")
    Call AddRaster(County & "NLCD", Workspace & "\Projected")

    Call AddFeature(County & "County", Workspace & "\Projected")
    Call AddFeature("Pop" & County & "00", Workspace & "\Projected")
    Call AddFeature("Parcel", Workspace & "\Projected")
    If County = "Bunco" Then
    Else
        Call AddFeature(County & "DFIRMS", Workspace & "\Projected")
    End If

    pMxDoc.ActiveView.Refresh
    Unload frmDataPrep
End Sub

'Function that adds raster to ArcMap
Public Sub AddRaster(LayerName As String, InputFile As String)
    Set pFactory = New RasterWorkspaceFactory
    Set pRWorkspace = pFactory.OpenFromFile(InputFile, 0)
    Set pRasterDataset = pRWorkspace.OpenRasterDataset(LayerName)
    Set pRasterLayer = New RasterLayer
    pRasterLayer.CreateFromDataset pRasterDataset
    pRasterLayer.Name = LayerName
    Set pLayer = pRasterLayer
    pMxDoc.AddLayer pLayer

    Set pFactory = Nothing
    Set pRWorkspace = Nothing
    Set pRasterDataset = Nothing
    Set pRasterLayer = Nothing
    Set pLayer = Nothing
End Sub

'Function that adds feature to ArcMap
Public Sub AddFeature(LayerName As String, InputFile As String)
    Set pFactory = New ShapefileWorkspaceFactory
```

```
    Set pFeatureWorkspace = pFactory.OpenFromFile(InputFile, 0)
    Set pFClass = pFeatureWorkspace.OpenFeatureClass(LayerName & ".shp")
    Set pFLayer = New FeatureLayer
    Set pFLayer.FeatureClass = pFClass
    pFLayer.Name = LayerName
    pMap.AddLayer pFLayer

    Set pFactory = Nothing
    Set pFClass = Nothing
    Set pFeatureWorkspace = Nothing
    Set pFLayer = Nothing
End Sub

'Clips all layers to the county boundary
Public Sub cmdClip_Click()
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap

    'Create Geoprocessor Object
    Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
    'check out necessary licenses
    gp.CheckOutExtension "spatial"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"

    'Check to see if files already exist
    File = Workspace & "\Projected\" & County & "County.shp"
    If gp.Exists(File) Then
        MsgBox "The County file has already been clipped."
    Else
        'Call the ClipCounty Public Sub
        Call ClipCounty(County, Workspace & "\Projected\County.shp", Workspace & "\Projected\" & County &
"County.shp")
    End If

    'Create the file to clip all other files too.
    Dim ClipFile As String
    ClipFile = Workspace & "\Projected\" & County & "County.shp"

    File = Workspace & "\Projected\" & County & "DFIRMS.shp"
    If gp.Exists(File) Then
        MsgBox "The DFIRM file has already been clipped."
    Else
        If County = "Bunco" Then
            MsgBox "No DFIRM file exists for Buncombe county."
        Else
            Call ClipDFIRMS(Workspace & "\Projected\DFIRMS.shp", Workspace & "\Projected\" & County &
"DFIRMS.shp", ClipFile)
        End If
    End If

    File = Workspace & "\Projected\FIRM.shp"
    If gp.Exists(File) Then
        MsgBox "The FIRM file has already been clipped."
    Else
```

```
        Call ClipFIRMS(Workspace & "\Projected\FIRM.shp", Workspace & "\Projected\" & County &
"FIRM.shp", ClipFile)
    End If

    File = Workspace & "\Projected\" & County & "NLCD.aux"
    If gp.Exists(File) Then
        MsgBox "The NLCD file has already been clipped."
    Else
        Call MaskNLCD(Workspace & "\Projected\NLCD" & County, Workspace & "\Projected\" & County &
"NLCD", ClipFile)
    End If

    File = Workspace & "\Projected\" & County & "DEM"
    If gp.Exists(File) Then
        MsgBox "The lidar dem file has already been clipped."
    Else
        'Have to write down the name of raster created for later entry
        Dim LidarRaster As String
        LidarRaster = InputBox("Enter the name of the projected lidar raster")
        Call MaskLidar(Workspace & "\Projected\" & LidarRaster, Workspace & "\Projected\" & County &
"DEM")
    End If

    Call DeleteAllLayers
End Sub

'Extracts county of interest in study area
Public Sub ClipCounty(LayerName As String, InputFile As String, OutputFile As String)
    'Process Select by attribute
    If LayerName = "Craven" Then
        gp.Select_analysis InputFile, OutputFile, """CONM"" = 'Craven'"
    ElseIf LayerName = "Wake" Then
        gp.Select_analysis InputFile, OutputFile, """CONM"" = 'Wake'"
    ElseIf LayerName = "Bunco" Then
        gp.Select_analysis InputFile, OutputFile, """CO_NAME"" = 'Buncombe'"
    ElseIf LayerName = "Durham" Then
        gp.Select_analysis InputFile, OutputFile, """CONM"" = 'Durham'"
    Else
        gp.Select_analysis InputFile, OutputFile, """CONM"" = 'Orange'"
    End If
    MsgBox LayerName & " county has been successfully extracted"
End Sub

'Clips DFIRM to study area
Public Sub ClipDFIRMS(InputFile As String, OutputFile As String, ClipFile As String)
    'Process Clip DFIRMS to County Extracted File
    gp.Clip_analysis InputFile, ClipFile, OutputFile, ""
    MsgBox County & " DFIRM has successfully been extracted"
End Sub

'Clips FIRM to study area
Public Sub ClipFIRMS(InputFile As String, OutputFile As String, ClipFile As String)
    'Process Clip FIRMS to County Extracted File
    gp.Clip_analysis InputFile, ClipFile, OutputFile, ""
    MsgBox County & " FIRM has successfully been extracted"
End Sub
```

```
'Masks raster data to study area
Public Sub MaskNLCD(InputFile As String, OutputFile As String, ClipFile As String)
'Process Extract by Mask the NLCD layer to the County layer
   gp.ExtractByMask_sa InputFile, ClipFile, OutputFile
   MsgBox County & " NLCD has successfully been extracted"
End Sub

Public Sub MaskLidar(InputFile As String, OutputFile As String)
'Process Extract by Attributes the Lidar M layer
   gp.ExtractByAttributes_sa InputFile, "Value > -9900", OutputFile
   MsgBox County & " Lidar DEM has successfully been extracted"
End Sub

'Repeats above process for 1990 data
Public Sub cmdPopTime_Click()
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")

   'check out necessary licenses
   File = Workspace & "\Projected\Pop" & County & "80.shp"

   If gp.Exists(File) Then
      MsgBox "The population data has already been projected."
   Else
      Call ProjectFeatures(Workspace + "\Raw\Population\" + County + "90.shp", Workspace +
"\Projected\Pop" + County + "90.shp")
   End If

   File = Workspace & "\Projected\NLCD92" & County & ".aux"
   If gp.Exists(File) Then
      MsgBox "The 1992 Landcover has already been projected."
   Else
      Call NLCDProject("NLCD92.tif", Workspace & "\Raw", Workspace + "\Projected\NLCD92" + County)
   End If

'Clip the 1992 Landcover Data
   Dim ClipFile As String
   ClipFile = Workspace & "\Projected\" & County & "County.shp"

   Call MaskNLCD(Workspace & "\Projected\NLCD92" & County, Workspace & "\Projected\" & County &
"NLCD92", ClipFile)
   Call DeleteAllLayers

   Call AddFeature("Pop" & County & "80", Workspace & "\Projected")
   Call AddFeature("Pop" & County & "90", Workspace & "\Projected")
   Call AddRaster(County & "NLCD92", Workspace & "\Projected")
   Unload frmDataPrep
End Sub

Public Sub cmdProject_Click()
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
'Check to see if the file already exists
```

```
    File = Workspace & "\Projected\Pop" & County & "00.shp"

    If gp.Exists(File) Then
        MsgBox "The population data has already been projected."
    Else
        Call ProjectFeatures(Workspace + "\Raw\Population\" + County + "00.shp", Workspace +
"\Projected\Pop" + County + "00.shp")
    End If

    File = Workspace & "\Projected\FIRM.shp"
    If gp.Exists(File) Then
        MsgBox "The FIRM data has already been projected."
    Else
        Call ProjectFeatures(Workspace + "\Raw\Floodmap\FIRM.shp", Workspace + "\Projected\FIRM.shp")
    End If

    File = Workspace & "\Projected\County.shp"
    If gp.Exists(File) Then
        MsgBox "The floodmap data has already been projected."
    Else
        Call CreateProjection("County_Area", Workspace + "\Raw\Floodmap")
        Call ProjectFeatures(Workspace + "\Raw\Floodmap\County_Area.shp", Workspace +
"\Projected\County.shp")

        Call CreateProjection("Flood_Hazards", Workspace + "\Raw\Floodmap")
        Call ProjectFeatures(Workspace + "\Raw\Floodmap\Flood_Hazards.shp", Workspace +
"\Projected\DFIRMS.shp")
    End If

    File = Workspace & "\Projected\Parcel.shp"
    If gp.Exists(File) Then
        MsgBox "The parcel, NLCD, and Lidar data have already been projected."
        Unload frmDataPrep
    Else
    'Projects Parcel data
        Call CreateProjection("Parcel", Workspace + "\Raw\Parcel")
        Call ProjectFeatures(Workspace + "\Raw\Parcel\Parcel.shp", Workspace + "\Projected\Parcel.shp")
        If County = "Craven" Then
            MsgBox "Add a bldvalue and landvalue double field and set equal to related tax columns (currently
strings). Not coded yet."
        Else
        End If

     'Projects NLCD 2001 data
        If County = "Craven" Then
            Call NLCDProject("02377525.tif", Workspace + "\Raw", Workspace + "\Projected\NLCD" + County)
        ElseIf County = "Wake" Then
            Call NLCDProject("56875972.tif", Workspace & "\Raw", Workspace + "\Projected\NLCD" + County)
        ElseIf County = "Bunco" Then
            Call NLCDProject("29985859.tif", Workspace & "\Raw", Workspace + "\Projected\NLCD" + County)
        Else
            Call NLCDProject("NLCD01.tif", Workspace & "\Raw", Workspace + "\Projected\NLCD" + County)
        End If

     'Projects Lidar data
        Call LidarProject(County + "20ft", Workspace + "\Raw")
```

```
    End If

    Call DeleteAllLayers
End Sub

'Remove all layers from the ArcMap
Public Sub DeleteAllLayers()
    For i = 0 To pMap.LayerCount - 1
        Dim pLayer As ILayer
        Set pLayer = pMap.Layer(0)
        pMap.DeleteLayer pLayer
    Next i

    pMxDoc.ActiveView.Refresh
End Sub

'Projects features to Nad1983 (m)
Public Sub ProjectFeatures(InputFile As String, OutputFile As String)
'Set Data Frame Projection
    'Create Projection for the Map
    Set pSRFactory = New SpatialReferenceEnvironment
    'Set the projected coordinate system equal to North Carolina State Plane, NAD 1983 (m)
    Set pPrjCoordSys = pSRFactory.CreateProjectedCoordinateSystem(32119)
    Set pMap.SpatialReference = pPrjCoordSys
    'Set the map units
    Dim pLinearUnit As ILinearUnit
    Dim pUnit As IUnit
    Set pUnit = pSRFactory.CreateUnit(esriSRUnit_Meter)
    Set pLinearUnit = pUnit
    'Tell the user which projection they are in
    MsgBox "The projection is " & pMap.SpatialReference.Name & " " & pLinearUnit.Name

    'Create the Geoprocessor Object
    Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
    gp.OverwriteOutput = 1
    'Load required toolboxes
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management Tools.tbx"

    If InputFile = Workspace + "\Raw\Population\" + County + "00.shp" Or InputFile = Workspace +
"\Raw\Floodmap\FIRM.shp" Then
        gp.Project_management InputFile, OutputFile,
"PROJCS['NAD_1983_StatePlane_North_Carolina_FIPS_3200',GEOGCS['GCS_North_American_1983',DAT
UM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0
.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Lambert_Conformal_Conic'],PARAMETER['False_
Easting',609601.22],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
79.0],PARAMETER['Standard_Parallel_1',34.33333333333334],PARAMETER['Standard_Parallel_2',36.1666
6666666666],PARAMETER['Latitude_Of_Origin',33.75],UNIT['Meter',1.0]]",
"NAD_1983_To_WGS_1984_1"
    ElseIf InputFile = Workspace & "\Raw\Population\" & County & "80.shp" Then
        gp.Project_management InputFile, OutputFile,
"PROJCS['NAD_1983_StatePlane_North_Carolina_FIPS_3200',GEOGCS['GCS_North_American_1983',DAT
UM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0
.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Lambert_Conformal_Conic'],PARAMETER['False_
Easting',609601.22],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
79.0],PARAMETER['Standard_Parallel_1',34.33333333333334],PARAMETER['Standard_Parallel_2',36.1666
6666666666],PARAMETER['Latitude_Of_Origin',33.75],UNIT['Meter',1.0]]", ""
```

```
    ElseIf InputFile = Workspace & "\Raw\Population\" & County & "90.shp" Then
        gp.Project_management InputFile, OutputFile,
"PROJCS['NAD_1983_StatePlane_North_Carolina_FIPS_3200',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Lambert_Conformal_Conic'],PARAMETER['False_Easting',609601.22],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-79.0],PARAMETER['Standard_Parallel_1',34.33333333333334],PARAMETER['Standard_Parallel_2',36.16666666666666],PARAMETER['Latitude_Of_Origin',33.75],UNIT['Meter',1.0]]", ""
    Else
        gp.Project_management InputFile, OutputFile,
"PROJCS['NAD_1983_StatePlane_North_Carolina_FIPS_3200',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Lambert_Conformal_Conic'],PARAMETER['False_Easting',609601.22],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-79.0],PARAMETER['Standard_Parallel_1',34.33333333333334],PARAMETER['Standard_Parallel_2',36.16666666666666],PARAMETER['Latitude_Of_Origin',33.75],UNIT['Meter',1.0]]"
    End If
    MsgBox "The " & OutputFile & " was successfully projected"
End Sub

Public Sub CreateProjection(LayerName As String, InputFile As String)
 'Create County Data, Flood Hazards, Flood Hazard Lines and Parks and Save to Projection File
    'Get shapefile workspace
    Set pFactory = New ShapefileWorkspaceFactory
    Set pFWorkspace = pFactory.OpenFromFile(InputFile, 0)

    Set pFeatureWorkspace = pFWorkspace
    Set pFClass = pFeatureWorkspace.OpenFeatureClass(LayerName)

    'Create layer
    Set pFLayer = New FeatureLayer
    Set pFLayer.FeatureClass = pFClass

    Set pSRFactory = New SpatialReferenceEnvironment
    'Set the projected coordinate Systems equal to North Carolina State Plane, NAD 1983 (ft) - original projection
    Dim pProjcoordSys As IProjectedCoordinateSystem
    Set pProjcoordSys = pSRFactory.CreateProjectedCoordinateSystem(2264)

    'alter the target layer's spatial reference
    Dim pGeoDataset As IGeoDataset
    Set pGeoDataset = pFLayer.FeatureClass

    Dim pGeoDatasetEdit As IGeoDatasetSchemaEdit
    Set pGeoDatasetEdit = pGeoDataset
    pGeoDatasetEdit.AlterSpatialReference pProjcoordSys

    Dim pTargetSR As ISpatialReference
    Set pTargetSR = pGeoDataset.SpatialReference
    MsgBox "The new spatial reference for " & pFLayer.Name & " is " & pTargetSR.Name
    gp.Project_management InputFile & "\" & LayerName & ".shp", InputFile & "\" & LayerName & ".prj",
"PROJCS['NAD_1983_StatePlane_North_Carolina_FIPS_3200',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Lambert_Conformal_Conic'],PARAMETER['False_Easting',609601.22],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
```

```
79.0],PARAMETER['Standard_Parallel_1',34.33333333333334],PARAMETER['Standard_Parallel_2',36.1666
6666666666],PARAMETER['Latitude_Of_Origin',33.75],UNIT['Meter',1.0]]"
   MsgBox "The " & LayerName & " was successfully projected"
End Sub

Public Sub NLCDProject(LayerName As String, InputFile As String, OutputFile As String)
'Create Raster Projection File for NLCD
   'Get Raster workspace
   Set pFactory = New RasterWorkspaceFactory
   'Open Raster workspace
   Set pRWorkspace = pFactory.OpenFromFile(InputFile, 0)

   'Open Raster dataset
   Set pRasterDataset = pRWorkspace.OpenRasterDataset(LayerName)
   ' Change from Raster Dataset to Raster Layer

   Set pRasterLayer = New RasterLayer
   pRasterLayer.CreateFromDataset pRasterDataset

   'Instantiate the raster from the raster layer
   Set pRaster = pRasterLayer.Raster
   Set pRasterProps = pRaster

   'Get the current cell size
   Set pCell = New Point
   pCell.X = pRasterProps.MeanCellSize.X
   pCell.Y = pRasterProps.MeanCellSize.Y

   'Create a new raster geometry process
   Set pRGeoProcess = New RasterGeometryProc

   'Set the spatial reference to NC FIPS NAD83 M
   Set pSpatRefFac = New SpatialReferenceEnvironment
   Set pSpatRef = pSpatRefFac.CreateProjectedCoordinateSystem(32119)

   'Project the image to the new spatial refrence
   pRGeoProcess.ProjectFast pSpatRef, RSP_NearestNeighbor, , pRaster

   'Instantiate a new Raster Band Collection
   Set pRasterBandCollection = pRaster

   'Set output workspace
   Set pOutWSF = New RasterWorkspaceFactory
   Set pOutWS = pOutWSF.OpenFromFile(Workspace & "\Projected", 0)

   'Set the output
   OutputFile = Workspace + "\Projected\NLCD" + County
   strOutType = "GRID"

   pRasterBandCollection.SaveAs OutputFile, pOutWS, strOutType
   MsgBox "The NLCD File was successfully projected"

   'Clean the objects out of memory
   Set pFactory = Nothing
   Set pRasterWorkspace = Nothing
   Set pRasterDataset = Nothing
```

```
    Set pRaster = Nothing
    Set pRasterProps = Nothing
    Set pCell = Nothing
    Set pRGeoProcess = Nothing
    Set pSpatRefFac = Nothing
    Set pSpatRef = Nothing
    Set pRasterBandCollection = Nothing
End Sub

Public Sub LidarProject(LayerName As String, InputFile As String)
'Transform Lidar 20ft DEM into Meters
     'Get Raster workspace
    Set pFactory = New RasterWorkspaceFactory
    'Open Raster workspace
    Set pRWorkspace = pFactory.OpenFromFile(InputFile, 0)
    'Open Raster dataset
    Set pRasterDataset = pRWorkspace.OpenRasterDataset(LayerName)
    ' Change from Raster Dataset to Raster Layer
    Set pRasterLayer = New RasterLayer
    pRasterLayer.CreateFromDataset pRasterDataset

    'Instantiate the raster from the raster layer
    Set pRaster = pRasterLayer.Raster
    Set pRasterProps = pRaster

    'Get the current cell size
    Set pCell = New Point
    pCell.X = pRasterProps.MeanCellSize.X
    pCell.Y = pRasterProps.MeanCellSize.Y

    'Create a new raster geometry process
    Set pRGeoProcess = New RasterGeometryProc

    'Set the spatial reference to NC FIPS NAD83 M
    Set pSpatRefFac = New SpatialReferenceEnvironment
    Set pSpatRef = pSpatRefFac.CreateProjectedCoordinateSystem(32119)

    'Project the image to the new spatial refrence
    pRGeoProcess.ProjectFast pSpatRef, RSP_NearestNeighbor, , pRaster

    'Instantiate a new Raster Band Collection
    Set pRasterBandCollection = pRaster

    'Set the output
    OutputFile = Workspace + "\projected\" + County + "M"
    strOutType = "GRID"

    pRasterBandCollection.SaveAs OutputFile, pRWorkspace, strOutType
    MsgBox "The " + LayerName + "toM was successfully projected"

    'Clean the objects out of memory
    Set pFactory = Nothing
    Set pRWorkspace = Nothing
    Set pRasterDataset = Nothing
    Set pRaster = Nothing
    Set pRasterProps = Nothing
```

```
Set pCell = Nothing
Set pRGeoProcess = Nothing
Set pSpatRefFac = Nothing
Set pSpatRef = Nothing
Set pRasterBandCollection = Nothing

'Set pEnv.OutWorkspace = pRWorkspace
Set pFactory = New RasterWorkspaceFactory
Set pRWorkspace = pFactory.OpenFromFile(InputFile, 0)
Set pRasterDataset = pRWorkspace.OpenRasterDataset(County + "M")
Set pRasterLayer = New RasterLayer
pRasterLayer.CreateFromDataset pRasterDataset
Set pRaster = pRasterLayer.Raster

 'Create the MathOps object
Dim pMathOp As IMathOp
Set pMathOp = New RasterMathOps

' Declare the input geoDataset1 object
Dim pInputDataset1 As IGeoDataset

' Calls function to open a raster dataset from disk
Set pInputDataset1 = pRasterLayer

Dim pRModel As IRasterModel
Set pRModel = New RasterModel
Dim pEnv As IRasterAnalysisEnvironment
Set pEnv = pRModel

'Set output workspace
Dim pOutWS As IWorkspace
Dim pOutWSF As IWorkspaceFactory
Set pOutWSF = New RasterWorkspaceFactory
Set pOutWS = pOutWSF.OpenFromFile(Workspace & "\Projected", 0)
Set pEnv.OutWorkspace = pOutWS

pRModel.Script = "[out] = [input1] * 0.3048"

pRModel.BindRaster pRaster, "input1"
pRModel.Execute

Dim pRasterOutput As IRaster
Set pRasterOutput = pRModel.BoundRaster("out")

pRModel.UnbindSymbol "input1"
Set pRLayer1 = New RasterLayer

Dim pRWS2 As IRasterWorkspace
Set pRWS2 = pOutWSF.OpenFromFile(Workspace & "\Projected", 0)
Dim pRDataset1 As IRasterDataset

pRLayer1.CreateFromRaster pRasterOutput
Set pRDataset1 = pRWS2.OpenRasterDataset(pRLayer1.Name)
MsgBox "Write down the name of the new raster for future use: " & pRLayer1.Name
pMap.AddLayer pRLayer1
```

```
    Dim pTempDS As ITemporaryDataset
    Set pTempDS = pRDataset1
    pTempDS.MakePermanentAs pRLayer1.Name, pOutWS, "GRID"
    pRLayer1.Name = County & "DEM"
End Sub

Private Sub cmdQuit_Click()
    'Unload the form
    Unload frmDataPrep
End Sub

Private Sub UserForm_Initialize()
   'Adds counties available to combobox
   cboCounty.AddItem "Buncombe"
   cboCounty.AddItem "Craven"
   cboCounty.AddItem "Durham"
   cboCounty.AddItem "Orange"
   cboCounty.AddItem "Wake"

   cboCounty.Value = "Buncombe"
End Sub
```

**Create Socioeconomic Layers and Floodplain Boundaries**

```
'Declare variables
Dim pMxDoc As IMxDocument
Dim pMap As IMap
Dim pLayer As ILayer
Dim gp As Object

Dim Workspace As String
Dim InputFile As String
Dim OutputFile As String
Dim LayerName As String
Dim County As String

'Declarations for vector features
Dim pFactory As IWorkspaceFactory
Dim pFWorkspace As IWorkspace
Dim pFeatureWorkspace As IFeatureWorkspace
Dim pFClass As IFeatureClass
Dim pFLayer As IFeatureLayer

'Delcarations for raster features
Dim pRWorkspace As IRasterWorkspace
Dim pRasterDataset As IRasterDataset
Dim pRasterLayer As IRasterLayer
Dim pRaster As IRaster

'Load form and set up workspace
Private Sub cboCountySelect_Change()
  If cboCountySelect.Value = "Craven" Then
    Workspace = "C:\MyDocs\Masters\Craven\"
  ElseIf cboCountySelect.Value = "Buncombe" Then
    Workspace = "C:\MyDocs\Masters\Buncombe\"
  ElseIf cboCountySelect.Value = "Wake" Then
    Workspace = "C:\MyDocs\Masters\Wake\"
  ElseIf cboCountySelect.Value = "Durham" Then
    Workspace = "C:\MyDocs\Masters\Durham\"
  ElseIf cboCountySelect.Value = "Orange" Then
    Workspace = "C:\MyDocs\Masters\Orange\"
  Else
    cmbCreateNLCD.Enabled = False
    cmbFloodplains.Enabled = False
    cmbCreateParcel.Enabled = False
    cmbCreatePop.Enabled = False
    cmdPopTime.Enabled = False
  End If

  If cboCountySelect.Value = "Buncombe" Then
    County = "Bunco"
  Else
    County = cboCountySelect.Value
  End If
End Sub

'Code for creating coefficient files
Private Sub cmbCreateNLCD_Click()
```

```
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap

    'Set up Geoprocessing Object
    Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Conversion Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"
    gp.OverwriteOutput = 1

    'Initialize Input and Output Files
    NLCDInputFile = Workspace & "Projected\" & County & "NLCD"
    ParcelInputFile = Workspace & "Projected\Parcel.shp"
    PopInputFile = Workspace & "Projected\Pop" & County & "00.shp"
    CellSize = Workspace & "Projected\" & County & "DEM"

    NLCDBuild = Workspace & "Created\NLCDBuild"
    GoodNLCDBuild = Workspace & "Created\GoodNLCDBuild"
    NLCDParSum = Workspace & "Created\NLCDParSum"

    NLCDPOP = Workspace & "Created\NLCDPOP"
    GoodNLCDPop = Workspace & "Created\GoodNLCDPop"
    NLCDPopSum = Workspace & "Created\NLCDPopSum"

    Pixels = Workspace & "Created\pixels"
    PixelCount = Workspace & "Created\pixelcount"

    ParcelBuild = Workspace & "Created\ParcelBuild"
    ParcelLand = Workspace & "Created\ParcelLand"
    Pop2000 = Workspace & "Created\Pop2000"

    File = GoodNLCDBuild & ".aux"
    If gp.Exists(File) Then
      MsgBox "The NLCD has already been reclassified for building values."
    Else
      'Process to reclassify the NLCD layer for parcel buildings and resample to Lidar scale
      gp.Reclassify_sa NLCDInputFile, "Value", "11 0;21 1000;22 10000;23 10000;24 10000;31 1; 41 100;42
100;43 100;52 1;71 1;81 100;82 100;90 1;95 1", NLCDBuild, "DATA"
      MsgBox "The NLCD Building Reclassification: Water = 0, Barren Shrubs Grass = 1; Crops Forest = 100;
LDR = 1000; HDR Commercial = 10000"
      MsgBox "Cell size is being set to Lidar Data - May take a few minutes to run"
      gp.Resample_management NLCDBuild, GoodNLCDBuild, CellSize, "NEAREST"
    End If

    File = NLCDParSum & ".aux"
    If gp.Exists(File) Then
      MsgBox "The NLCD reclassified values have already been summed by parcel block."
    Else
      If County = "Craven" Then
        'Process to sum the number NLCD value per parcel block
        MsgBox "Summing the NLCD reclassified values by parcel block. This may take several minutes."
        gp.ZonalStatistics_sa ParcelInputFile, "COUNTY_", GoodNLCDBuild, NLCDParSum, "SUM",
"DATA"
      ElseIf County = "Bunco" Then
```

```
            MsgBox "There are too many parcel blocks. The parcels must be run in halves. This part has not yet been coded"
            gp.ZonalStatistics_sa ParcelInputFile, "PINNUM", GoodNLCDBuild, NLCDParSum, "SUM", "DATA"
        ElseIf County = "Durham" Then
            MsgBox "Summing the NLCD reclassified values by parcel block. This may take several minutes."
            gp.ZonalStatistics_sa ParcelInputFile, "DURPARS2_", GoodNLCDBuild, NLCDParSum, "SUM", "DATA"
        ElseIf County = "Orange" Then
            MsgBox "Summing the NLCD reclassified values by parcel block. This may take several minutes."
            gp.ZonalStatistics_sa ParcelInputFile, "PARCELS_ID", GoodNLCDBuild, NLCDParSum, "SUM", "DATA"
        ElseIf County = "Wake" Then
            MsgBox "There are too many parcel blocks. The parcels must be run in fours. This part has not yet been coded."
            gp.ZonalStatistics_sa ParcelInputFile, "OBJECTID", GoodNLCDBuild, NLCDParSum, "SUM", "DATA"
        End If
    End If

    File = GoodNLCDPop & ".aux"
    If gp.Exists(File) Then
        MsgBox "The NLCD has already been reclassified for population values."
    Else
        'Process to reclassify the NLCD for the population and resample to Lidar scale
        gp.Reclassify_sa NLCDInputFile, "Value", "11 0;21 10;22 35;23 65;24 90;31 0;41 5;42 5;43 5;52 0;71 1;81 1;82 5;90 0;95 0", NLCDPOP, "DATA"
        MsgBox "The Ambient NLCD Population Reclassification during a storm: Water Barren Shrubs = 0; Grass Forest Crops = 5, LDR = 10 to 35, Commercial to HDR = 65 to 90"
        MsgBox "Cell size is being set to Lidar Data - May take a few minutes to run"
        gp.Resample_management NLCDPOP, GoodNLCDPop, CellSize, "NEAREST"
    End If

    File = NLCDPopSum & ".aux"
    If gp.Exists(File) Then
        MsgBox "The NLCD reclassified values have already been summed by population block group."
    Else
        'Process to sum the number of NLCD reclassified values per population block group
        If County = "Bunco" Then
            MsgBox "Summing the NLCD reclassified values by population block. This may take several minutes."
            gp.ZonalStatistics_sa PopInputFile, "BLOCKGROUP", GoodNLCDPop, NLCDPopSum, "SUM", "DATA"
        Else
            MsgBox "Summing the NLCD reclassified values by population block. This may take several minutes."
            gp.ZonalStatistics_sa PopInputFile, "FIPS", GoodNLCDPop, NLCDPopSum, "SUM", "DATA"
        End If
    End If

    File = Pixels & ".aux"
    If gp.Exists(File) Then
        MsgBox "The number of pixels in each parcel block has been summed already."
    Else
        'Process to count the number of pixels in each parcel for the land classification
        gp.Reclassify_sa GoodNLCDBuild, "Value", "0 50000 1", Pixels, "DATA"
        MsgBox "Counting the number of pixels inside each parcel for land tax distribution. This may take several minutes."
        If County = "Craven" Then
```

```
        gp.ZonalStatistics_sa ParcelInputFile, "COUNTY_", Pixels, PixelCount, "SUM", "DATA"
    ElseIf County = "Bunco" Then
        MsgBox "The parcel blocks are too numerous and must split in 2 to run. This has not been coded yet."
        gp.ZonalStatistics_sa ParcelInputFile, "PINNUM", Pixels, PixelCount, "SUM", "DATA"
    ElseIf County = "Wake" Then
        MsgBox "The parcel blocks are too numerous and must split in 2 to run. This has not been coded yet."
        gp.ZonalStatistics_sa ParcelInputFile, "PINNUM", Pixels, PixelCount, "SUM", "DATA"
    ElseIf County = "Durham" Then
        gp.ZonalStatistics_sa ParcelInputFile, "DURPARS2_", Pixels, PixelCount, "SUM", "DATA"
    ElseIf County = "Orange" Then
        gp.ZonalStatistics_sa ParcelInputFile, "PARCELS_ID", Pixels, PixelCount, "SUM", "DATA"
    End If
End If

File = ParcelBuild & ".aux"
If gp.Exists(File) Then
    MsgBox "The parcel building and land values have already been converted into raster format."
Else
    'Process to create a raster layer for the building tax value and the land tax value from the feature layer
    If County = "Craven" Then
        MsgBox "Converting the parcel building field into a raster. This may take several minutes."
        Call AddField("Parcel", Workspace & "Projected")
        gp.FeatureToRaster_conversion ParcelInputFile, "BldValue", ParcelBuild, CellSize
        MsgBox "Converting the parcel land tax field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "landvalue", ParcelLand, CellSize
    ElseIf County = "Bunco" Then
        MsgBox "Converting the parcel building field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "BLDGVAL", ParcelBuild, CellSize
        MsgBox "Converting the parcel land tax field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "LANDVAL", ParcelLand, CellSize
    ElseIf County = "Durham" Then
        MsgBox "Converting the parcel building field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "BLDG_VALUE", ParcelBuild, CellSize
        MsgBox "Converting the parcel land tax field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "LAND_VALUE", ParcelLand, CellSize
    ElseIf County = "Orange" Then
        MsgBox "Converting the parcel building field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "HOUSEVALUE", ParcelBuild, CellSize
        MsgBox "Converting the parcel land tax field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "LANDVALUE", ParcelLand, CellSize
    ElseIf County = "Wake" Then
        MsgBox "Converting the parcel building field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "BLDG_VAL", ParcelBuild, CellSize
        MsgBox "Converting the parcel land tax field into a raster. This may take several minutes."
        gp.FeatureToRaster_conversion ParcelInputFile, "LAND_VAL", ParcelLand, CellSize
    End If
End If


File = Pop2000 & ".aux"
If gp.Exists(File) Then
    MsgBox "The population values have already been converted into raster format."
Else
    'Process to create a raster layer for the 2000 Craven Population
    MsgBox "Converting the 2000 population field into a raster. This may take several minutes."
    If County = "Bunco" Then
```

```
      gp.FeatureToRaster_conversion PopInputFile, "PERSONS", Pop2000, CellSize
    ElseIf County = "Orange" Or County = "Durham" Then
      gp.FeatureToRaster_conversion PopInputFile, "TOTAL_POP", Pop2000, CellSize
    Else
      gp.FeatureToRaster_conversion PopInputFile, "POP2000", Pop2000, CellSize
    End If
  End If

  MsgBox "Step 2 has been completed."
End Sub

'Add field to the parcel layer to make sure it is a number and not general value
Public Sub AddField(LayerName, InputFile)
  Set pMxDoc = ThisDocument
  Set pMap = pMxDoc.FocusMap

  Set pFactory = New ShapefileWorkspaceFactory
  Set pFeatureWorkspace = pFactory.OpenFromFile(InputFile, 0)
  Set pFClass = pFeatureWorkspace.OpenFeatureClass(LayerName & ".shp")
  Set pFLayer = New FeatureLayer
  Set pFLayer.FeatureClass = pFClass
  pFLayer.Name = LayerName

  'Set up the new field
  Dim pField1 As IFieldEdit
  Set pField1 = New Field
  pField1.Name = "BldValue"
  pField1.Type = esriFieldTypeDouble
  pField1.Length = 32

  Dim pFields As IFields
  Dim ii As Integer
  Set pFields = pFClass.Fields
  ii = pFields.FindField("BldValue")

  'Add the new field to the feature class
  If ii > 1 Then
  Else
    pFClass.AddField pField1
  End If

  'Calculate the values for the new field
  Dim pCursor As ICursor
  Dim pCalculator As ICalculator
  'Prepare a cursor with all records
  Set pCursor = pFClass.Update(Nothing, True)
  'Define a Calculator
  Set pCalculator = New Calculator

  With pCalculator
    Set .Cursor = pCursor
    .Expression = "[BLDG_VAL]"
    .Field = "BldValue"
  End With

  'Calculate the field values
```

```
    pCalculator.Calculate

    Set pField1 = New Field
    pField1.Name = "landValue"
    pField1.Type = esriFieldTypeDouble
    pField1.Length = 32

    Set pFields = pFClass.Fields
    ii = pFields.FindField("landValue")
     'Add the new field to the feature class
    If ii > 1 Then
    Else
       pFClass.AddField pField1
    End If

    'Prepare a cursor with all records
    Set pCursor = pFClass.Update(Nothing, True)

    'Define a Calculator
    Set pCalculator = New Calculator

    With pCalculator
       Set .Cursor = pCursor
       .Expression = "[LAND_VAL]"
       .Field = "landValue"
    End With

    'Calculate the field values
    pCalculator.Calculate
End Sub

'Create the parcel surface
Private Sub cmbCreateParcel_Click()
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap

    'Set up Geoprocessing Object
    Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Conversion Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"
    gp.OverwriteOutput = 1

    'Set up Input and Output Variables
    GoodNLCDBuild = Workspace & "Created\GoodNLCDBuild"
    NLCDParSum = Workspace & "Created\NLCDParSum"
    ParcelBuild = Workspace & "Created\ParcelBuild"
    ParcelLand = Workspace & "Created\ParcelLand"
    PixelCount = Workspace & "Created\pixelcount"

    NLCDPercent = Workspace & "Created\NLCDPercent"
    FinParBuild = Workspace & "Created\FinParBuild"
    FinParLand = Workspace & "Created\FinParLand"
    TaxSurface = Workspace & "Created\TaxSurface"
```

```
    File = NLCDPercent & ".aux"
    If gp.Exists(File) Then
        MsgBox "The percent NLCD reclassified value for each pixel in a parcel block has already been
calculated."
    Else
        If County = "Craven" Then
            'Process determine the percent NLCD for each pixel in a parcel block
            MsgBox "Calculating the percent of each pixel to attract tax value from total parcel block."
            gp.Divide_sa GoodNLCDBuild, NLCDParSum, NLCDPercent
        ElseIf County = "Bunco" Then
            MsgBox "The parcel file is too large. Must be split in half and then mosaiced. This has not been coded
yet."
            'Process determine the percent NLCD for each pixel in a parcel block
            MsgBox "Calculating the percent of each pixel to attract tax value from total parcel block."
            gp.Divide_sa GoodNLCDBuild, NLCDParSum, NLCDPercent
        ElseIf County = "Durham" Then
            'Process determine the percent NLCD for each pixel in a parcel block
            MsgBox "Calculating the percent of each pixel to attract tax value from total parcel block."
            gp.Divide_sa GoodNLCDBuild, NLCDParSum, NLCDPercent
        ElseIf County = "Orange" Then
            'Process determine the percent NLCD for each pixel in a parcel block
            MsgBox "Calculating the percent of each pixel to attract tax value from total parcel block."
            gp.Divide_sa GoodNLCDBuild, NLCDParSum, NLCDPercent
        ElseIf County = "Wake" Then
            MsgBox "The parcel block group file is too large. Must be split in 4 and then mosaiced. This has not
been coded yet."
            'Process determines the percent NLCD for each pixel in a parcel block
            MsgBox "Calculating the percent of each pixel to attract tax value from total parcel block."
            gp.Divide_sa GoodNLCDBuild, NLCDParSum, NLCDPercent
        End If
    End If

    File = TaxSurface & ".aux"
    If gp.Exists(File) Then
        MsgBox "The parcel building and parcel land tax surface have already been created."
    Else
        'Process to multiply the percent likely for each pixel by the building tax value in the block
        MsgBox "Creating the Parcel Building Value surface"
        gp.Times_sa NLCDPercent, ParcelBuild, FinParBuild

        'Process to divide the land tax value by the number of pixels in each parcel block to determine land parcel
value / pixel
        MsgBox "Creating the Parcel Land Value Surface. This may take a few minutes."
        gp.Divide_sa ParcelLand, PixelCount, FinParLand

        'Process to add the building value surface and the land value surface together for the Total Tax Value
Surface
        MsgBox "Creating the TaxSurface as the raster to use for future analyses."
        gp.Plus_sa FinParBuild, FinParLand, TaxSurface
    End If

End Sub

'Code to create the population surface
Private Sub cmbCreatePop_Click()
    Set pMxDoc = ThisDocument
```

```
    Set pMap = pMxDoc.FocusMap

'Set up Geoprocessing Object
    Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Conversion Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management Tools.tbx"
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"
    gp.OverwriteOutput = 1

'Declare variables
    GoodNLCDPop = Workspace & "Created\GoodNLCDPop"
    NLCDPopSum = Workspace & "Created\NLCDPopSum"
    Pop2000 = Workspace & "Created\Pop2000"

    NLCDPopPer = Workspace & "Created\NLCDPopPer"
    Pop00Surface = Workspace & "Created\Pop00Surface"

    File = Pop00Surface & ".aux"
    If gp.Exists(File) Then
        MsgBox "The population coefficient file and surface have already been created."
    Else
    'Run the geoprocessing object to determine the percent likelihood of ambient population per pixel
        MsgBox "The population coefficient file is being created. This may take a few minutes."
        gp.Divide_sa GoodNLCDPop, NLCDPopSum, NLCDPopPer

    'Run the geoprocessing object to determine the percent likelihood of ambient population per pixel
        MsgBox "The population surface is being created of ambient population likely present / pixel during a
flood. This may take a few minutes."
        gp.Times_sa Pop2000, NLCDPopPer, Pop00Surface
    End If

    For i = 0 To pMap.LayerCount - 1
         Set pLayer = pMap.Layer(0)
         pMap.DeleteLayer pLayer
    Next i

    Call AddRaster("TaxSurface", Workspace & "Created")
    Call AddRaster("Pop00Surface", Workspace & "Created")
    Call AddRaster("FinParBuild", Workspace & "Created")

    If County = "Bunco" Then
    Else
        Call AddFeature(County & "100DF", Workspace & "Created")
        Call AddFeature(County & "500DF", Workspace & "Created")
    End If

    Call AddFeature(County & "100F", Workspace & "Created")
    Call AddFeature(County & "500F", Workspace & "Created")

    pMxDoc.ActiveView.Refresh
    Unload frmCreateLayers
End Sub

Private Sub cmbFinish_Click()
    'Unload the Form
```

```
    Unload frmCreateLayers
End Sub

'Extract floodplain boundaries
Private Sub cmbFloodplains_Click()
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap

    'Set up Geoprocessing object
    Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
    gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"
    gp.OverwriteOutput = 1

    'Initialize Input and Output Files
    InputFile = Workspace & "Projected\" & County & "DFIRMS.shp"
    OutputFile = Workspace & "Created\" & County & "100DF.shp"

    If gp.Exists(OutputFile) Then
        MsgBox "The 100 and 500 year DFIRM boundaries have already been created"
    Else
        If County = "Bunco" Then
            MsgBox "No DFIRM files exist yet for this county."
        Else
            'Run the geoprocssing objects for the 100 and then the 500 year floodplains
            gp.Select_analysis InputFile, OutputFile, """FLOODZONE"" = 'AE' OR ""FLOODZONE"" = 'AEFW'
OR ""FLOODZONE"" = 'A' OR ""FLOODZONE"" = 'AO'"
            MsgBox "The " & County & " 100 yr floodplain shapefile has been created."

            OutputFile = Workspace & "Created\" & County & "500DF.shp"
            gp.Select_analysis InputFile, OutputFile, """FLOODZONE"" = 'SHADED X'"
            MsgBox "The " & County & " 500 yr floodplain shapefile has been created."
        End If
    End If

   'Initialize Input and Output Files
    InputFile = Workspace & "Projected\FIRM.shp"
    OutputFile = Workspace & "Created\" & County & "100F.shp"

    If gp.Exists(OutputFile) Then
        MsgBox "The 100 and 500 year FIRM boundaries have already been created."
    Else
        'Run the geoprocssing objects for the 100 and then the 500 year floodplains
        gp.Select_analysis InputFile, OutputFile, """ZONE"" = 'AE' OR ""ZONE"" = 'A' OR ""ZONE"" = 'FW'"
        MsgBox "The " & County & " 100 yr floodplain shapefile has been created."

        OutputFile = Workspace & "Created\" & County & "500F.shp"
        gp.Select_analysis InputFile, OutputFile, """ZONE"" = 'X500'"
        MsgBox "The " & County & " 500 yr floodplain shapefile has been created."
    End If
End Sub

'Code for creating 1990 surface
Public Sub cmdPopTime_Click()
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap
    'Set up Geoprocessing Object
```

```
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx"
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Conversion Tools.tbx"
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management Tools.tbx"
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"

   'Set up Input Variables
   Dim PopInputFile90 As String
   PopInputFile90 = Workspace & "Projected\Pop" & County & "90.shp"
   CellSize = Workspace & "Projected\" & County & "DEM"

   'Set up Output Variables
   Dim Pop1990 As String
   Pop1990 = Workspace & "Created\Pop1990"

   File = Pop1990 & ".aux"
   If gp.Exists(File) Then
      MsgBox "The population values have already been converted into raster format."
   Else
      'Process to create a raster layer for the 1990 population
      MsgBox "Converting the temporal population field into a raster. This may take several minutes."
      gp.FeatureToRaster_conversion PopInputFile90, "P0010001", Pop1990, CellSize
   End If

'Variables needed to create the 1992 reclassified NLCD files
   NLCDInputFile = Workspace & "Projected\" & County & "NLCD92"
   NLCDPOP = Workspace & "Created\NLCD92POP"
   GoodNLCDPop = Workspace & "Created\GoodNLCD92Pop"

   File = GoodNLCDPop & ".aux"
   If gp.Exists(File) Then
      MsgBox "The 1992 NLCD has already been reclassified for population values."
   Else
      'Process to reclassify the NLCD for the population and resample to Lidar scale
      gp.Reclassify_sa NLCDInputFile, "Value", "11 0;21 35;22 65;23 90;31 0;32 0;33 3;41 5;42 5;43 5;81 1;82
3;85 3;91 0;92 0", NLCDPOP, "DATA"
      MsgBox "The NLCD Population Reclassification during a storm: Water Barren = 0 Grass Forest Crops = 1
to 5, LDR = 35, Commercial and HDR = 65 to 90"
      MsgBox "Cell size is being set to Lidar Data - May take a few minutes to run"
      gp.Resample_management NLCDPOP, GoodNLCDPop, CellSize, "NEAREST"
   End If

   NLCDPopSum = Workspace & "Created\NL92PopSum90"
   File = NLCDPopSum & ".aux"
   If gp.Exists(File) Then
      MsgBox "The NLCD reclassified values have already been summed by population block group."
   Else
   'Process to sum the number of NLCD reclassified values per population block group
      MsgBox "Summing the NLCD reclassified values by population block. This may take several minutes."
      NLCDPopSum = Workspace & "Created\NL92PopSum90"
      gp.ZonalStatistics_sa PopInputFile90, "AreaKey", GoodNLCDPop, NLCDPopSum, "SUM", "DATA"
   End If

'Variables needed for final part
   Pop90Surface = Workspace & "Created\Pop90Surface"
   'Call modules to be run
```

```
    File = Pop90Surface & ".aux"
    If gp.Exists(File) Then
        MsgBox "The temporal population coefficient files and surfaces have already been created."
    Else
        'Run the geoprocessing object to determine the percent likelihood of ambient population in a pixel
        NLCDPopPer = Workspace & "Created\NL92PopPer90"
        NLCDPopSum = Workspace & "Created\NL92PopSum90"
        gp.Divide_sa GoodNLCDPop, NLCDPopSum, NLCDPopPer
        NLCDPopPer = Workspace & "Created\NL92PopPer90"
        gp.Times_sa Pop1990, NLCDPopPer, Pop90Surface
    End If

    MsgBox "The temporal population surfaces have been created."
    Unload frmCreateLayers
End Sub

Private Sub UserForm_Initialize()
    'Initialize the county select boxes
    cboCountySelect.AddItem "Buncombe"
    cboCountySelect.AddItem "Craven"
    cboCountySelect.AddItem "Durham"
    cboCountySelect.AddItem "Orange"
    cboCountySelect.AddItem "Wake"

    cboCountySelect.Value = "Buncombe"
End Sub

Public Sub AddRaster(LayerName As String, InputFile As String)
    Set pFactory = New RasterWorkspaceFactory
    Set pRWorkspace = pFactory.OpenFromFile(InputFile, 0)
    Set pRasterDataset = pRWorkspace.OpenRasterDataset(LayerName)
    Set pRasterLayer = New RasterLayer
    pRasterLayer.CreateFromDataset pRasterDataset
    pRasterLayer.Name = LayerName
    Set pLayer = pRasterLayer
    pMxDoc.AddLayer pLayer
    Set pFactory = Nothing
    Set pRWorkspace = Nothing
    Set pRasterDataset = Nothing
    Set pRasterLayer = Nothing
    Set pLayer = Nothing
End Sub

Public Sub AddFeature(LayerName As String, InputFile As String)
    Set pFactory = New ShapefileWorkspaceFactory
    Set pFeatureWorkspace = pFactory.OpenFromFile(InputFile, 0)
    Set pFClass = pFeatureWorkspace.OpenFeatureClass(LayerName & ".shp")
    Set pFLayer = New FeatureLayer
    Set pFLayer.FeatureClass = pFClass
    pFLayer.Name = LayerName
    pMap.AddLayer pFLayer
    Set pFactory = Nothing
    Set pFClass = Nothing
    Set pFeatureWorkspace = Nothing
    Set pFLayer = Nothing
End Sub
```

**Zonal Statistics**

```
'Variables declared
Dim pMxDoc As IMxDocument
Dim pMap As IMap
Dim pLayer As ILayer
Dim gp As Object

'Set up String Variables
Dim Workspace As String
Dim InputFile As String
Dim OutputFile As String
Dim LayerName As String
Dim LayerName1DF As String
Dim LayerName5DF As String
Dim LayerName1F As String
Dim LayerName5F As String
Dim LayerNameDiff As String
Dim LayerNameSame As String
Dim LayerNameDDiff As String
Dim LayerNameFDiff As String
Dim County As String
Dim File As String

Dim Query As String
Dim OneDF As String
Dim OneF As String
Dim FiveDF As String
Dim FiveF As String
Dim Pop As String
Dim Par As String
Dim Build As String
Dim DEM As String
Dim NLCD As String
Dim shp As String
Dim dbf As String
Dim Year As String

'Set up Feature Layer Variables
Dim pFactory As IWorkspaceFactory
Dim pFeatureWorkspace As IFeatureWorkspace
Dim pFClass As IFeatureClass
Dim pFLayer As IFeatureLayer

'Delcarations for raster features
Dim pRWorkspace As IRasterWorkspace
Dim pRasterDataset As IRasterDataset
Dim pRasterLayer As IRasterLayer
Dim pRaster As IRaster
Dim pRasterProps As IRasterProps
Dim pCell As IPoint
Dim pRGeoProcess As IRasterGeometryProc
Dim pSpatRefFac As ISpatialReferenceFactory2
Dim pSpatRef As ISpatialReference
Dim pRasterBandCollection As IRasterBandCollection
Dim pOutWS As IWorkspace
```

```
Dim pOutWSF As IWorkspaceFactory
Dim strOutType As String
Dim pRLayer1 As IRasterLayer

'Set up GUI and workspace
Public Sub cboCountySelect_Change()
   If cboCountySelect.Value = "Craven" Then
      Workspace = "C:\MyDocs\Masters\Craven\"
   ElseIf cboCountySelect.Value = "Buncombe" Then
      Workspace = "C:\MyDocs\Masters\Buncombe\"
   ElseIf cboCountySelect.Value = "Durham" Then
      Workspace = "C:\MyDocs\Masters\Durham\"
   ElseIf cboCountySelect.Value = "Orange" Then
      Workspace = "C:\MyDocs\Masters\Orange\"
   Else
      Workspace = "C:\MyDocs\Masters\Wake\"
   End If

   If cboCountySelect.Value = "Buncombe" Then
      County = "Bunco"
   Else
      County = cboCountySelect.Value
   End If
End Sub

'Zonal statistics between 100yr DFIRM and FIRM
Public Sub cmd100yrDtoF_Click()
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap

   'Set up Geoprocessing Object
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"
   gp.OverwriteOutput = 1

   If County = "Bunco" Then
      MsgBox "No DFIRMS are available at this time. No further analysis can be done."
      Exit Sub
   End If

   'Set up local variables
   Pop = Workspace & "Created\Pop00Surface"
   Par = Workspace & "Created\TaxSurface"
   Build = Workspace & "Created\finparbuild"
   DEM = Workspace & "Projected\" & County & "DEM"
   NLCD = Workspace & "Projected\" & County & "NLCD"
   dbf = ".dbf"
   OneF = "100F"
   OneDF = "100DF"

   LayerName1DF = Workspace & "Created\" & County & "100DF.shp"
   LayerName1F = Workspace & "Created\" & County & "100F.shp"
   LayerNameDiff = Workspace & "DtoFirm\100yr\DF100FDiff.shp"
   LayerNameSame = Workspace & "DtoFirm\100yr\DF100FSame.shp"
   LayerNameDDiff = Workspace & "DtoFirm\100yr\D100Diff.shp"
   LayerNameFDiff = Workspace & "DtoFirm\100yr\F100Diff.shp"
```

```
'Check to see if file exists. Assume if one exists, they all exist
If gp.Exists(LayerNameSame) Then
   MsgBox "The shapefiles have already been created. Skipping ahead."
Else
   MsgBox "Creating the shapefiles that overlap and are different"
   'Intersecting the floodplains
   MsgBox "Intersecting overlapping areas"
   Query = LayerName1DF + " " + "";" + LayerName1F + " " + """
   Call Intersect(Query, LayerNameSame)
   MsgBox "Extracting differences"
   Call SymmetricalDiff(LayerName1F, LayerName1DF, LayerNameDiff)
   MsgBox "Extracting DFIRM Difference"
   Query = LayerName1DF + " " + "";" + LayerNameDiff + " " + """
   Call Intersect(Query, LayerNameDDiff)
   MsgBox "Extracting FIRM Differences"
   Query = LayerName1F + " " + "";" + LayerNameDiff + " " + """
   Call Intersect(Query, LayerNameFDiff)
End If

'Add field ZoneStat to shapefiles for zonal statistics analysis
MsgBox "Adding ZoneStat field to run summary statistics"
Call AddField("D100Diff", Workspace & "DtoFirm\100yr")
Call AddField("F100Diff", Workspace & "DtoFirm\100yr")
Call AddField("DF100FSame", Workspace & "DtoFirm\100yr")
Call AddField("DF100FDiff", Workspace & "DtoFirm\100yr")

'Check to see if one file is there for each category - assume all or nothing
'Creating population tables for floodplain boundaries
MsgBox "Running population"
If gp.Exists(Workspace & "DtoFIRM\100yr\Pop\F100DiffPop" & dbf) Then
   MsgBox "The population surface has been summarized for " & County & "County."
Else
   Call ZonalStat(LayerNameSame, Pop, Workspace & "DtoFirm\100yr\Pop\DF100FPop" & dbf)
   Call ZonalStat(LayerNameDiff, Pop, Workspace & "DtoFirm\100yr\Pop\DF100FDiffPop" & dbf)
   Call ZonalStat(LayerNameDDiff, Pop, Workspace & "DtoFirm\100yr\Pop\D100DiffPop" & dbf)
   Call ZonalStat(LayerNameFDiff, Pop, Workspace & "DtoFirm\100yr\Pop\F100DiffPop" & dbf)
End If

'Creating Tax surface tables for floodplain boundaries
 MsgBox "Running Tax"
If gp.Exists(Workspace & "DtoFirm\100yr\Tax\F100DiffTax" & dbf) Then
   MsgBox "The tax surface has been summarized for " & County & "County."
Else
   Call ZonalStat(LayerNameSame, Par, Workspace & "DtoFirm\100yr\Tax\DF100FTax" & dbf)
   Call ZonalStat(LayerNameDiff, Par, Workspace & "DtoFirm\100yr\Tax\DF100FDiffTax" & dbf)
   Call ZonalStat(LayerNameDDiff, Par, Workspace & "DtoFirm\100yr\Tax\D100DiffTax" & dbf)
   Call ZonalStat(LayerNameFDiff, Par, Workspace & "DtoFirm\100yr\Tax\F100DiffTax" & dbf)
End If

'Creating building tax surface tables for floodplain boundaries
If gp.Exists(Workspace & "DtoFirm\100yr\Build\F100DiffBld" & dbf) Then
   MsgBox "The building tax surface has been summarized for " & County & "County."
Else
   Call ZonalStat(LayerNameSame, Build, Workspace & "DtoFirm\100yr\Build\DF100FBld" & dbf)
   Call ZonalStat(LayerNameDiff, Build, Workspace & "DtoFirm\100yr\Build\DF100FDiffBld" & dbf)
```

```
      Call ZonalStat(LayerNameDDiff, Build, Workspace & "DtoFirm\100yr\Build\D100DiffBld" & dbf)
      Call ZonalStat(LayerNameFDiff, Build, Workspace & "DtoFirm\100yr\Build\F100DiffBld" & dbf)
   End If

    MsgBox "Running DEM"
   'Creating DEM surface tables for floodplain boundaries
   If gp.Exists(Workspace & "DtoFirm\100yr\Lidar\F100DiffDEM" & dbf) Then
      MsgBox "The Elevation surface has been summarized for " & County & "County."
   Else
      Call ZonalStat(LayerNameSame, DEM, Workspace & "DtoFirm\100yr\Lidar\DF100FDEM" & dbf)
      Call ZonalStat(LayerNameDiff, DEM, Workspace & "DtoFirm\100yr\Lidar\DF100FDiffDEM" & dbf)
      Call ZonalStat(LayerNameDDiff, DEM, Workspace & "DtoFirm\100yr\Lidar\D100DiffDEM" & dbf)
      Call ZonalStat(LayerNameFDiff, DEM, Workspace & "DtoFirm\100yr\Lidar\F100DiffDEM" & dbf)
   End If

    MsgBox "Running NLCD"
   'Creating NLCD mask for floodplain boundaries
   If gp.Exists(Workspace & "DtoFirm\100yr\NLCD\F100DiffNLCD.aux") Then
      MsgBox "The NLCD fields have been summarized for " & County & "County."
   Else
      MsgBox "Creating NLCD Summary Raster, this will take a few minutes."
      Call NLCDMask(NLCD, Workspace & "DtoFirm\100yr\NLCD\DF100FNLCD", LayerNameSame)
      Call NLCDMask(NLCD, Workspace & "DtoFirm\100yr\NLCD\D100DiffNLCD", LayerNameDDiff)
      Call NLCDMask(NLCD, Workspace & "DtoFirm\100yr\NLCD\F100DiffNLCD", LayerNameFDiff)
   End If
   MsgBox "The Second step is finished running."
End Sub

'Locating areas where 100-yr DFIRM and FIRM Intersect
Public Sub Intersect(Query As String, Output As String)
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap

   'Set up Geoprocessing Object
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"
   gp.OverwriteOutput = 1

   gp.Intersect_analysis Query, Output, "ALL", "", "INPUT"
End Sub

Public Sub AddFeature(LayerName As String, InputFile As String)
   Set pFactory = New ShapefileWorkspaceFactory
   Set pFeatureWorkspace = pFactory.OpenFromFile(InputFile, 0)
   Set pFClass = pFeatureWorkspace.OpenFeatureClass(LayerName & ".shp")
   Set pFLayer = New FeatureLayer
   Set pFLayer.FeatureClass = pFClass
   pFLayer.Name = LayerName
   pMap.AddLayer pFLayer

   Set pFactory = Nothing
   Set pFClass = Nothing
   Set pFeatureWorkspace = Nothing
   Set pFLayer = Nothing
End Sub
```

```
'Finds where the 100-yr FIRM and 100-yr DFIRM don't intersect
Public Sub SymmetricalDiff(LayerName1F, LayerName1DF, LayerNameDiff)
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap

   'Set up Geoprocessing Object
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management Tools.tbx"
   gp.OverwriteOutput = 1

   'Symmetrical Difference being run
   gp.SymDiff_analysis LayerName1DF, LayerName1F, LayerNameDiff, "ALL", ""
End Sub

'Repeats the above process for the marginal 500-yr floodplain
Private Sub cmd500yrDtoF_Click()
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap

   'Set up Geoprocessing Object
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx"
   gp.OverwriteOutput = 1

   If County = "Bunco" Then
      MsgBox "No DFIRMS are available at this time. No further analysis can be done."
      Exit Sub
   End If

   'Set up local variables
   Pop = Workspace & "Created\Pop00Surface"
   Par = Workspace & "Created\TaxSurface"
   Build = Workspace & "Created\finparbuild"
   DEM = Workspace & "Projected\" & County & "DEM"
   NLCD = Workspace & "Projected\" & County & "NLCD"
   dbf = ".dbf"

   LayerName5DF = Workspace & "Created\" & County & "500DF.shp"
   LayerName5F = Workspace & "Created\" & County & "500F.shp"
   LayerNameDiff = Workspace & "DtoFirm\500yr\DF500FDiff.shp"
   LayerNameSame = Workspace & "DtoFirm\500yr\DF500FSame.shp"
   LayerNameDDiff = Workspace & "DtoFirm\500yr\D500Diff.shp"
   LayerNameFDiff = Workspace & "DtoFirm\500yr\F500Diff.shp"

   'Check to see if file exists. Assume if one exists, they all exist
   If gp.Exists(LayerNameFDiff) Then
      MsgBox "The shapefiles have already been created. Skipping ahead."
   Else
      MsgBox "Creating the shapefiles that overlap and are different"
      'Intersecting the floodplains
      MsgBox "Intersecting overlapping areas"
      Query = LayerName5DF + " " + "";" + LayerName5F + " " + """
      Call Intersect(Query, LayerNameSame)
      MsgBox "Extracting differences"
      Call SymmetricalDiff(LayerName5F, LayerName5DF, LayerNameDiff)
      MsgBox "Extracting DFIRM Difference"
```

```
    Query = LayerName5DF + " " + "";" + LayerNameDiff + " " + """
    Call Intersect(Query, LayerNameDDiff)
    MsgBox "Extracting FIRM Differences"
    Query = LayerName5F + " " + "";" + LayerNameDiff + " " + """
    Call Intersect(Query, LayerNameFDiff)
End If

'Add field ZoneStat to shapefiles for zonal statistics analysis
MsgBox "Adding ZoneStat field to run summary statistics"
Call AddField("D500Diff", Workspace & "DtoFirm\500yr")
Call AddField("F500Diff", Workspace & "DtoFirm\500yr")
Call AddField("DF500FSame", Workspace & "DtoFirm\500yr")
Call AddField("DF500FDiff", Workspace & "DtoFirm\500yr")

'Check to see if one file is there for each category - assume all or nothing
'Creating population tables for floodplain boundaries
MsgBox "Running population"
If gp.Exists(Workspace & "DtoFIRM\500yr\Pop\F500DiffPop" & dbf) Then
    MsgBox "The population surface has been summarized for " & County & "County."
Else
    Call ZonalStat(LayerNameSame, Pop, Workspace & "DtoFirm\500yr\Pop\DF500FPop" & dbf)
    Call ZonalStat(LayerNameDiff, Pop, Workspace & "DtoFirm\500yr\Pop\DF500FDiffPop" & dbf)
    Call ZonalStat(LayerNameDDiff, Pop, Workspace & "DtoFirm\500yr\Pop\D500DiffPop" & dbf)
    Call ZonalStat(LayerNameFDiff, Pop, Workspace & "DtoFirm\500yr\Pop\F500DiffPop" & dbf)
End If

'Creating Tax surface tables for floodplain boundaries
 MsgBox "Running Tax"
If gp.Exists(Workspace & "DtoFirm\500yr\Tax\F500DiffTax" & dbf) Then
    MsgBox "The tax surface has been summarized for " & County & "County."
Else
    Call ZonalStat(LayerNameSame, Par, Workspace & "DtoFirm\500yr\Tax\DF500FTax" & dbf)
    Call ZonalStat(LayerNameDiff, Par, Workspace & "DtoFirm\500yr\Tax\DF500FDiffTax" & dbf)
    Call ZonalStat(LayerNameDDiff, Par, Workspace & "DtoFirm\500yr\Tax\D500DiffTax" & dbf)
    Call ZonalStat(LayerNameFDiff, Par, Workspace & "DtoFirm\500yr\Tax\F500DiffTax" & dbf)
End If

'Creating building tax surface tables for floodplain boundaries
If gp.Exists(Workspace & "DtoFirm\500yr\Build\F500DiffBld" & dbf) Then
    MsgBox "The building tax surface has been summarized for " & County & "County."
Else
    Call ZonalStat(LayerNameSame, Build, Workspace & "DtoFirm\500yr\Build\DF500FBld" & dbf)
    Call ZonalStat(LayerNameDiff, Build, Workspace & "DtoFirm\500yr\Build\DF500FDiffBld" & dbf)
    Call ZonalStat(LayerNameDDiff, Build, Workspace & "DtoFirm\500yr\Build\D500DiffBld" & dbf)
    Call ZonalStat(LayerNameFDiff, Build, Workspace & "DtoFirm\500yr\Build\F500DiffBld" & dbf)
End If

 MsgBox "Running DEM"
'Creating DEM surface tables for floodplain boundaries
If gp.Exists(Workspace & "DtoFirm\500yr\Lidar\F500DiffDEM" & dbf) Then
    MsgBox "The Elevation surface has been summarized for " & County & "County."
Else
    Call ZonalStat(LayerNameSame, DEM, Workspace & "DtoFirm\500yr\Lidar\DF500FDEM" & dbf)
    Call ZonalStat(LayerNameDiff, DEM, Workspace & "DtoFirm\500yr\Lidar\DF500FDiffDEM" & dbf)
    Call ZonalStat(LayerNameDDiff, DEM, Workspace & "DtoFirm\500yr\Lidar\D500DiffDEM" & dbf)
    Call ZonalStat(LayerNameFDiff, DEM, Workspace & "DtoFirm\500yr\Lidar\F500DiffDEM" & dbf)
```

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    End If

     MsgBox "Running NLCD"
    'Creating NLCD mask for floodplain boundaries
    If gp.Exists(Workspace & "DtoFirm\500yr\NLCD\F500DiffNLCD.aux") Then
        MsgBox "The NLCD fields have been summarized for " & County & "County."
    Else
        MsgBox "Creating NLCD Summary Raster, this will take a few minutes."
        Call NLCDMask(NLCD, Workspace & "DtoFirm\500yr\NLCD\DF500FNLCD", LayerNameSame)
        Call NLCDMask(NLCD, Workspace & "DtoFirm\500yr\NLCD\D500DiffNLCD", LayerNameDDiff)
        Call NLCDMask(NLCD, Workspace & "DtoFirm\500yr\NLCD\F500DiffNLCD", LayerNameFDiff)
    End If

    MsgBox "The final step is finished running."
    Unload frmFDFAnalyze
End Sub

'Zonal statistics are calculated for the different floodplain boundaries
Public Sub cmdFDFIRM_Click()
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap

    'Set up Geoprocessing Object
    Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")

    'Set up local variables
    OneF = "100F"
    OneDF = "100DF"
    FiveDF = "500DF"
    FiveF = "500F"
    Pop = Workspace & "Created\Pop00Surface"
    Par = Workspace & "Created\TaxSurface"
    Build = Workspace & "Created\finparbuild"
    DEM = Workspace & "Projected\" & County & "DEM"
    NLCD = Workspace & "Projected\" & County & "NLCD"
    shp = ".shp"
    dbf = ".dbf"

    MsgBox "Adding ZoneStat field to run summary statistics"
    If County = "Bunco" Then
    Else
        Call AddField(County & OneDF, Workspace & "Created")
        Call AddField(County & FiveDF, Workspace & "Created")
    End If
    Call AddField(County & OneF, Workspace & "Created")
    Call AddField(County & FiveF, Workspace & "Created")

    'Set up LayerNames for analysis
    If County = "Bunco" Then
        MsgBox "There are no DFIRM files available for Buncombe County at this time."
    Else
        LayerName1DF = Workspace & "Created\" & County & "100DF.shp"
        LayerName5DF = Workspace & "Created\" & County & "500DF.shp"
    End If

    LayerName1F = Workspace & "Created\" & County & "100F.shp"
```

```
LayerName5F = Workspace & "Created\" & County & "500F.shp"

'Check to see if one file is there for each category - assume all or nothing
'Creating population tables for floodplain boundaries
MsgBox "Running population"
If gp.Exists(Workspace & "DFIRM\Pop" & OneDF & dbf) Then
   MsgBox "The population surface has been summarized for " & County & "County."
Else
   If County = "Bunco" Then
      MsgBox "There are no DFIRM files available for Buncombe County at this time."
   Else
      Call ZonalStat(LayerName1DF, Pop, Workspace & "DFIRM\Pop" & OneDF & dbf)
      Call ZonalStat(LayerName5DF, Pop, Workspace & "DFIRM\Pop" & FiveDF & dbf)
   End If
   Call ZonalStat(LayerName1F, Pop, Workspace & "FIRM\Pop" & OneF & dbf)
   Call ZonalStat(LayerName5F, Pop, Workspace & "FIRM\Pop" & FiveF & dbf)
End If

'Creating Tax surface tables for floodplain boundaries
 MsgBox "Running Tax"
If gp.Exists(Workspace & "DFIRM\Tax" & OneDF & dbf) Then
   MsgBox "The tax surface has been summarized for " & County & "County."
Else
   If County = "Bunco" Then
      MsgBox "There are no DFIRM files available for Buncombe County at this time."
   Else
      Call ZonalStat(LayerName1DF, Par, Workspace & "DFIRM\Tax" & OneDF & dbf)
      Call ZonalStat(LayerName5DF, Par, Workspace & "DFIRM\Tax" & FiveDF & dbf)
   End If
   Call ZonalStat(LayerName1F, Par, Workspace & "FIRM\Tax" & OneF & dbf)
   Call ZonalStat(LayerName5F, Par, Workspace & "FIRM\Tax" & FiveF & dbf)
End If

'Creating building tax surface tables for floodplain boundaries
If gp.Exists(Workspace & "DFIRM\Build100DF.dbf") Then
   MsgBox "The building tax surface has been summarized for " & County & "County."
Else
   If County = "Bunco" Then
      MsgBox "There are no DFIRM files available for Buncombe County at this time."
   Else
      Call ZonalStat(LayerName1DF, Build, Workspace & "DFIRM\Build" & OneDF & dbf)
      Call ZonalStat(LayerName5DF, Build, Workspace & "DFIRM\Build" & FiveDF & dbf)
   End If
   Call ZonalStat(LayerName1F, Build, Workspace & "FIRM\Build" & OneF & dbf)
   Call ZonalStat(LayerName5F, Build, Workspace & "FIRM\Build" & FiveF & dbf)
End If

 MsgBox "Running DEM"
'Creating DEM surface tables for floodplain boundaries
If gp.Exists(Workspace & "DFIRM\DEM" & OneDF & dbf) Then
   MsgBox "The Elevation surface has been summarized for " & County & "County."
Else
   If County = "Bunco" Then
      MsgBox "There are no DFIRM files available for Buncombe County at this time."
   Else
      Call ZonalStat(LayerName1DF, DEM, Workspace & "DFIRM\DEM" & OneDF & dbf)
```

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            Call ZonalStat(LayerName5DF, DEM, Workspace & "DFIRM\DEM" & FiveDF & dbf)
        End If
        Call ZonalStat(LayerName1F, DEM, Workspace & "FIRM\DEM" & OneF & dbf)
        Call ZonalStat(LayerName5F, DEM, Workspace & "FIRM\DEM" & FiveF & dbf)
    End If

     MsgBox "Running NLCD"
    'Creating NLCD mask for floodplain boundaries
    If gp.Exists(Workspace & "DFIRM\NLCD" & OneDF & ".aux") Then
        MsgBox "The NLCD fields have been summarized for " & County & "County."
    Else
        If County = "Bunco" Then
            MsgBox "There are no DFIRM files available for Buncombe County at this time."
        Else
            MsgBox "Creating NLCD Summary Raster, this will take a few minutes."
            Call NLCDMask(NLCD, Workspace & "DFIRM\NLCD" & OneDF, LayerName1DF)
            Call NLCDMask(NLCD, Workspace & "DFIRM\NLCD" & FiveDF, LayerName5DF)
        End If
        MsgBox "Creating NLCD Summary Raster, this will take a few minutes."
        Call NLCDMask(NLCD, Workspace & "FIRM\NLCD" & OneF, LayerName1F)
        Call NLCDMask(NLCD, Workspace & "FIRM\NLCD" & FiveF, LayerName5F)
    End If

    MsgBox "The first step is finished running."
End Sub

Public Sub AddField(LayerName, InputFile)
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap

    Set pFactory = New ShapefileWorkspaceFactory
    Set pFeatureWorkspace = pFactory.OpenFromFile(InputFile, 0)
    Set pFClass = pFeatureWorkspace.OpenFeatureClass(LayerName & ".shp")
    Set pFLayer = New FeatureLayer
    Set pFLayer.FeatureClass = pFClass
    pFLayer.Name = LayerName

    'Set up the new field to run table zone stats on
    Dim pField1 As IFieldEdit
    Set pField1 = New Field
    pField1.Name = "ZoneStat"
    pField1.Type = esriFieldTypeInteger
    pField1.Length = 4

    Dim pFields As IFields
    Dim ii As Integer
    Set pFields = pFClass.Fields
    ii = pFields.FindField("ZoneStat")

    'Add the new field to the feature class
    If ii > 1 Then
    Else
        pFClass.AddField pField1
    End If
End Sub
```

```
'Zonal statistics tool
Public Sub ZonalStat(LayerName, InputFile, OutputFile)
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap

   'Set up Geoprocessing Object
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx"
   gp.OverwriteOutput = 1

   gp.ZonalStatisticsAsTable_sa LayerName, "ZoneStat", InputFile, OutputFile, "DATA"
End Sub

'Extract the NLCD by floodplain boundary
Public Sub NLCDMask(InputFile, OutputFile, LayerName)
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap

    'Set up Geoprocessing Object
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")
   gp.AddToolbox "C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx"
   gp.OverwriteOutput = 1

   gp.ExtractByMask_sa InputFile, LayerName, OutputFile
End Sub

'Repeat above procedure for the 1990 population surface
Private Sub cmdPopTime_Click()
   Set pMxDoc = ThisDocument
   Set pMap = pMxDoc.FocusMap

   'Set up Geoprocessing Object
   Set gp = CreateObject("esriGeoprocessing.GPDispatch.1")

   'Set up local variables
   OneF = "100F"
   OneDF = "100DF"
   FiveDF = "500DF"
   FiveF = "500F"
   Pop = Workspace & "Created\Pop90Surface"
   dbf = ".dbf"

   MsgBox "Adding ZoneStat field to run summary statistics"
   If County = "Bunco" Then
   Else
      Call AddField(County & OneDF, Workspace & "Created")
      Call AddField(County & FiveDF, Workspace & "Created")
   End If
   Call AddField(County & OneF, Workspace & "Created")
   Call AddField(County & FiveF, Workspace & "Created")

   'Set up LayerNames for analysis
   If County = "Bunco" Then
      MsgBox "There are no DFIRM files available for Buncombe County at this time."
   Else
      LayerName1DF = Workspace & "Created\" & County & "100DF.shp"
```

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      LayerName5DF = Workspace & "Created\" & County & "500DF.shp"
   End If

   LayerName1F = Workspace & "Created\" & County & "100F.shp"
   LayerName5F = Workspace & "Created\" & County & "500F.shp"

'Run the DFIRMTOFIRM ANALYSIS
   'Creating population tables for floodplain boundaries
   MsgBox "Running temporal population"
   If gp.Exists(Workspace & "DFIRM\Pop" & OneDF & "90" & dbf) Then
      MsgBox "The population surface has been summarized for " & County & "County."
   Else
      If County = "Bunco" Then
         MsgBox "There are no DFIRM files available for Buncombe County at this time."
      Else
         Call ZonalStat(LayerName1DF, Pop, Workspace & "DFIRM\Pop" & OneDF & "90" & dbf)
         Call ZonalStat(LayerName5DF, Pop, Workspace & "DFIRM\Pop" & FiveDF & "90" & dbf)
      End If

      'Run the 1990 FIRMS
      Call ZonalStat(LayerName1F, Pop, Workspace & "FIRM\Pop" & OneF & "90" & dbf)
      Call ZonalStat(LayerName5F, Pop, Workspace & "FIRM\Pop" & FiveF & "90" & dbf)
   End If

'Run the 100 year DFIRM FIRM differences
   If County = "Bunco" Then
      MsgBox "No DFIRMS are available at this time. No further analysis can be done."
      Exit Sub
   ElseIf gp.Exists(Workspace & "DtoFirm\100yr\DF100FDiff.shp") Then
         'Set up local variables
      Pop = Workspace & "Created\Pop90Surface"
      dbf = ".dbf"

      LayerNameDiff = Workspace & "DtoFirm\100yr\DF100FDiff.shp"
      LayerNameSame = Workspace & "DtoFirm\100yr\DF100FSame.shp"
      LayerNameDDiff = Workspace & "DtoFirm\100yr\D100Diff.shp"
      LayerNameFDiff = Workspace & "DtoFirm\100yr\F100Diff.shp"

      'Creating population tables for floodplain boundaries
      MsgBox "Running population"
      If gp.Exists(Workspace & "DtoFIRM\100yr\Pop\F100DiffPop90" & dbf) Then
         MsgBox "The temporal population surfaces have been summarized for " & County & "County."
      Else
         'Run the 1990 100 year floodplain analysis
         Call ZonalStat(LayerNameSame, Pop, Workspace & "DtoFirm\100yr\Pop\DF100FPop90" & dbf)
         Call ZonalStat(LayerNameDiff, Pop, Workspace & "DtoFirm\100yr\Pop\DF100FDiffPop90" & dbf)
         Call ZonalStat(LayerNameDDiff, Pop, Workspace & "DtoFirm\100yr\Pop\D100DiffPop90" & dbf)
         Call ZonalStat(LayerNameFDiff, Pop, Workspace & "DtoFirm\100yr\Pop\F100DiffPop90" & dbf)
      End If

'Run for the 500 year floodplain differences
      'Set up local variables
      Pop = Workspace & "Created\Pop90Surface"
      dbf = ".dbf"

      LayerNameDiff = Workspace & "DtoFirm\500yr\DF500FDiff.shp"
```

```
    LayerNameSame = Workspace & "DtoFirm\500yr\DF500FSame.shp"
    LayerNameDDiff = Workspace & "DtoFirm\500yr\D500Diff.shp"
    LayerNameFDiff = Workspace & "DtoFirm\500yr\F500Diff.shp"

    'Creating population tables for floodplain boundaries
    MsgBox "Running population"
    If gp.Exists(Workspace & "DtoFIRM\500yr\Pop\F100DiffPop90" & dbf) Then
      MsgBox "The temporal population surfaces have been summarized for " & County & "County."
    Else
      'Run the 1990 100 year floodplain analysis
      Call ZonalStat(LayerNameSame, Pop, Workspace & "DtoFirm\500yr\Pop\DF500FPop90" & dbf)
      Call ZonalStat(LayerNameDiff, Pop, Workspace & "DtoFirm\500yr\Pop\DF500FDiffPop90" & dbf)
      Call ZonalStat(LayerNameDDiff, Pop, Workspace & "DtoFirm\500yr\Pop\D500DiffPop90" & dbf)
      Call ZonalStat(LayerNameFDiff, Pop, Workspace & "DtoFirm\500yr\Pop\F500DiffPop90" & dbf)
    End If
  Else
    MsgBox "Run the other buttons first to create necessary files."
  End If
  MsgBox "You are done my son!!"
End Sub

Private Sub cmdQuit_Click()
  'Hide form
  Unload frmFDFAnalyze
End Sub

Private Sub UserForm_Initialize()
  'Initialize the county select boxes
  cboCountySelect.AddItem "Buncombe"
  cboCountySelect.AddItem "Craven"
  cboCountySelect.AddItem "Durham"
  cboCountySelect.AddItem "Orange"
  cboCountySelect.AddItem "Wake"

  cboCountySelect.Value = "Buncombe"
End Sub
```

**Appendix Figures:**

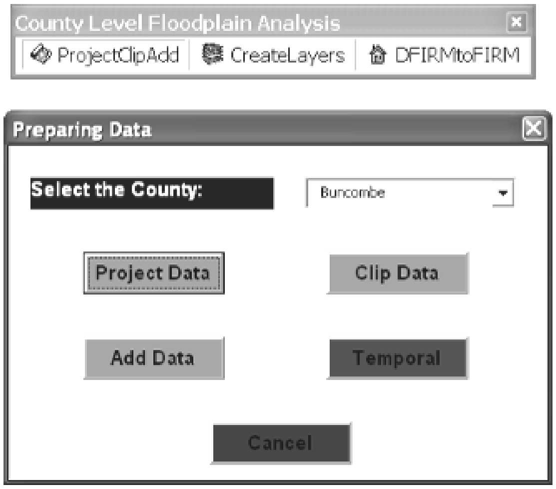


**Figure A.1:** Created Toolbar and the data preparation GUI

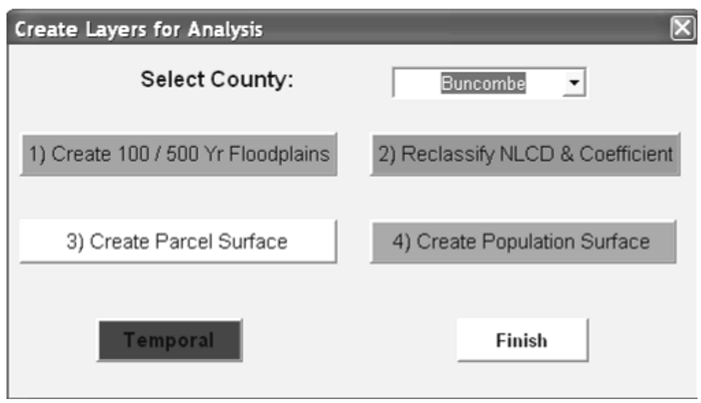


**Figure A.2:** NLCD coefficient, floodplain, parcel, population and temporal socioeconomic surface creation GUI

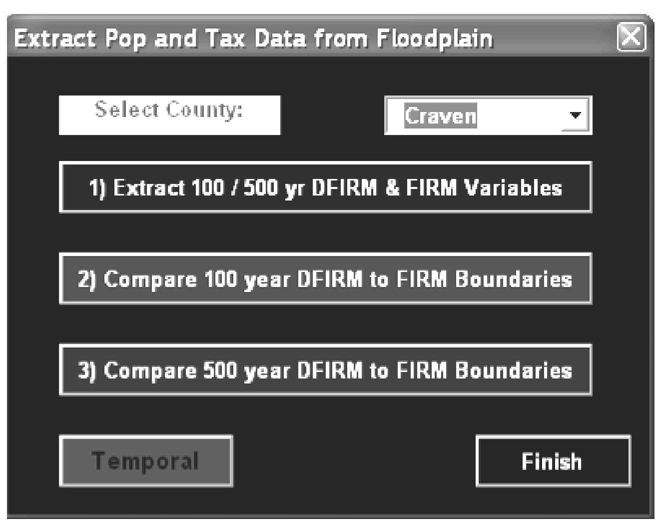


**Figure A.3**: Zonal Statistics GUI for comparison of exposure to floodplain boundaries

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