Impact Assessments of Extreme Weather Events using Geographical Approaches

by

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ABSTRACT

Recent extreme weather events such the 2020 Nashville, Tennessee tornado and Hurricane Maria highlight the devastating economic losses and loss of life associated with weather-related disasters. Understanding the impacts of extreme weather events is critical to mitigating disaster losses and increasing societal resilience to future events. Geographical approaches are best suited to examine social and ecological factors in extreme weather event impacts because they systematically examine the spatial interactions (e.g., flows, processes, impacts) of the earth's system and human-environment relationships. The goal of this research is to demonstrate the utility of geographical approaches in assessing social and ecological factors in extreme weather event impacts. The first two papers analyze the social factors in the impact of Hurricane Sandy through the application of social geographical factors. The first paper examines how knowledge disconnect between experts (climatologists, urban planners, civil engineers) and policy-makers contributed to the damaging impacts of Hurricane Sandy. The second paper examines the role of land use suitability as suggested by Ian McHarg in 1969 and unsustainable planning in the impact of Hurricane Sandy. Overlay analyses of storm surge and damage buildings show damage losses would have been significantly reduced had development followed McHarg's suggested land use suitability. The last two papers examine the utility of Unpiloted Aerial Systems (UASs) technologies and geospatial methods (ecological geographical approaches) in tornado damage surveys. The third paper discusses the benefits, limitations, and procedures of using UASs technologies in tornado damage surveys. The fourth paper examines topographical

influences on tornadoes using UAS technologies and geospatial methods (ecological geographical approach). This paper highlights how topography can play a major role in tornado behavior (damage intensity and path deviation) and demonstrates how UASs technologies can be invaluable tools in damage assessments and improving the understanding of severe storm dynamics (e.g., tornadic wind interactions with topography). Overall, the significance of these four papers demonstrates the potential to improve societal resilience to future extreme weather events and mitigate future losses by better understanding the social and ecological components in extreme weather event impacts through geographical approaches.

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CHAPTER 1

INTRODUCTION

1.1. Introduction

Recent extreme weather events of Hurricanes Maria, Harvey, Irma, 2018 Western Wildfires, and the 03 March 2020 Nashville, TN tornado highlight an alarming trend of increasing economic losses and loss of life in weather-related disasters. In the case of Hurricane Maria, approximately 4,465 people lost their lives with damage loss estimates at 102 billion USD (Kishore et al. 2018). While the death toll associated with Hurricane Harvey was considerably lower than Maria, economic losses were higher amounting to 130 billion USD, making it the second costliest weather-related disaster, following Hurricane Katrina (165 billion USD) (NOAA, 2020). Billion dollar disasters, like Maria and Harvey, have cost the US economy more than 1.75 trillion USD in damage losses (NOAA, 2020) since 1980 with the majority of these losses (1.16 trillion USD) occurring within the past 15 years (2005-2019) (NOAA, 2020).

The rise in disaster losses can be partially attributed to changing demographics (Bouwer, 2010; Chang and Franczyk, 2008; IPCC, 2012; McPhillips et al. 2018; Klotzbach et al. 2018), increases in population growth and urbanization (Kunkel et al. 1999; Klotzbach et al. 2018; Broska et al. 2020), and rise in wealth (Klotzbach et al. 2018). In terms of changing demographics, more people are relocating to hazard-prone areas. For example, approximately 40% of the U.S. population now live in coastal locations, increasing their exposure to tropical cyclones, coastal flooding, and rising sea

levels (OCM, 2020; Klotzbach et al. 2018). Continued population growth and increasing urbanization have also contributed to higher disaster losses as a result of increasing exposure and higher population densities (Hoeppe et al. 2016; Dinan, 2017; Klotzbach et al. 2018). Additionally, the rise in wealth means societies now have more to lose as measured by material wealth and reflected in the rising cost of disaster payouts and individual insurance claims (Pielke et al. 2005; Klotzbach et al. 2018). Disaster losses will likely continue to rise as extreme weather events are projected to increase under climate change, (IPCC, 2012; Wagner et al. 2014).

These losses are not caused by one factor alone, but rather due to the combination of exposure, resiliency, and adaptive capacity (Gallopin, 2006; Lei et al. 2014; Broska et al. 2020). This perspective considers how the resiliency of a system can attenuate or amplify the impacts of an extreme event defined here as *"a dynamic occurrence within a limited time frame that impedes the 'normal' functioning of a system or systems"* (Broska et al. 2020:4). Resiliency is the capacity of a system to absorb the disturbance, reorganize, or maintain essentially the same functions and feedbacks over time and continue to develop along a particular trajectory (Folke et al. 2002; Folke et al. 2010; Elmqvist, 2019). The potential for a system to cope with and organize to challenges, or adaptive capacity, depends on the characteristics, complexity, and behavior of a system, as well as the connectivity to other systems (Smit and Wandel, 2006; Adger, 2006; Elmqvist et al. 2019; Broska et al. 2020). For example, the anomalously high death toll following Hurricane Maria was attributed to disruptions in medical care as a result of extensive infrastructure damage, lack of secondary power supply, and interruptions in

supply chains (Kishore et al. 2018). These factors amplified the impact of Maria, affecting their ability to adapt.

Embedded in these concepts (resiliency, adaptive capacity) is the idea that extreme event impacts have social and ecological (biophysical) components, which can be intricately linked (Adger, 2000; Walker et al. 2004; McGinnis and Ostrom, 2014). Drawing from the field of ecology, socio-ecological theory recognizes the dynamic relationship between a system and its environment, where a feedback in one system will affect another (Walker et al. 2004; McGinnis and Ostrom, 2014). For example, removing mangrove forests strips away natural protective barriers along coastlines and increases coastal inundation and storm surge, harming both social and ecological systems (Lee et al. 2014; Spalding et al. 2014). Understanding social and ecological factors in extreme weather events would better identify how resiliency and adaptive capacity can amplify or attenuate the impacts of extreme weather events.

Previous research have examined extreme weather event impacts from economic, sociological, and health perspectives. Economic-based assessments of extreme weather event impacts tend to focus on economic efficiency of protective infrastructure and resiliency-based strategies in terms of cost-benefit analysis (Mechler, 2016; Botozen et al. 2019), multi-criteria assessments (Barquet and Cuminskey, 2018), or economic modeling (Okuyama, 2007; MacKenzie et al. 2014). Sociological perspectives of extreme weather event impacts primarily concentrate on decision-making processes in terms of social and psychological behaviors providing context for disaster preparedness (Drabek, 2012), evacuation (Huang and Lindell, 2016; Sadri and Gladwin, 2017), and recovery

(Rivera, 2020). Health perspectives tend to focus on health impacts (e.g., mortality, casualties) relative to policies (Clemens and Casani, 2016) and environmental conditions (Cruz-Cano and Mead, 2019). These views, while shedding light on economic factors, behavior aspects, and health implications, may fail to capture the importance of geographical information and spatial context, interactions between physical and human components, and connections tied to scale.

Geographical approaches systematically examine the spatial interactions (e.g., flows, processes, impacts) of the earth's system as well as human-environment relationships (Clifford et al. 2016). Depending on the nature of the data, geographical approaches can be quantitative or qualitative. Quantitative methods include multivariate and data driven analysis, spatial modeling, and GIS and remote sensing techniques. Qualitative methods include policy analysis, participatory action engagement, interviews, and survey analysis. In both methods, spatial context matters and can lead to geographic knowledge discoveries, especially in the case of data-driven analyses (Miller and Goodchild, 2015). Geographical approaches can also be used to assess individual components of a system or entire system depending on the scale of analysis and research. Assessing extreme weather event impacts using geographical approaches enable the ability to examine social and ecological (biophysical) factors in extreme weather event impacts, conduct place-based analyses, and assess impacts at different scales. Therefore, geographical approaches can provide a deeper and more comprehensive understanding of extreme weather event impacts.

1.2. Problem Statement

Extreme weather event impacts are affected by both social and ecological (biophysical) factors. Social factors (e.g., resource availability, institutions, governance, technology) can amplify the damaging impacts of extreme weather events as seen with Hurricanes Katrina, Maria, and Harvey, and the 2019 Alabama Tornado Outbreak. In the case of Hurricane Harvey, increased urbanization, poor planning, and inadequate infrastructure exacerbated urban flooding by restricting natural flood pathways, retarding recession of flood waters, and increasing storm total rainfall (Zhang et al. 2018). Storm rainfall totals associated with Hurricane Harvey, however, were also ecological (biophysical) due to anomalously high atmospheric moisture and stationary storm track over the Houston/Beaumont area (Emanuel, 2017; Brauer et al. 2020). The ecological components of extreme weather event impacts can be related to storm characteristics (e.g., hurricane strength, tornadic wind speeds, storm surge heights) as well as land cover interactions.

Geographical approaches are uniquely suited to examine both social and ecological factors in extreme weather event impacts because of the nature of the discipline. Geographical research is often segregated into two subdisciplines cultural (social) and physical (ecological), necessitating two types of geographical approaches: social and ecological. Social geographical approaches are used to evaluate social factors in extreme weather event impacts. Because social factors can be characterized as abstract or unquantifiable, qualitative methods such as policy and interview analyses may be used. For example, policy analysis can evaluate how the role of institutions and knowledge

disconnect contribute to the magnitude of impact as well as assess how the impact varies with the disaster affected area. In addition to qualitative methods, quantitative methods such as spatial statistics (e.g. geoweighted regression, point pattern analysis) and land use suitability analysis can also be used to measure the degree of impact relative to social factors (e.g., demographics) investigated.

Ecological geographical approaches focus on quantifying the impact of the extreme weather event as well as measuring the biophysical characteristics and dynamics of the event. Ecological geographical approaches related to measurements, observations, or modeling can be used to assess storm characteristics and dynamics. Other approaches, such as remote sensing methodologies and geographical information system (GIS) approaches, are often used to analyze land cover changes relative to the extreme weather event. Remote sensing methodologies such as multispectral analysis and change detection can be used to detect changes in land cover as well as classify the degree of change. Additionally, GIS approaches can be used to assess the extent and type of land cover affected as well as investigate land cover influences in extreme weather event impacts.

The goal of this research is to demonstrate the utility of geographical approaches in assessing social and ecological factors in extreme weather event impacts. Consequently, I break my research goal into two distinct components:

a) Assessment of the social factors of extreme weather events impacts through application of social geographical approaches
b) Assessment of the ecological (biophysical) effects of extreme weather events impacts through application of ecological geographical approaches

Chapters 2 and 3 address social factors of extreme weather event impacts of goal (a). Chapters 4 and 5 address the ecological factors of extreme weather event impacts of goal (b).

1.3. Dissertation Framework

My dissertation is structured to address specific social and ecological problems in assessing extreme weather events impacts through the application of geographical approaches. There are four chapters, in which each addresses a specific extreme weather event using a specific geographical approach. Impacts from hurricanes and tornadoes are considered.

Chapter 2 uses a social geographical approach to examine the impact of Hurricane Sandy from a climate change and policy perspective. It is argued that knowledge disconnect between experts (climatologists, planners, and engineers), and policy-makers contributed to the extensive damage observed in Hurricane Sandy. This article uses a socio-ecological framework to qualitative assess the knowledge disconnect via the four elements of adaptive capacity to social ecological resiliency: resources, knowledge, institutions, and innovation. This article discusses how discursive and co-produced knowledge, as illustrated by the Dutch model of flood policy, can lead to robust socio-ecological systems. This research was published in *Applied Geography* in 2014 under the title "Adaptive capacity in light of Hurricane Sandy: the need for policy engagement" with co-authors Netra Chhetri and Melanie Sturm (*Applied Geography*, 24, 15-23).

Chapter 3 uses a social geographical approach to assess the role of land use suitability, as suggested by Ian McHarg in 1969, and unsustainable planning in the

impact of Hurricane Sandy. The role of land use suitability in the impact of Hurricane Sandy is examined by comparing storm surge affected areas and damaged buildings to both McHarg's suggested land use suitability and 2012 land use data. Damage area by storm surge and number of damaged buildings are calculated for each land use class in McHarg's land use and 2012 land use. Z-tests are performed to assess whether the difference in damaged areas were statistically significant. Additionally, zoning data (historical (1960) and current (2102)) are compared to McHarg's land use suitability, and 2012 land use to investigate whether McHarg's land use suitability could have been realized. This research was published in Landscape and Urban Planning in 2016 under the title, "Design with Nature: key lessons from McHarg's intrinsic suitability in the wake of Hurricane Sandy" with co-authors Elizabeth Wentz and Joanna Merson (*Landscape and Urban Planning*, 155, 33-46).

Chapter 4 discusses the benefits, limitations, and procedures of using Unpiloted Aerial Systems (UASs) in tornado damage surveys, from an ecological geographical approach. It is important that the meteorological community understands both the benefits and limitations of these technologies. Benefits include the ability to 1) access remote or impassable locations, 2) better capture perishable data (Womble et al. 2018), and 3) provide more detailed information to better discern damage and estimate EF-scale rating. Equipment limitations, scale of operations, navigating FAA and other agency specific policy, and working in disaster zones must be considered to successfully collect, analyze, and disseminate UAS-based damage information. This research was published in the *Bulletin of American Meteorological Society (BAMS)* in 2019 under the title

"Unpiloted Aerial Systems (UASs) Application for tornado damage surveys" with co-authors Robert K. Doe, Aaron Johnson, Zhiang Chen, Jnaneshwar Das, and Randall S. Cerveny (*BAMS* 100(12), 2405-2409).

Chapter 5 investigates the influence of topography on tornadoes with a particular attention to microscale features using an ecological geographical approach. This is accomplished by examining UAS-based visible imagery, visible difference vegetation index (VDVI) imagery, point cloud data, and digital surface models (DSMs) to assess the influence of terrain on the tornado track. Spatial comparisons and overlay analysis of UAS-based imagery with UAS DSM information are performed to assess changes in damage intensity relative to micro-topographical features and elevation. Additionally, transects of VDVI imagery and elevation information are evaluated to assess changes in tornadic intensity relative to the elevation. This article, titled: "High resolution observations of microtopographical influences on tornado damage utilizing Unpiloted Aerial Systems (UASs)", will be submitted to the AMS journal *Monthly Weather Review* in April 2020.

The final chapter (Chapter 6) of the dissertation concludes with an overview of the research contributions. Here I highlight findings from the paper contributions, identify limitations of geographical approaches, and discuss the possibility of next steps.

1.4. Significance of the Work

Understanding extreme weather event impacts is critical to increasing our resiliency to future extreme weather events. Research evolves our understanding on how

extreme weather events affect society (NCEI, 2020). Improving our knowledge of extreme event impacts necessitates mobilizing knowledge to decision-makers, policy-makers, and the general public. Because knowledge is socially constructed, discursive, and mediated through various social and political processes (Levin, 2008), it is important to effectively communicate knowledge through a multitude of platforms and media channels to mitigate any gap in knowledge. This also requires engaging multiple stakeholders at various scales (local to global) (Boezeman et al. 2013). When well-informed, society is more likely to adopt robust adaptation strategies and increase their resiliency to future events.

Together, these four research papers comprising chapters 2-5 demonstrate the importance of geographical approaches in assessing the social and ecological components of extreme weather event impacts. The critical aspect of this research is knowledge gained in these assessments can provide researchers, policy-makers, first responders, and the general public with valuable information, that could ultimately save lives and protect property from extreme weather events.

CHAPTER 2

ADAPTIVE CAPACITY IN LIGHT OF HURRICANE SANDY: THE NEED FOR POLICY ENGAGEMENT

Wagner, M., N. Chhetri, and M. Sturm, 2014: Adaptive capacity in light of Hurricane Sandy: The need for policy engagement. Applied Geography, 50, 15-23.

2.1. Introduction

Climate change is expected to bring an increase in the frequency, intensity, spatial extent, and duration of weather and climate extremes (Lavell et al. 2012:30). Recent report of the Intergovernmental Panel on Climate Change (IPCC) shows that over the last 50 years, extreme events have been on the rise in most regions of the world (Field et al. 2012). In fact, recurring 'rare' events have been occurring in relatively quick succession over the last 50 years (Field et al. 2012) with events (e.g. heat waves (Fouillet et al. 2008; DSE, 2008), droughts (Peterson et al. 2012; Rupp and Mote, 2012), forest fires (Parliament of Victoria, 2010; NCDC, 2013), and severe storms (NCDC, 2013)) pointing to the need for robust adaptation.

As the frequency and intensity of these events increase with climate change (IPCC, 2012), socio-ecological systems not only become more exposed, but their interdependence heightens its sensitivity to change (Turner et al. 2003). Resiliency is becoming a central tenet for assessing society's ability to respond to climate change. Nested within this broader context of vulnerability, resiliency refers to the magnitude of a

disturbance that can be absorbed before a system radically changes to a different state as well as the capacity to self-organize to emerging circumstances (Keessen et al. 2013; Folke, 2006). Adaptive capacity assesses the potential for a socio-ecological system to cope with challenges posed by climate change (Adger, 2006). Therefore, enhancing the adaptive capacity of socio-ecological systems is central to building resiliency to extreme events (Adger, 2006; O'Brien et al. 2012).

Following Nelson et al. (2010), we argue that robust adaptation necessitates flexible governance, institutional organization and investment in innovation of technologies on demand. Adaptation strategies may range from short-term fixes to incremental change or transformation of whole systems. For example, the unprecedented flood of 1953 in the Netherlands triggered a paradigm shift prompting the government to redesign their water management system nationwide (Haasnoot and Middlekoop 2012: 111). Following this transformative approach of the First Delta Committee policy and engineering feats of the Deltaworks project (Delta Committee 1960), the Dutch continued to expand on their ideology of national flood safety recognizing stressors of climate change and spatial planning in 'Room for the River' (Vink et al. 2013; Haasnoot and Middlekoop, 2012). This subsequent policy laid the foundation for flexible and innovative adaptation approaches by using 'soft' measures (e.g. ecological engineering) or natural systems such as wetland restoration in addition to the traditional 'hard' measures (e.g. dams) (Haasnoot and Middlekoop, 2012; Inman, 2010).

Recent literature has highlighted the linkages and multi-scalar processes between environment and society, demonstrating the value of place-based approaches to

innovations (Rodima-Tayler et al, 2012; Chhetri et al, 2012). Adding to the growing body of literature on human and social dimensions of climate change, we explore the sensitivity of socio-ecological systems in the wake of Hurricane Sandy as a case study. More specifically, this paper: a) identify the importance of institutions and governance in minimizing the vulnerability of socio-ecological system; b) provide additional examples of the disconnect between knowledge about disaster impacts and policy; c) highlight the value of resource flow; and d) discuss the importance of integrating knowledge and policy to increase the resiliency of socio-ecological systems. We review the Dutch model as an example of a robust socio-ecological system to shed light on how integrating policy and knowledge can lead to successful adaptation.

In the following section, we provide a conceptual foundation of this paper that explores the significance of resources, knowledge, governance and innovation of technology in light of the potential ramifications of climate change adaptation. Section three presents a case study of Hurricane Sandy using specific examples from New York (NY) and New Jersey (NJ) to demonstrate disconnect between knowledge and policy and the negative implications for socio-ecological systems. We further discuss the admonition of climatologists, urban planners, and engineers that preceded Sandy yet failed to enact effective resiliency measures. In section four, we offer examples of robust systems that effectively integrate knowledge and draw contrasts between U.S. governance and the evolving Dutch flood policy. This article concludes by offering recommendations for decision makers to improve socio-ecological systems through knowledge co-production and multi-level collaboration.

2.2. Conceptual Framework

While society may not alter the risk of threats stemming from impending climate change (see Fig. 2.1), its impacts may be reduced through increasing the resiliency of socio-ecological systems. Different forms of adaptation have been illustrated and defined in Table 2.1 as a means to improve societal resilience (Levin et al. 2011; Richards and Howden, 2012). Following Pelling (2011) we argue that pathways for enhancing adaptive capacity demands four elements: a) resources; b) knowledge; c) institutions; and d) innovation of technologies (see Fig. 2.1). We recognize that vulnerability may emanate from other external drivers (e.g. demographic change, land cover change, technological change), however, we argue that even these threats can be successfully managed when these four elements are synchronized harmoniously. On the other hand, dysfunctional or disconnected systems can lead to maladaptive situations, amplifying the vulnerability of socio-ecological systems. Therefore, attention must focus on multi-level collaboration, knowledge co-production and governance to design robust socio-ecological systems. While climate change threats can serve as opportunities, barriers to adaptation have been raised from several fronts, including inadequate climate information (Deressa et al. 2009), partial understanding of climate impacts, and uncertainty about the benefits of adaptation (Hammill and Tanner, 2010), institutional inertia and lock-in (path dependency) (Chhetri et al. 2010), lack of use-inspired research (Moser, 2010), lack of credit (Bryan et al. 2008), weak market systems (Kabubo-Mariara, 2009), and lack of foresight in technology innovation.

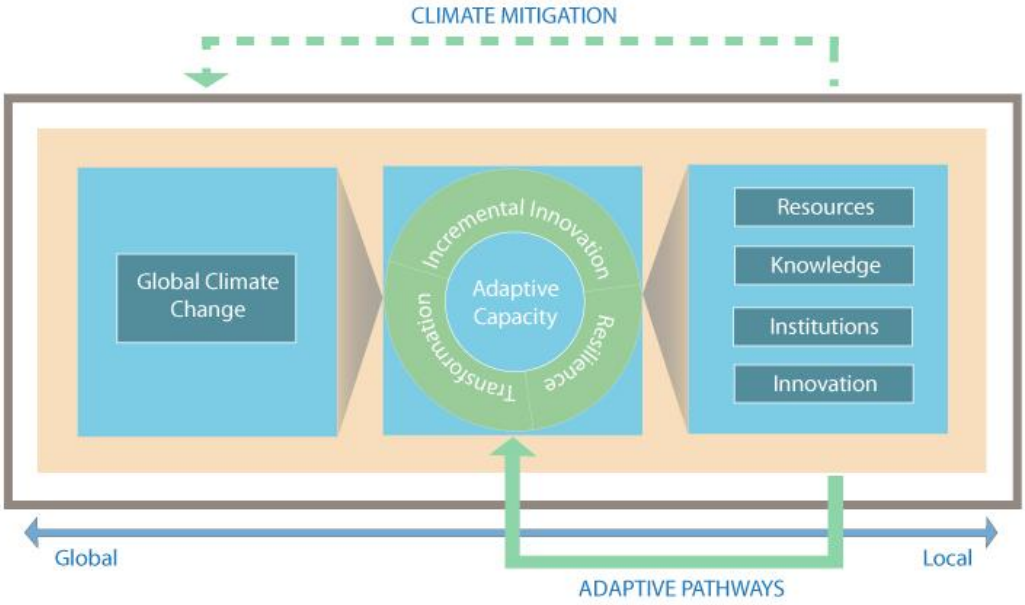


Fig. 2.1. Adaptive Pathways to Social Ecological Resiliency.

Table 2.1. Types of Adaptation from Levine Levide, Ludi and Jones, (2011) and Richards and Howden (2012).

Type	Actor(s)	Scale	Description
Reactive	Private	Local level	Adaptation that occurs naturally and is triggered by ecological changes in natural systems and by market or welfare changes in human systems. It does not constitute a conscious response to climatic stimuli.
Incremental	Public & Private	Regional & National	Adaptation actions that are the result of deliberate policy decision or action on the part of public agencies. It results in small incremental changes, generally aimed at enabling a person or community to maintain its functional objectives under changing conditions.
Transformative	Public institutions	National & International	Adaptation that results in a change in the individual or community's primary structure and function
Maladaptation	Public & Private	Local, Regional, National & International	An adaptive response made without consideration for interdependent systems that may, inadvertently, increase risks to other systems that are sensitive to climate change.

Resources are universally noted as determinant factors in enhancing adaptive capacities (Chapin et al. 2006). Although resource rich countries or groups may also be vulnerable to climatic events, often it is deemed that vulnerability is greater in poorer countries or areas where resource poor reside (Pelling, 2011). Extensive evidence of disparate impacts on marginalized subgroups raises concerns of disproportionate effects of climate change on these already vulnerable subgroups (Bohle et al. 1994). Resources are consequently a function of institutional arrangements and knowledge.

Knowledge is instrumental in devising robust adaptation strategies. While increased knowledge and understanding of past events has improved the processes for anticipating and dealing with extreme events (Pelling, 2011), knowledge must be mobilized to reach a consensus and implement corrective actions (Vink et al. 2013). For example, the Dutch model frames recurring flood risk as a matter of national policy, but negotiates consensual decision-making at the local level (Vink et al. 2013). It is this local pattern of reciprocity and knowledge exchange that elucidates multiple stakeholders from public to private of the vulnerability and rallies their willingness to invest by understanding the adaptation costs (Rodima-Taylor et al. 2012). In the case of Hurricane Katrina, recurring flood risk has been known for almost three centuries with scientists and media repeatedly warning New Orleans of the "Big One" four years prior to Katrina (Kates et al. 2006). Thus, information alone may not guarantee a desirable outcome due to the social and cultural constructs of risk, perception of the hazard incidents and their expectations (Adger et al. 2005; McIvor and Paton, 2007). As Vink and colleagues (2013: 92) point out, different publics assign different meanings to the problem and this plurality of publics and associated problem definitions make it difficult to define what is at stake and what should be done. This concept along with market-driven behaviors may help explain past use of ineffective incremental approaches (extending levee heights post-flood) and shift towards transformational strategies (Kates et al. 2006, 2012).

Limitations to adaptation also include our inability to recognize climate change signals due to problems of detection and appreciation (Chhetri et al. 2010). Our preoccupation with other pressing concerns can divert attention away from climate

change (van Aalst et al. 2008). Additionally, knowledge gap in understanding, planning, and management can precludes us from designing appropriate disaster responses (Moser and Ekstrom, 2010). The lack of administrative and social support for making adaptive decisions adds another layer of complexity. Although investments in advancing knowledge, warning systems, and technologies may be costly in the short-term, the return on long-term benefits will likely save both money and lives in the future. Lastly, knowledge dissemination must be timely to effectively minimize hazards (O'Brien et al. 2012).

Institutions play a critical role in shaping adaptive capacity of society, because they influence the distribution of social vulnerability (Næss et al. 2005). Institutions provide formal (e.g. legislation) and informal (e.g. cultural norms) rules for how actors and stakeholders interrelate (North, 1990). Due to their specific nature, informal institutions remain highly localized and understand the local dynamics of climate trends and adaptation outcomes (Crane et al. 2011). Additionally, local patterns of reciprocity and exchange can be a major determinant of a society's ability to adapt (Rodima-Taylor et al. 2012). While top-down approaches assume policies are directly translated into actions on the ground, bottom-up approaches recognize the importance of other actors in shaping policy (Urwin and Jordan, 2008). Both have the ability to advance policy but are contingent on synergistic organization (Berman et al. 2012).

Institutions lacking mandates and knowledge to implement climate adaptation not only leads to poor use of existing resources for adaptation, but also diminishes adaptive capacity (Moser, 2010). Institutions designed to support activities under conditions of

"normal" climate may resist change and impede adaptations (Agrawal and Perrin, 2009). Existing centralized top-down institutions are increasingly being complemented and sometimes challenged by new forms of collaboration including boundary institutions (Chhetri et al. 2012). These innovative institutions, like the IPCC and NPCC (New York City Panel on Climate Change), function as intermediaries between science and policy (Guston, 2001; Solecki 2012; Boezeman et al. 2013). These changes are largely driven by dissatisfaction with the perceived inability of existing institutions to devise a comprehensive adaptation program. This stalemate can stem from the lack of institutional interaction and integration between different agencies resulting in redundant or conflicting policies (Mitchell and van Aalst, 2008).

Institutionalized research is the key factor for producing innovation leading to advanced technologies capable of making socio-ecological systems resilient and adaptable. Institutional change, in turn, is induced by changes in factor supplies (e.g., land, water) and product demand (e. g. food) and by technological change (e.g., high yielding varieties). Within this premise, climate insecurity can become a powerful driver of technological and institutional innovation. Thus, innovation of appropriate technologies depends on the sensitivity of institutions to progressively adapt. It is the product of constant interaction and feedback between social space (where individuals interact) and organizational space mediated by infrastructure individuals and institutions (North, 1990). Therefore, technological innovation involves plurality in engagement and is determined by the type of adaptation. In some cases, incremental adjustments in practices or technologies may represent innovative steps toward adaptation, while other

cases may necessitate transformation. According to Chhetri and Easterling (2010), multiple stakeholders, including farmers and NGOs, have worked together to develop technologies that consider local needs and climatic conditions.

2.3. A Case Study of Hurricane Sandy

With sustained wind speeds peaking at 85 mph, Hurricane Sandy made landfall on October 29, 2012, near Atlantic City, NJ, inundating the Northeastern U.S. with heavy rains and high storm surge (Simpson and Lawrence, 1971; Blake et al. 2013). This Category 1 storm swept over the coast during high tide with storm surge heights of 14 feet, resulting in widespread damages primarily attributable to the inundation of floodwaters and their slow recession (Blake et al. 2013). Within its path, NY and NJ withstood the greatest impact totaling 87 deaths and 650,000 damaged or destroyed houses at an estimated loss of 42.0 and 29.4 billion USD, respectively (Blake et al. 2013). Due to more extensive damages and availability of information, we focus on NY as a case study of a maladaptive socio-ecological system with some discussion extended to NJ.

Disasters, such as Hurricane Sandy, highlight failures to redesign policy often deemed beyond human control, yet aftermath analyses generally reveal consequential damages due to overtaxed systems (i.e. high population density, inappropriate land use, and social inequities) and poorly prepared societies (Pielke, 2007; Comfort et al. 1999). In the case of Sandy, widespread damages were not just a function of storm surge and winds, rather the product of a dysfunctional and disconnected socio-ecological system.

Although the 1938 Hurricane, a Category 3 storm with sustained winds exceeding 115 mph that struck Long Island, NY during high tide, was a much stronger storm yielding storm surge heights between 14 to 18 feet, damages from Sandy proved to be more extensive. Economic losses associated with Sandy surpassed those of the 1938 Hurricane at an estimated cost of 70 billion USD compared to 41.2 billion USD normalized to 2010 inflation (Blake and Gibney, 2011). Following Pielke (2007), we argue that these losses could have been significantly mitigated had there been adequate coordination and collaboration among various stakeholders including scholars, urban planners and policy makers. Discursive knowledge that engages a plurality of stakeholders including the public is more likely to lead consensual decision-making and induce the necessary behavioral change to redesign policy.

Climatologists such as Simpson and Lawrence (1971), Elsner and Kara (1999), and Keim and colleagues (2007) have been warning policymakers for almost four decades about the vulnerability of the northeastern seaboard to storms based on return periods of 6 and 10 years. Yet, these warnings have largely been ignored as private firms and governing policy have been guided by rent seeking behavior. Even the threat of increased coastal flooding due to sea level rise (Rosenzweig and Solecki, 2010) and severe storm (Lin et al. 2012) has provided little incentives for policymakers to timely act on the indicated risk. However, the NPCC, convened by Mayor Bloomberg in 2008, has been discussing this knowledge along with climate change projections and adaptation approaches to advise local government on climate change issues and adaptation strategies (Rosenzweig et al. 2011). The Climate Change Task, backed by the NPCC, Force has

been working towards on identifying risk and opportunities towards interagency collaboration on adaptation strategies since 2004 (Solecki, 2012). However, due to constraints of time, budgets and need to quantify risk uncertainty, robust adaptation strategies were either not consensually perceived or enacted.

Urban planners have also been warning of the perils of coastal flooding, emphasizing the need for innovative land use. Comparison of Ian McHarg's land suitability analysis of Staten Island (1969) (Fig. 2.2) and damage assessments of Hurricane Sandy (Fig. 2.3a) shows that much of the flooding caused by Sandy coincided with land originally defined as unsuitable for urbanization. According to McHarg, developed areas (Fig. 2.3b) inundated by storm surge (the northwest and southern sections) were best suited for passive recreation and/or conservation based on climate (e.g. tidal inundation from hurricanes), geology, hydrology, pedology, wildlife, vegetation and land use (e.g. cultural assignments of historical and scenic use). Moreover, these areas coincided with FEMA's 100-flood zone, only recently updated in 2013 since 1983 (NPCC, 2013). Closing this knowledge-action gap is critical to reducing climate change-related disasters in the future. Past successes of policy change (e.g. clean air act, mitigation of downstream flooding through large dams, and traffic efficiency of interstate highways) have demonstrated this feasibility by first building narratives to explain the issue and then framing them as a matter of public health policy.

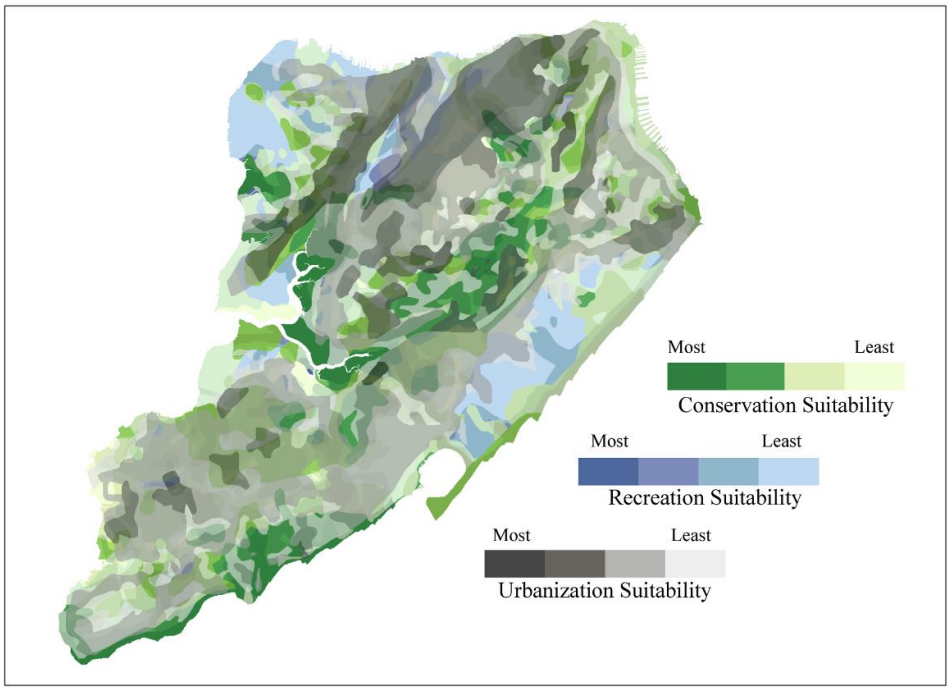


Fig. 2.2. Land Use Suitability for Staten Island, NY – According to McHarg (1969).

Environmental constraints discussed above should have been recognized as opportunities for innovative land use policy. Urban development sprawled into these unsuitable and vulnerable regions, consequently amplifying the damaging impacts of Hurricane Sandy. As a result, the southern shore was devastated by storm surge, washing whole blocks of houses in the communities of Midland, New Dorp and Oakland Beach out to sea (Blake et al. 2013). In addition to market driven forces, coastal development has been encouraged by government subsidies. The National Flood Insurance Program (NIFP) is particularly problematic by providing subsidies to coastal and floodplain developers, private insurance industry and repetitive losses to homeowners. Other problems with the NIFP are the lack of policyholders' premiums to commensurate with risk, asymmetric knowledge between builders and buyers and gaps in policy coverage

(Bagstad et al. 2007). State incentives for industry and tax incentives for second properties have compounded the attraction of habituating in such vulnerable regions (Bagstad et al. 2007). Additionally, post-disaster subsidies from the Stafford Act coupled with budgetary restraints of mitigation reform strategies enforce status-quo rebuilds to the pre-disaster state (Bagstad et al. 2007). Prior to Katrina, New Orleans repeatedly rebuilt buildings to the pre-disaster state relying solely of the protection of incremental adjustments of levee heights that only advanced one foot higher than the last high-water stage (Kates et al. 2006). However, even in Post-Katrina, rebuilding the familiar has been favored in some locations due to constraints of timely updating policy or competing planning visions (Kates et al. 2006). If we continue to follow the existing land use trajectory, economic losses will only heighten and jeopardize adaptive capacities of social-ecological systems (Pielke et al. 2008; Aerts et al. 2009; Botzen and van den Bergh, 2009).

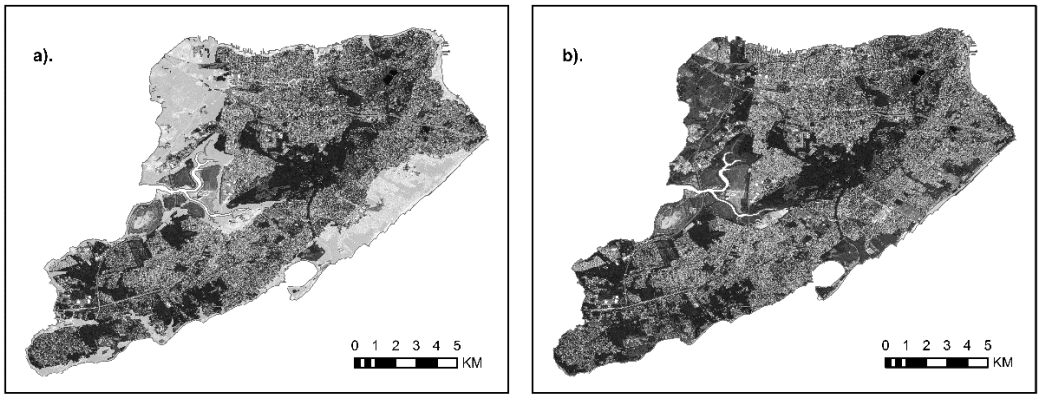


Fig. 2.3. (a) Storm Surge Impacts to Staten Island, NY from Hurricane Sandy (Shown in White) Overlaid onto (b) Digital Ortho Photo in Gray Scale.

Other questionable land use policies include development on barrier islands spanning the NJ and NY shores. Shaped and molded by ocean currents and coastal winds, barrier islands are fragile and highly vulnerable ecosystems that undergo habitual biophysical changes. Although ecosystems such as the barrier islands are meant to protect coastlines from storm surge and serve as refuges for wildlife, they face the diminishing ability to buffer against the elements due to societal transformation (Boruff et al. 2005). Thus, storm surge proved catastrophic in the barrier island communities of Seaside Heights, Long Beach Island, Union Beach and Sea Bright with the majority of structures, badly damaged or destroyed (Blake et al. 2013). One barrier island community in Mantoloking, NJ bore the brunt of Sandy's direct hit as storm surge carved two new inlets into its coast (Blake et al. 2013). In Fire Island, NY, although ocean waters breached the barrier island and wreaked havoc in three areas, some sections were spared by sand dunes constructed by the Army Corps of Engineers through a multi-million dollar project (Navarro and Nuwer, 2012, NYT). On Coney Island, soft adaptations measures (e.g. beach nourishment) proposed by the NPCC also mitigated localized impacts from Sandy, illustrating the role of natural capital in designing landscapes that harmonize social and ecological systems (PlaNYC, 2013; Minteer, 2012).

Within sections of these barrier islands, questionable land use practices (e.g. mixed zoning and flood prone areas) compounded Sandy's impacts among marginalized subgroups. Although urban planners (e.g., McHarg, 1969) advocate for mixed land use, collocation of industrial businesses and residential housing proved hazardous due to lack of adherence to building code, regulations, and safety measures. Marginalized subgroups

that are pushed into the industrial fringe, such as sections of Red Hook (NJ) and Staten Island (NY), are exposed to environmental pollutants and residual toxins due to fewer housing choices, employments options, and resources (Kamel, 2012). Sandy 's heavy storm surge exacerbated the vulnerability of these low-income neighborhoods as industrial pollutants and toxins were washed into these regions. These residents not only face the added health costs of industrial effluence, but their road to recovery is also challenged as insurance companies are deterred from serving residents in such high risk areas (Botzen and van den Bergh, 2009).

Attuned to this existing fragility of socio-ecological systems, the American Society of Civil Engineers (ASCE) urged New York officials to erect protective sea barriers to mitigate potential storm surge and sea level rise. In collaboration with the U.S. Army Corps of Engineers and other agencies, ASCE modeled worst-case scenarios of storm surge flooding, which were mapped by the New York City office of Emergency Management (NYOEM, 2009; Hill, 2013). Acknowledging the vulnerability of the entire region, storm surge barriers emerged for this first time as a valued need during a 1996 conference, “The Baked Apple? Metropolitan New York In the Greenhouse" (Hill, 1996). Pioneered at the School of Marine and Atmospheric Sciences at Stony Brook University, the idea of protective sea barriers materialized as a project to protect New York City (NYC) and its surrounding boroughs and NJ coast (Gornitz, 2001; Stony Brook Storm Research Group (SBSRG), 2013; Hill, 2013). This project, revisited at the 2009 ASCE conference, was advocated as the best way to regionally mitigate storm surge (Hill, 2013).

In conjunction with the ASCE, the Dutch hydrologists also advised multiple government agencies including NYC local officials including NYC Climate Change Task Force, state and federal agencies on possible flood mitigation strategies given their expertise in water management (e.g. the Deltaworks project in the Netherlands). Guided by complacency over risk perceptions, U.S. governing ideologies have remained locked in stale path-dependent trajectories as cost-benefit analysis are weighted heavily on budgetary constraints (Aerts et al. 2008; Botzen and van den Bergh, 2008; Chhetri et al. 2010). This could partially explain why NYC Climate Change Task Force did not accept this hard measure as a viable strategy, even though long-term benefits of preventing losses like Sandy outweighed the initial cost of 10 billion USD. Due to limitations of risk perceptions, mutual agreement, and financial support from regional and national level, NYC officials and NY state agencies sought cost-effective alternatives (e.g. raising pumps, soft measures of beach nourishment, wetlands and dune restoration (Rosenzweig et al. 2010, Rosenzweig et al. 2011), and improving evacuation routes) that proved only locally effective. As a result, these inactions did little to help the public and other institutions recognize and adapt to the disaster risk potential, evidenced by Hurricane Sandy's aftermath (Hill, 2013). After Sandy, multiple-layers of resiliency measures (e.g. beach nourishment, bulkheads, dunes, wetlands, groins, local surge barriers and multi-purpose levees) are still advocated over this large-scale measure because of their cost-effectiveness and modest scale. Building in flexibility and redundancy with these measures could elevate NYC to transformative adaptation, but will this cumulative effect be enough to successful mitigate rising sea levels.

Due to the lack of protective sea barriers, storm surge also incapacitated transportation and energy infrastructures that were already overtaxed. With only a few subway entrances constructed as elevated platforms, eight tunnels were submerged, resulting in the worst damages in the New York City Metropolitan Transit Authority (MTA) 108-year history at an estimated loss of 5 billion USD (Blake et al. 2013). The MTA and supporting institutions constructed the subway's power supply underground and unprotected, which failed to weigh the long-term benefits of enhancing technical resiliency. Given the increased probability of extreme climatic events (IPCC, 2012; Lin et al. 2012), maintaining the status quo of socio-technical systems through coping strategies and minimal innovation are inadequate. Institutions like ConEdison, the primary energy supplier to the Northeast U.S., are then driven by economic gains that perform basic restoration of downed power lines instead of upgrading to buried networks as seen in Europe. Although initial costs are required to upgrade these systems, the latter approach is four times more resilient than the former and could have prevented much of the energy disruption felt by 5 million customers in NY and NJ (Chairamonte 2012). As Holdren (2008), adaptation requires large-scale efforts and could mean sharing the initial cost, considering the national costs of disasters.

We argue that the willingness to invest in large-scale projects like protective sea barriers, flood-proof subways and durable energy platforms should be based on discursive knowledge, institutional collaboration and innovation of technologies. Unfortunately, catastrophic events (e.g.1,835 lives lost in the Dutch flood of 1953 and 1,800 due to Hurricane Katrina in 2005) act as tipping points for enacting robust

adaptation strategies (Aerts et al. 2009). In the wake of Katrina, transformative adaptation strategies such as relocation, elevated structures and the Inner Harbor Canal Surge Barrier (Kates et al. 2006) have been implemented as result of updated subjective probabilities of risks (Filatova et al. 2011) and institutional education and collaboration. As Roth (2013) purports, prior to a tragedy, knowledge capital is poor as the political culture fails to understand the potential for catastrophe and submits to an insufficient value of risk. More commonly, low probability disaster events with potentially high catastrophic losses are diminished to a low level of perceived risk. Even in the case of coastal flooding threats to NY and NJ, this high probability was not fully perceived or adequately addressed by formal institutions at the local, regional and national levels (e.g. FEMA and U.S. Congress) leading to the unwillingness to invest in robust adaptive measures and a highly vulnerable society (Roth, 2013).

Different perceptions of risk, economic rationality, and tipping points explain why Governor Cuomo expressed interest in regional mitigation strategies like protective sea barriers, while Mayor Bloomberg expressed skepticism. While Bloomberg has advocated for sustainable societies and climate change adaptation with programs like PlaNYC, he has voiced concerns about engineering feats and initial costs and questioned the long-term gains (Feuer, 2012, NYT). Although Mayor Bloomberg and Governor Cuomo showed concern about the risk of flooding, their contrasting perspectives highlight how perceptions are a key determinant of disaster policy, adaptation to coastal flooding, and management responses (Slovic, 2000). While disparities in perception of risks through individual and social lenses could initially ignore, dismiss, or modify biophysical risk,

this notion becomes critical as political interpretations of elected officials and decision-makers can feed the public attitudes and perceptions (Peacock et al. 2007). Although the feasibility and success of this project was modeled and assessed using historical events, no amount of engineering can offset organizational disagreement if decision-makers fail to envision and communicate the long-term benefits (Roth, 2013:13).

2.4. Discussion

Given the increased sensitivity of coastal cities to climate change, socio-ecological systems must improve their adaptive capacities through the appropriate use of resources, discursive knowledge, stakeholder engagement, and investment in technologies. The aftermath of Hurricane Sandy illuminates how a competing vision of NYC and surrounding boroughs are underpinned by different ideological, material, and economic interests and affect the priorities and actions of stakeholders and policy outcomes. Land use policies in coastal regions continue to be guided by rent seeking behavior and government subsidies, adding further vulnerability to already sensitive locations (Pielke, 2007). Although knowledge of these vulnerabilities and those of associated with climate change have been discussed in scientific-stakeholder engagements (e.g. NPCC, NYC Climate Change Task Force), current institutional approaches and limited resources make it difficult to redesign policy. Hurricane Sandy reveals the absence of collective learning, power sharing, and iterative reflection.

Fragmented perceptions of risk can inhibit communication and collective anticipatory actions among local, regional, and federal agencies as well as informal

institutions, consequently affecting their willingness to invest. Perceptions of risks are filtered by individual, social and informational lenses and framed as a result of personal experiences, cultural and social norms, media coverage and difficulty understanding probabilistic risk (Slovic, 1987; Leiserowitz 2006). For the majority of NY and NJ populations, climatological risk may have been tainted by the lack of personal experience since the 1938 Hurricane, Carol (1954), Donna (1960) and Agnes (1972) were the last significant storms to directly impact the region (NCDC, 2013). Excluding Tropical Storm Irene, more recent storms (e.g. Bertha 1996, Floyd 1999) only grazed the region, resulting in localized flooding from heavy rainfall. Further complicating this matter, the usage of probabilistic measures employed by scientists can be difficult to understand and are often misinterpreted by non-scientists like decision-makers (Hill, 2013). This knowledge gap diminishes the biophysical risk and may explain local and regional complacency and ineffective adaptive measures. Additionally, communication of risk through media has been primarily focused on hurricane hotspots, such as the Gulf region and Carolina Coast, diminishing coverage and communication of biophysical risk to certain geographies (Slovic, 1987; Leiserowitz, 2006).

While future hazards may not necessarily be predicted, the urgency of developing resiliency of socio-ecological systems suggests we need to learn how to live with the fuzziness of climate change (Pelling, 2011). A failure to fully comprehend exposure and vulnerability to climate change and sea level rise may provide a sense of complacency given our disagreements about this subject. One of the reasons we disagree is that we receive multiple and conflicting messages about climate change and we interpret them in

different ways (Hulme, 2009:214). In addition to perceptions of risk, information about climate change can be polarizing as the message may lack a neutral medium in which it is conveyed or may not be neutral as a result of how it is framed (Hulme, 2009). Frames organize central ideas, defining a controversy to resonate with core values and assumptions. They allow citizens to rapidly identify why an issue matters, who might be responsible and what should be done (Nisbet and Mooney, 2007: 56; Hulme, 2009). Different climate change frames can highlight different aspects and solutions to this 'wicked' problem, and thus explain why climate changes are not being acted upon (Rittel and Webber, 1973; Vink et al. 2013).

How risk has been framed has been critical to the success of Dutch policy on water management. In the past, the Delta Committee, the Netherlands' group of policy advisors, has framed flooding as a matter of national safety, urgency, national interest in 'Room for the River', 'Working together with Water', and 'Dutch level-headedness' respectively (Keesen et al. 2013; Vink et al. 2013). Flood risk is framed as safety issue by government agencies in narratives that tailor words in such a way that they become responsive to social rationales and criteria (Vink et al. 2013; Boezeman et al. 2013). These narratives based on scientific principles are sufficiently clear to the political actors, connect a range of policy programs and are acceptable for various stakeholders (Boezeman et al. 2013:169).

Knowledge, upon which these narratives are built, must be mobilized through a plurality of stakeholders in order to design robust strategies. Boundary organizations, such as the NPCC and Delta Committee (a Netherlands' group of policy advisors),

organize and exchange knowledge between science and policy (Rosenzweig et al. 2011; Boezeman et al. 2013). Knowledge is negotiated through ongoing consultations with stakeholders and continual updates (Boezeman et al. 2013). However, in order for consensual decision-making to occur, discursive discourse must also actively engage the public to reconcile local interests (Keesen et al. 2013). In terms of Dutch water management, local water boards serve as intermediaries, continually organizing consensus between top-down governance and bottom-up interests (Vink et al. 2013). This discursive discourse allows local, regional and national institutions to get behind a common goal and reiteratively negotiate the supply and demand for knowledge, necessary to redesign their socio-ecological systems (Keesen et al. 2013). For this reason, the Dutch have been able to tackle wicked problems like rising sea level and climate change by striking a balance with the political climate and social values.

In addition to plurality, the Dutch are also known for imagination and investment in innovation of technologies. The Dutch designed their Deltaworks program based on return periods ranging from 1/1,250 years to 1/10,000 years to assure robust measures considering two-thirds of the population lives under sea level (Aerts et al. 2013). Recognizing that climate change will lower these return periods, the Dutch are not only retrofitting the Deltaworks program to maintain national law standards of safety, but also seizing the opportunity to collocate wind turbines atop sea barriers and dykes (Aerts et al. 2013; Lord Hunt, 2013). Unlike the Dutch, standard U.S. engineering practices are based on 100 years events (e.g. the IHNC barrier). According to Wolcott 2009 and other colleagues, these practices are inherently flawed due to reliance on significantly outdated

intensity-duration-frequency (IDF) curves used to assess hydrological impacts on infrastructure design. Such design practices are a relic of our dependence on climate consistency of 100-year storms given the NPCC projections of these events occurring once every 35 to 55 years by 2050 (Rosenzweig et al. 2011). Thus, low threshold designs can lull the public and institutions into a false sense of security, inhibiting innovative design and opportunities.

Robust adaptation strategies should be reflexive and redundant. While hard measures like the aforementioned may initially protect socio-ecological systems, rigid designs can leave little room for uncertainty especially when designed for low thresholds (Haasnoot and Middlekoop, 2012). Both the Netherlands and NYC have recognized soft measures as a means to buffer against uncertainty while simultaneously harmonize social-ecological system. This idea has induced a paradigm shift away from traditional hard feats to soft measures with the Dutch already renegotiating policy (Vink et al. 2013). In terms of NYC, success stories of this approach were evident on portions of Coney and Fire Islands as localized damages from Sandy were attenuated because of natural capital. As a result, these measures are expected to be implemented in other regions as part of the Special Initiative for Rebuilding and Resiliency (SIRR), bore out of institutional collaboration. However, to combat coastal flooding, this plan also calls for hard measures of multi-purpose levees, floodwalls, and local storm surge barriers to regionally protect NYC and surrounding boroughs (PlaNYC, 2013). In addition to these measures, this plan seeks redundant measures with multiple flood barriers for protection and additional energy and transportation infrastructure to sustain demand. Given the past history of

incremental designs and limited financial resources, questions remain if the combined effect of these designs will be enough to withstand the next extreme event.

Limited financial resources could limit NY's ability to enact the proposed adaption strategies as budget gaps have already been noted. Historically, financial resources, policies and public support have coalesced after catastrophic events (e.g. Hurricane Katrina and the 1953 Dutch flood) thereby acting as catalysts for communication and policy change (Hill, 2013). After Katrina and public outcry, Congress approved 6 billion USD for United States Army Corps of Engineer (USACOE) flood projects and another 1.1 billion USD to construct the Inner Harbor Canal Surge Barrier (USACOE, 2012; PlaNYC, 2013). However, the untimely arrival of Hurricane Sandy amidst the U.S. economic crisis has already affected the allocation of federal funds. Disaster relief appropriations of 50.7 billion USD (already less than actual losses of 70 billion USD) have been reduced to 48 billion USD citing issues of sequestration stemming from the failure to reduce the federal deficit (PlaNYC, 2013). In addition to the disappointing 5,350 million USD in USACOE allocations, NYC notes a 4.5 billion USD gap with the present 10 billion USD not totally secured. (PlaNYC, 2013) Potential funding sources could come from utility rate increases, collecting undelivered 2 billion USD from Congress regarding the September 11, 2001 attacks, and proposed property and casualty insurance resiliency assurance surcharge (PlaNYC, 2013). Given that updated flood zones have been meant with public outcry due to additional costs, additional insurance could be met with resistance. In order for society to receive the sender's message, we must frame adaptation strategies and climate change hazards in

narratives that engage the plurality of stakeholders including the public to mobilize knowledge and necessary resources.

2.5. Conclusion

As climate changes and sea levels rise, coastal cities become even more vulnerable due to their sensitivity given their high population density and critical infrastructure (Chatterjee and Rosenzweig et al. 2010). Therefore, we must protect these socio-ecological systems by enhancing their adaptive capacities. Pathways to robust adaptation require harmonious synchronization of resources, knowledge, institutions and technological innovation. Societies would be more willing to invest in resources and technological innovation if knowledge is mobilized and discursive. This requires framing climate change in a narrative that concisely identifies why it matters, who may be responsible and what can be done (Nisbet and Mooney 2007:20; Hulme 2009) in order to tackle this wicked problem. Thus, institutional organization is key in redesigning policy.

Climate adaptation calls for learning as an iterative process in order to enhance adaptive capacities now, rather than in the distant future. Adaptive measures must shift away from the current mode of risk management to preparedness if we are to mitigate future damage to socio-ecological systems. Given the trajectory of climate change, current recovery practices are ineffective and short-sighted as they leave societies just as vulnerable as they were before by returning them to their pre-disaster state. Thus, it is in our best interest to embrace opportunities exposed in the aftermath of disasters like Sandy to learn where weaknesses lie. These extreme events can serve as 'policy windows'

encouraging behavioral and institutional reform, necessary for robust adaption (Solecki et al. 2012; Kates et al. 2012).

CHAPTER 3

DESIGN WITH NATURE: KEY LESSONS FROM MCHARG'S INTRINSIC SUITABILITY IN THE WAKE OF HURRICANE SANDY

Wagner, M., J. Merson, and E. A. Wentz, 2016: Design with Nature: Key lessons from McHarg's intrinsic suitability in the wake of Hurricane Sandy. Landscape and Urban Planning, 155, 33-46.

3.1. Introduction

Sustainability science and ecological wisdom are complementary research areas that can be leveraged to mitigate disaster impacts and climate change threats in urban areas through sustainable design (Steiner et al. 2013; Xiang 2014). Sustainability science provides a broad framework for actionable science, which creates a space for discourse about human and environment interactions and facilitates the generation and application of knowledge to guide urban design (Anderies et al. 2013). Ecological wisdom supports this framework by calling for theoretical and practical knowledge to address relevant societal issues in the form of domain knowledge that encompasses declarative (knowing that) and procedural (knowing how) knowledge (Xiang, 2014: 67). This allows one to understand the central problem, perceive situations and come up with wise recommendations in line with their commitment to doing real and permanent good (Xiang, 2014: 67). This wisdom guides sustainable designs that are ecologically inspired

to provide lasting ecological services at a minimal cost to the coupled human-environment system (CHES), which sustainable science also aims to do.

The coupled human-environment relationship highlights the importance of geographical context for sustainable solutions with a focus on ecologically inspired designs (Xiang, 2014). Both sustainability science and ecological wisdom draw upon the core concept of resilience: the ability of a system to respond to a disturbance, capacity to learn or adapt, or to self-organize (Holling 1973, Walker et al. 2004; Turner, 2010) and seek to enhance system resilience. Sustainability science focuses on outcomes (i.e., sustainable design and planning) aligning itself with decision making frameworks (Anderies et al. 2013), whereas, ecological wisdom concentrates on knowledge production and engagement through the project lifecycle. Understanding how hazards, disasters and their associated risks are intrinsically linked to place is critical to devising sustainable designs due to locally specific natural and social conditions (Cutter et al. 2008). These solutions must consider land use suitability constraints in terms of carrying capacity and opportunities for multifunctional landscape design (Yang and Li, 2013). This involves the role of ecosystem services in providing provisional food and cash crops, regulating systems (e.g., water purification, flood mitigation), protecting cultural areas (e.g., recreation, sacred place), services for human well-being, and creating opportunities for ecological engineering to mitigate disaster impacts (Carpenter et al. 2009; Steiner et al. 2013).

Ian McHarg created a legacy of ecologically inspired designs that resonate today as sustainable and ecologically wise (Xiang, 2014). His concept of intrinsic suitability

helped to optimize the greatest benefits of an area, while minimizing the cost to both society and environment (McHarg, 1969). According to McHarg, environmentally sensitive areas can be put to limited use with restrictions, whereas, vulnerable locations should remain undeveloped to avoid loss of life and property (McHarg, 2007; Steiner et al. 2013; Xiang, 2014). McHarg placed water issues, such as stormwater management, at the forefront in his designs. He viewed stormwater management as flood adaptation strategies instead of flood control by either incorporating natural stormwater management systems (e.g., The Woodlands, TX design) or designating flood prone areas as unsuitable for development (e.g., Staten Island project) (Steiner et al. 2013). This approach recognized dynamic linkages in CHES and explored tradeoffs that incorporated ecologically inspired designs. Additionally, it required a deep understanding of place in terms of landscape limitations and opportunities.

In the 1960s, McHarg introduced these ideologies in his book, *Design by Nature*. In one chapter of his book, Processes as Values, he assessed the intrinsic suitability of Staten Island and revealed potential land uses for the City of New York and Department of Parks (McHarg, 1969). Through this, he pioneered the "map overlay" concept as he illustrated how the combination of map variables, such as soil type, slope, cultural sites, and flooding potential, could be useful in prioritizing the land's suitability for a given use. What became of his study largely remains unknown, but it is clear that development on Staten Island followed a trajectory largely guided by economic decisions instead of McHarg's intrinsic suitability.

Because McHarg's intrinsic suitability was not implemented on Staten Island (Steiner et al. 2013; Wagner et al. 2014; Xiang, 2014), damage from Hurricane Sandy was extensive across the island, as well as along the northeastern seaboard. Hurricane Sandy made landfall near Atlantic City, New Jersey on October 29th, 2012 with 4.3-meter storm surge and sustained wind speeds of 85 mph (Blake et al. 2013). Sandy crippled the region's transportation network with flooding in eight New York City (NYC) subway tunnels, left 5 million residents without power, and closed the New York Stock Exchange for two days (NCDC, 2012). New York and New Jersey withstood the greatest losses with 91 deaths and 650,000 structures damaged or destroyed (NCDC, 2012; Wagner et al. 2014). Staten Island, New York bore the brunt of Sandy's damaging impacts with 23 deaths concentrated along the eastern shore and 6,817 structures damaged or destroyed (NCDC, 2012; FEMA, 2013).

The goal of this research is to examine the impact of Hurricane Sandy, focusing on Staten Island land uses subjected to unsustainable planning on Staten Island. We examine McHarg's Staten Island study as an example of sustainable planning and ecological wisdom. Except for a few case studies including Lee (1982) and the research by Yang and Li (2011; 2013), there has been little attention to the direct impact of McHarg's principles. We draw upon McHarg's study to evaluate how damage from Hurricane Sandy could have been attenuated had development followed McHarg's intrinsic suitability. First, we modify McHarg's mechanical map overlay analysis by using computer GIS overlay and a common classification scheme to compare McHarg's land use suitability with 2012 land use and areas damaged by Hurricane Sandy. Second, we

evaluate whether McHarg's recommendations were realistically possible by analyzing historical (i.e., 1960) and contemporary (i.e., 2012) zoning for Staten Island using a classification scheme of urban versus green space. Lastly, we discuss how unwise decisions contributed to unsustainable development on Staten Island and conclude with a brief discussion on sustainable designs that are being implemented post-Hurricane Sandy.

3.2. Background

3.2.1. Land Suitability Analysis

Emerging from a legacy of land use planning methods that include Olmsted, Eliot, and Cleveland of the late 1800s and early 1900s (Fábos, 2004), land suitability analysis emerged as a method for ecological planning. These early works used maps to select and identify areas best suited for greenway development and reclamation of urban coastal and river areas for parks and recreation areas. By the 1960s, Phil Lewis's work on environmental corridors highlighted the importance of identifying environmentally sensitive areas for conservation, through map assessments and analysis (Lewis, 1964; Fábos, 2004). Around the same time, the "map overlay" concept used by McHarg, emerged as a primary methodology for land suitability analysis and ecological planning (Steinitz and Jordan, 1976). Land use suitability analysis relies on formulating decision criteria and ranking the suitability of a land parcel for a specific land use (Steinitz, 1993). Beyond greenway development, examples of land use suitability identification include habitat protection and biological reserve design (Zucca et al. 2008), housing (Joerin et al. 2001), route selection (Jankowski and Richard, 1994), landfills (Kontos et al. 2005) and

agriculture (de la Rosa et al. 2004; Lovett et al. 2009). The decision criteria for ranking parcels on the suitability of land use types are derived from expert opinion, stakeholder input, and empirical studies to maximize outcomes (Steinitz, 1993). Software tools such as geographic information systems (GIS), remote sensing, and methodologies such as multi-criteria decision-making statistics, neural networks, expert systems, and cellular automata are used to evaluate options and alternatives in land use planning (Cerreta and De Toro, 2012; Miller et al. 1998; De la rose et al. 2004, Wang, 1994; Arciniegas and Janssen, 2012).

Implementations of the land use suitability approach, described above, often limit land use to a single function. Alternatively, more complex suitability analyses, such as McHarg's approach, recognize that assigning more than one land use can result in a parcel that serves several functions, such as mitigation of environmental impacts, economic growth and development, and urban forms that are artistic or aesthetic. To understand the influence of multifunctional landscape design, Yang et al. (2013) evaluated the long term impacts of McHarg's ecological design on stormwater runoff, urban heat island (UHI) effect, and social acceptance in The Woodlands, TX community. The Woodlands, TX community was designed and implemented using McHarg's principles with the goal of using soil type, forest preserves, and open drainage systems to manage stormwater (Yang and Li, 2011). Over time newer developments in The Woodlands, TX community shifted away from McHarg's multifunctional landscape designs toward conventional suburban designs that emphasized efficient use of space. Results of Yang et al. (2013) show positive influences of multifunctional landscape

designs for stormwater management and UHI mitigation but high personal safety concerns in ecologically designed areas compared to conventionally designed areas.

3.2.2. Ecosystem Services and Ecological Engineering

Land use suitability, ecological engineering and ecosystem services are increasingly recognized as important strategies to mitigate disaster impacts especially in flood prone areas (Dunn, 2010, Steiner et al. 2013). Hard engineering measures (e.g., sea walls, dams and other artificial structures) have been favored in the past as a means to address water management issues such as tidal inundations and coastal flooding. These measures, however, are usually associated with higher economic and ecological costs than ecologically inspired measures and potentially lead to greater damage due to the release of larger volumes of water associated with system failure (Chapman and Underwood, 2011; Van Slobbe et al. 2013). Ecologically inspired measures are seen as sustainable alternatives to hard engineering measures that ameliorate negative impacts associated with development, by working with ecological processes and land use suitability (Cooper and McKenna, 2008; Chapman and Underwood, 2011; Van Slobbe et al. 2013). These measures are more likely to sustainably attenuate current and future threats of flooding, because they consider dynamic processes of ecosystems, allow for flexibility in their designs and have lower maintenance costs.

Ecosystem services are widely recognized as strategies that enhance human livelihood through functions associated with biological systems, such as stormwater management and urban heat island mitigation. Other examples include the way in which

vegetation and trees contribute to air quality improvement, carbon sequestration, biodiversity enrichment, and recreational/cultural/aesthetic value (Bolund and Hunhammer, 1999; Roy et al. 2012; Akbari et al. 2001; Yang et al. 2013; Werling et al. 2014). Greenways, as recreational, cultural, and historical sites, form an example of multifunctional landscape design that provides a range of ecosystem services (Fábos, 2004). Performance metrics on ecosystem services have reported mixed results showing land use combinations produce trade-offs rather than direct linkages to human well-being (LaGro, 1996; Yang et al. 2013; Werling et al. 2014). These results, however, are contingent on relationship typologies, and highlight the importance of drivers and interactions among ecosystem services (Bennett et al. 2009). LaGro (1996) has challenged the need to rely on ecosystem services (e.g., depth to bedrock, soil permeability, and slope) as determinants for urban development because of technological advances such as improved wastewater management and transportation infrastructure. Ecosystem services, unlike technological advancements, are more likely to manage human-environment relationships with fewer expenses and enhance ecosystem resilience to extreme events (Bennett et al. 2009).

Ecological engineering supplements traditional engineering with the inclusion of ecological processes to reduce environmental impacts, solve problems or create amenities for society (Chapman and Underwood, 2011; Mitsch, 2012). It requires a systems-based approach to understand potential benefits and impacts to both human and environment systems (Mitsch and Jorgensen, 2003; Odum and Odum, 2003). 'Self-organizing' design maximizes design performance with the idea that ecosystems organize to fit with

technology or adapt to new conditions (Mitsch and Jorgensen, 2003; Odum and Odum, 2003; Mitsh, 2012). These designs have been used to restore environmentally degraded areas such as rivers (Bednarek and Hart, 2005), wetlands (Brown and Ulgiati; 1997) and mangrove forests (Lewis, 2005) or to develop resilient ecosystems that are valued by CHES (Odum and Odum, 2003) such as shoreline stabilization (Jones and Hanna, 2004) and wastewater treatment wetlands (Hammer, 1989). In the case of The Woodlands, TX design, bioswales were engineered to replicate the ecological performance of wetlands in order to maintain the hydrological balance associated with residential land use (Yang and Ming-Han, 2010; Steiner, 2014). Implementing robust designs like bioswales entail using McHarg's principle of intrinsic suitability to minimize the environmental impacts of a particular land use (Yang and Ming-Han, 2010).

3.2.3. Ecological Wisdom

Ecological wisdom is a theoretical framework and set of practices for implementing ecologically inspired designs that have lasting socio-ecological benefits. By combining eastern and western conceptions of the nature of reality, ecological wisdom advances a more holistic approach to urban sustainability. Similar to resiliency theory, ecological wisdom focuses on the dynamic coupling in CHES by recognizing how things are interconnected. The principal of interconnectedness is critical to identifying the limitations and constraints as well as the potential or possibility of a particular location (McHarg, 1969, Xiang, 2014). This directly connects with McHarg's idea of intrinsic suitability; however, intrinsic suitability also entails engaging ethical,

social, environmental, and cultural concerns especially with the goal of developing sustainably. Advancing sustainability requires a deep understanding of the problem and, in some instances, negotiates a community of concerns and competing claims about what sustainable development entails in order to materialize long-lasting solutions (Xiang, 2014). Thus, ecological wisdom views sustainability as a set of practices intent on raising awareness about the human impact on material reality (economic, social, cultural), within an ethical register that inspires both innovative and interventionist initiatives and strategies.

Studies have shown that ecologically-inspired designs are more likely to produce efficacious solutions: capable of inducing desired results and effects, as seen with Li Bing's Dujiangyan irrigation system and Ian McHarg's Woodland, TX design (Xiang, 2014). Ecological wisdom is attained by combining evidence-based knowledge from diverse philosophical, cultural, historical and disciplinary backgrounds (Xiang, 2014: 67). As Xiang (2014: 67) notes, ecological wisdom can be used in conjunction with principles and strategies of economic, political, social and cultural relevance to inform the practice of urban sustainability research, planning, design, and management. By drawing upon principles advanced by ecological wisdom (i.e., interconnectedness), sustainable solutions could offer permanent immunity to current and future hazards, because they incorporate flexibility in their designs that are locally specific to the natural and social conditions of a region (Cutter et al. 2008; Xiang, 2014).

3.3. Methods

3.3.1. Study Area

The study area is Staten Island, one of five New York City boroughs (see Fig. 3.1). Nestled in the bight of the Northeastern Atlantic Seaboard, Staten Island lies between Brooklyn, New York and the eastern coast of New Jersey. This triangular shaped island is 22.4 kilometers long and 11.7 kilometers wide and covers an expanse of approximately 152.8 square kilometers (U.S. Census, 2014). The Raritan and Lower New York Bays border its eastern and southern shores, respectively.



Fig. 3.1. Study Area: Staten Island, New York.

Although Staten Island is the least populated NYC borough, roughly 500,000 residents inhabit the island (U.S. Census, 2014). The northern and eastern shores are heavily developed extending to the center part of the island near LaTourette Park. Development in these regions was largely encouraged with the erection of the Verranzo-Narrows Bridge in 1964 connecting the island to Brooklyn (McHarg, 1969). Over the years, urbanization continued especially along the eastern shore. Within this region, conservation and recreation areas (e.g., Great Kills Park, Miller Field, Ocean Breeze Park and Franklin D. Roosevelt Boardwalk and Beach) are bordered by residential communities of Midland Beach, New Dorp and Oakwood. Dubbed the 'Greenest Borough', the southern area is also speckled with conservation and recreation areas (e.g., Wolfe's Pond Park, Mount Loretto State Forest, Clay Pitt Ponds State Park Preserve and Bloomingdale Park). The western shore is comprised of wetland areas, parks and manufacturing and industry.

3.3.2. Data Sources

The four primary data sources for the study are land suitability recommendations from McHarg's study, 2012 land use, storm damage boundaries from Hurricane Sandy and zoning delineations from 1960 and 2012. All datasets were converted into the Universal Transverse Mercator Zone 18 North coordinate system for analysis.

To create McHarg's land use suitability, we created a digital representation from McHarg's maps (1969). Although McHarg presents the combined suitability layers in a single composite map (p 114), we reconstructed this map from urban, recreation and

conversation suitability maps for two reasons (pages 110, 112, and 113 respectively). First, it was extremely difficult to disentangle subtle differences in color defining 28 possible suitability classes in his composite map. Second and more importantly, the legend colors did not match the colors in the composite map due to moiré, a printing artifact created when different colored inks are superimposed in the printing process. Consequently, maps of urban, recreation, and conservation suitability were scanned, georeferenced to 2012 digital orthophotography, and subsequently digitized into vector maps with 5 levels of suitability (most, high, moderate, slight and unsuitable see Figs. 3.2a-c). We recreated the composite map following McHarg's classification scenarios and overlay analysis (see Fig. 3.3). Because actual land use is defined by class type only, and not degree of suitability, we could only evaluate class type. Therefore, we removed suitability degrees and collapsed 28 classes into 7 categories: urban, conservation, recreation, urban-conservation, urban-recreation, conservation-recreation and urban-conservation-recreation in order to compare McHarg land use suitability with 2012 land use. An additional category 'Other' was added to the map layer to capture the slivers that McHarg left unclassified including the arterial roads. This reduced McHarg's original 28 classes down to 8 categories and, therefore, modified McHarg's original composite map (see Fig. 3.4).

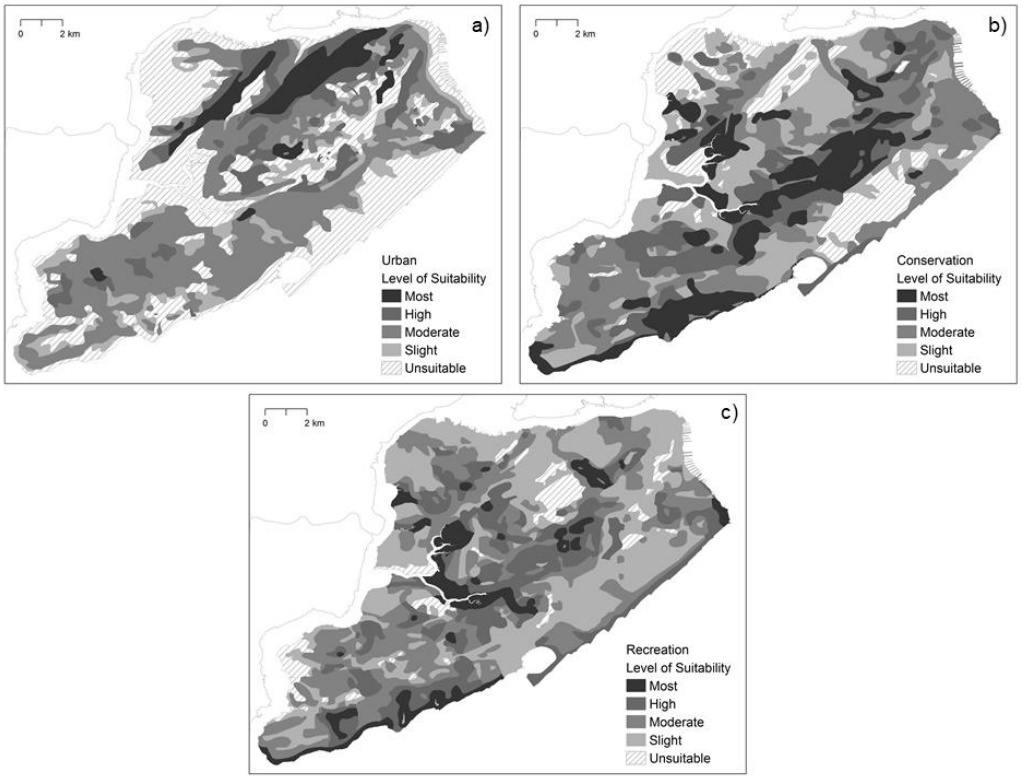


Fig. 3.2. Land Use Suitability According to McHarg for a) Urbanization b) Conservation c) Recreation for Staten Island with Dark Areas Representing Most Suitable and White Hatched Areas Representing Unsuitable.

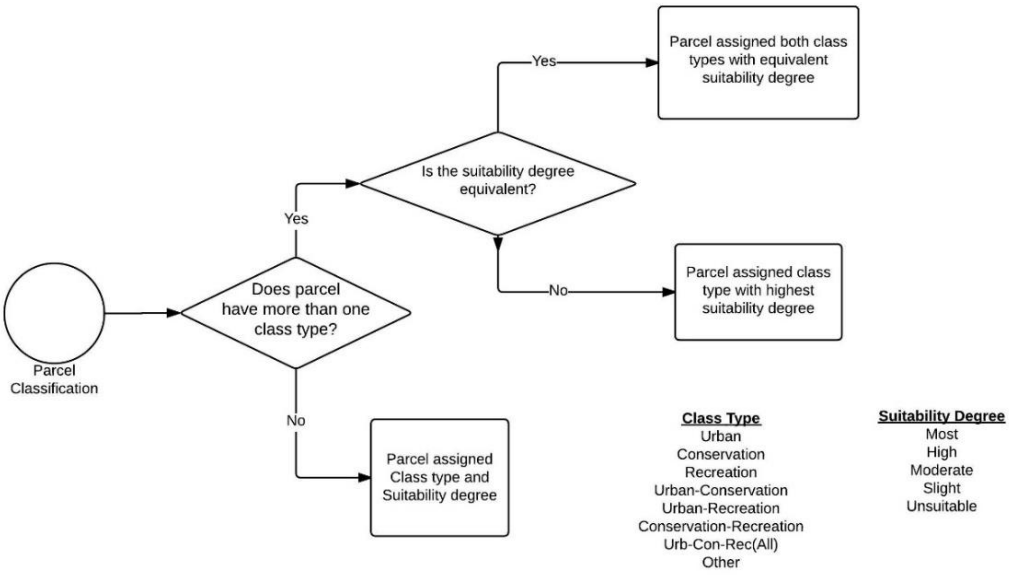


Fig. 3.3. Decision Tree for McHarg Land Use Classification.

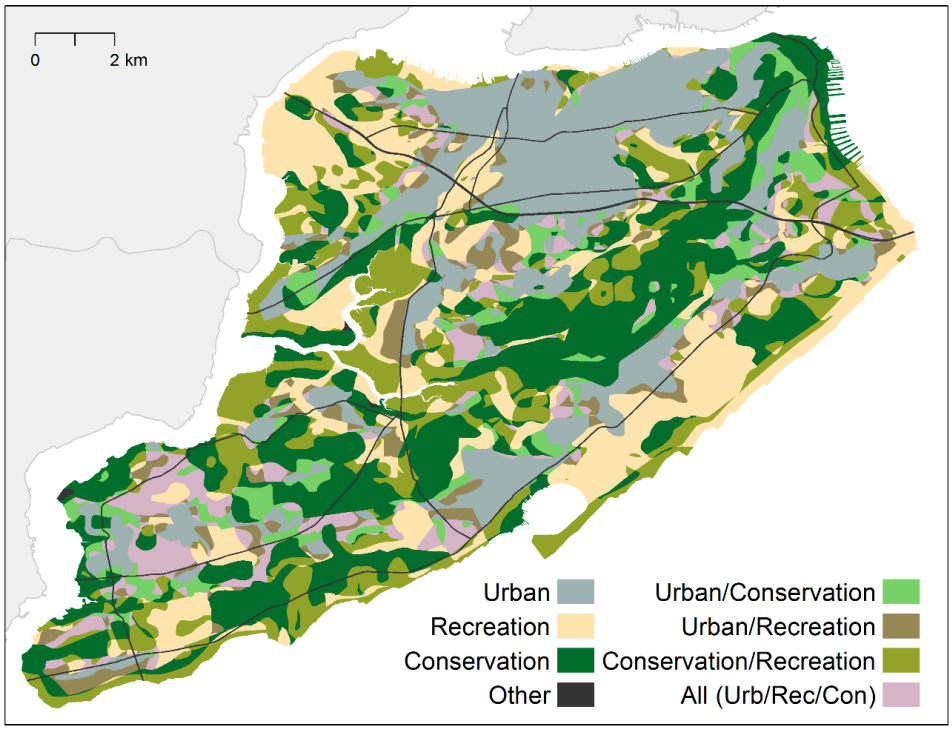


Fig. 3.4. McHarg's Land Use Suitability Composite Classification for Staten Island.

The 2012 land use data were created from a combination of municipal, state, and federal datasets (see Table 3.1). Urban areas were classified based on the presence of residential areas, commercial development, or collector and local roads. Recreation areas were classified following McHarg's definitions of active and passive recreation usage. Active recreation areas were defined as regions designated for intensive recreational use (e.g., beaches and athletic fields), whereas, passive recreation areas have less intensive usage (e.g., unique physiographic features, scenic areas, high quality forests or marshes, and ecological regions) (McHarg, 1969). Conservation areas were classified based on the need to preserve scarce, unique or historical lands as well as open spaces (e.g., wetlands, nature sanctuaries and cemeteries). Lastly, the ‘Other’ class included the same arterial roads as in McHarg's analysis and the Fresh Kills Landfill. While the Fresh Kills landfill is transitioning into a park over the course of 30 years, we only included completed sections of the Fresh Kills parks in the recreation and conservations classes. Fig. 3.5 illustrates the 2012 land use.

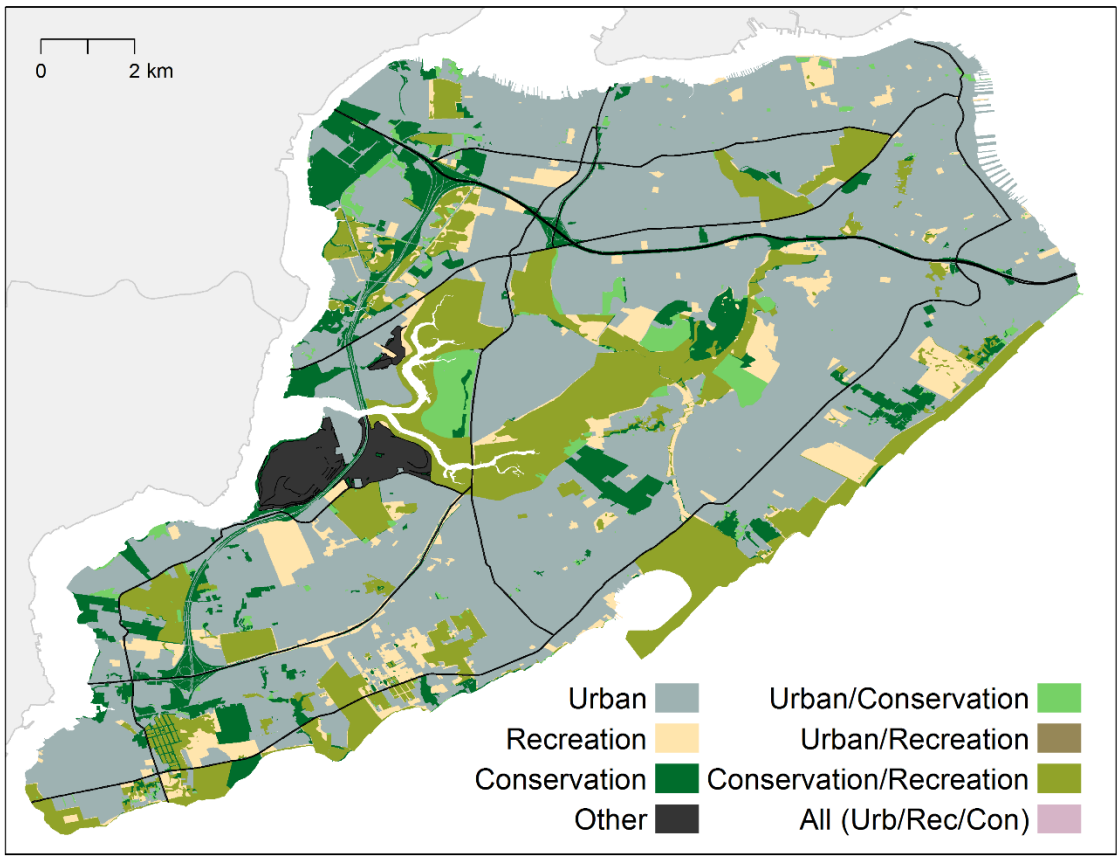


Fig. 3.5. 2012 Observed Land Use for Staten Island.

Table 3.1. List of 2012 Land Use Source, Year, Attribute, Land Use Classification.

Data	Source	Year	Attribute/Feature	Land Use Classification
NYC Map Pluto 13V1	NYC Dept of Planning, Information Technology Division	2013	one & two family, multi-family walk-up, multi-family elevator, mixed residential and commercial and office buildings	urban
			industrial & manufacturing	urban
			transportation & utility	urban
			public facilities (institutions)	urban
			parking	urban
			public facilities (religious, education and government institutions)	urban
			public facilities (jointly owned playgrounds and sport facilities)	recreation
			open space and outdoor recreation	recreation
National Registry of Historical Buildings	NY State Office of Parks, Recreation & Historic Preservation	2013	historical buildings	urban, conservation

Data	Source	Year	Attribute/Feature	Land Use Classification
NY Public Land Boundaries	NY State Office of Cyber Security & Critical Infrastructure	2005	municipal recreation	recreation, conservation
NY Public Land Boundaries	NY State Office of Cyber Security & Critical Infrastructure	2005	state recreation	recreation, conservation
			federal recreation	recreation, conservation
			federal recreation	recreation, conservation
NYC Beaches	NY State Office of Parks, Recreation & Historic Preservation		beaches	recreation, conservation
Parks	NY State Office of Parks, Recreation & Historic Preservation	2013	all parks except cemeteries & industrial parks	recreation
Parks	NY State Office of Parks, Recreation & Historic Preservation	2013	cemeteries	conservation
			industrial park	urban
Open Space	InfoTech/GeoDecisions	2008	malls and plazas	urban
			highway and street green spaces	Conservation

Data	Source	Year	Attribute/Feature	Land Use Classification
Open Space	Info Tech GeoDecisions	2008	parks, beaches, playground, athletic fields and boardwalk	recreation
			wetlands, nature sanctuary, undeveloped	conservation
NY Parks	NY State Office of Parks, Recreation & Historic Preservation	2010	state park preserve	recreation, conservation
Natural Heritage Community Occurrences	NY State Dept of Environmental Conservation	2013	uplands, freshwater non-tidal wetlands	conservation
National Wetlands Inventory	U.S. Fish and Wildlife Service, Division of Habitat and Resource	2010	freshwater forested/shrub, estuarine and marine and freshwater emergent wetlands	conservation
Conserved Lands	NY State Dept of Environmental Conservation	2013	tidal wetlands, shoreline, ponds, unique area, woods	conservation
NYC Zoning	NYC Dept of Planning	2013	zoning classifications	urban/park & green spaces

Hurricane Sandy storm surge and building damage data were obtained from the Federal Emergency Management Agency (FEMA Modeling Task Force 2013; FEMA 2013), shown in Fig. 3.6. Storm surge data were derived from field-verified high water mark in vector and raster formats. We used the vector format to focus on the extent of flood waters. Building damage data are geographically referenced points that identify buildings affected by storm surge, high winds or heavy rains. This dataset assigns ratings of affected, minor, major and destroyed based on observed damage and estimated costs of repair.

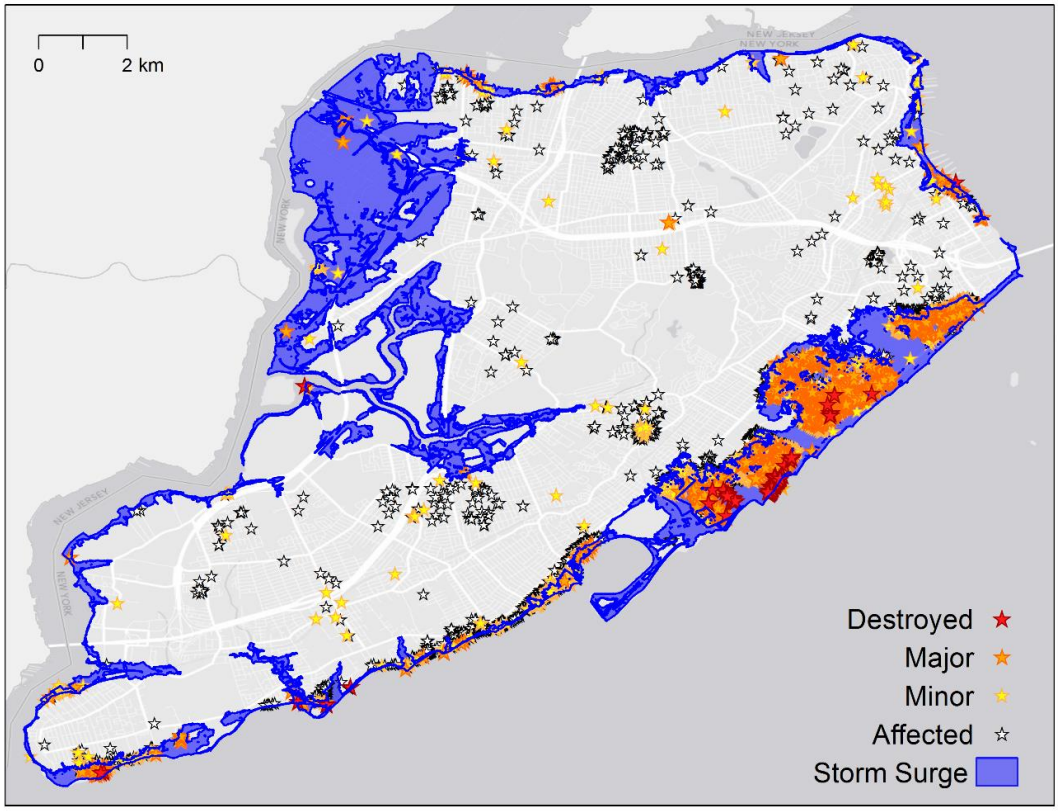


Fig. 3.6. FEMA Storm Surge Data and Building Point Damage Estimates for Staten Island (Source: FEMA Modeling Task Force).

We also obtained 1960 and 2012 zoning data from the City of New York City Planning Commission in print and digital formats, respectively. The 1960 zoning data were digitized and georeferenced. To focus on urban vulnerability to coastal flooding and storm surge, zoning datasets were reclassified into urban (residential, commercial and manufacturing zones) and park and green spaces (zoned parks and cemeteries), (see Figs. 3.7a-b).

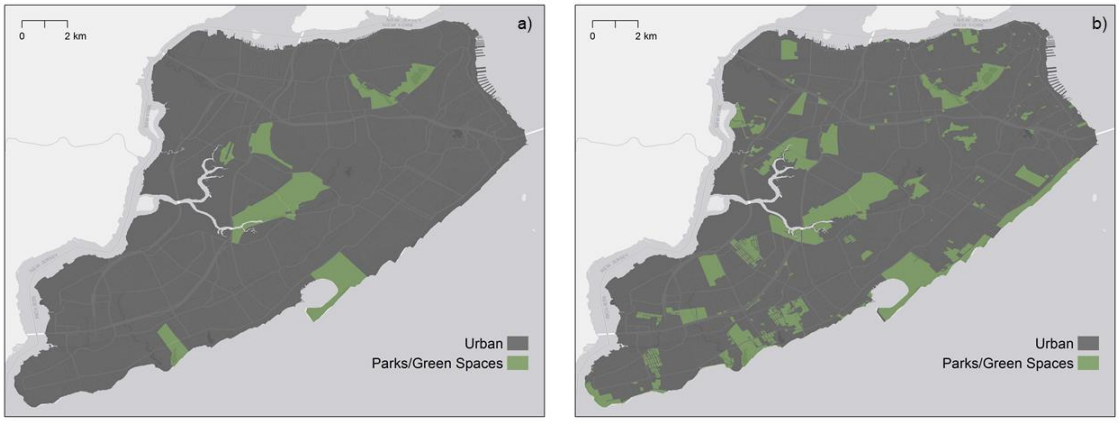


Fig. 3.7. Zoning Map for Staten Island a) 1960 (Source: City of New York City Planning Commission) b) 2012 (Source: New York City Department of City Planning).

3.3.3. Analysis

The first part of the analysis examines the role of land use suitability by comparing damaged buildings and storm surge affected areas from Hurricane Sandy to both McHarg's land use suitability and 2012 land use. This analysis calculates the area damaged by Hurricane Sandy storm surges for each land use class from McHarg's land use suitability map and 2012 land use (see Table 3.2). We perform z-tests to evaluate whether the difference in areas per land use class between McHarg's land use suitability

and 2012 land use is statistically significant. These tests compare the difference between the total area and surge impacted area, per land use class. In addition to storm surge, we intersected building damage with each land class to compare the number of damaged buildings, per class, for each time period (see Figs. 3.8-3.9; Tables 3.3a-b).

Table 3.2. McHarg's and 2012 Land Use Classification for Total Area and Storm Surge Impacted Area.

Land Use Class	Total Area				Surge Impact			
	McHarg's Land Use Suitability		Observed Land Use		McHarg's Land Use Suitability		Observed Land Use	
	Area (km2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Urban	30.4	20.4	92.8	62.4*	1.4	4.9	11.3	39.9*
Conservation	37.4	25.2	12.5	8.4**	6.1	21.5	5.4	19.1
Recreation	27.5	18.5	9.8	6.6*	10.9	38.6	2.1	7.5*
Urban-Conservation	9.1	6.1	3.9	2.6	0.3	1.2	0.9	3.2
Urban-Recreation	7.1	4.8	0.0	0.0	0.7	2.6	0.0	0.0
Conservation-Recreation	25.1	16.9	24.1	16.2	8.0	28.4	8.1	28.5
Urb-Con-Rec (All)	10.1	6.8	0.9	0.6	0.6	2.0	0.0	0.1
Other	1.9	1.3	4.7	3.2	0.3	0.9	0.5	1.8

*Z-test two population proportions difference significant at *0.01, **0.05*

Table 3.3. Building Damage by Land Classification

		Percent of damage found in each land cover class using McHarg's classification								
		Urb	Con	Rec	Urb/Con	Urb/Rec	Con/Rec	Other	All	Total
Percent of damage found in each land cover using the contemporary classification	Urban	6.2%	15.3%	46.2%	1.6%	3.3%	21.3%	0.0%	1.8%	95.6%
	Con	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%
	Rec	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
	Urb/Con	0.1%	0.7%	1.5%	0.2%	0.1%	0.4%	0.0%	0.0%	3.0%
	Urb/Rec	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Con/Rec	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
	Other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	All	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Total	6.3%	16.1%	48.6%	1.8%	3.4%	21.9%	0.0%	1.8%	

Urb = Urban, Con = Conservation, Rec = Recreation

Table 3.4. Building Damage by Land Classification in Storm Surge affected areas.

		Percent of storm surge damage found in each land cover class using McHarg's classification								
Percent of storm surge damage found in each land cover using the contemporary classification		Urb	Con	Rec	Urb/Con	Urb/Rec	Con/Rec	Other	All	Total
	Urb	3.6%	15.5%	52.8%	1.1%	2.2%	18.2%	0.0%	1.6%	94.9%
	Con	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%
	Rec	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
	Urb/Con	0.2%	0.8%	1.9%	0.3%	0.1%	0.3%	0.0%	0.1%	3.6%
	Urb/Rec	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Con/Rec	0.0%	0.0%	1.1%	0.0%	0.0%	0.1%	0.0%	0.0%	1.2%
	Other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	All	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Total	3.7%	16.6%	55.7%	1.4%	2.3%	18.6%	0.0%	1.7%	

Urb = Urban, Con = Conservation, Rec = Recreation

The second part of the analysis examines the trajectory of urban development and implications for policy to evaluate whether McHarg's recommendations could have been realistically implemented then or in 2012. We calculate the total area for urban and park and green spaces for both 1960 and 2012 zoning (see Table 3.4). Next, we make the following comparisons: *1960 vs. 2012 zoning*, *1960 zoning vs. McHarg's land use suitability*, *2012 zoning vs. 2012 land use* by calculating the percent of McHarg's land use suitability and 2012 land use for each zoning class. For urban areas, we summed urban, urban-recreation and urban-conservation classes. For park and green spaces, we summed conservation, recreation and conservation-recreation classes.

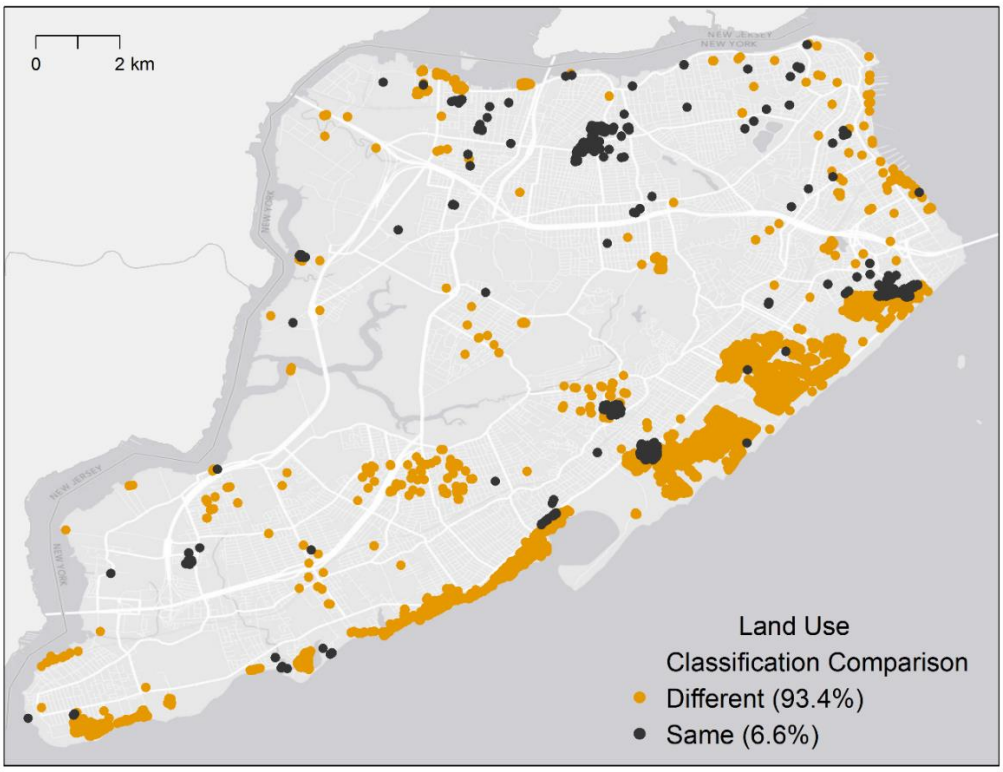


Fig. 3.8. Land Use Classification Comparison between McHarg's Land Use Suitability and 2012 Land Use Based on Location of Building Damage Estimates.

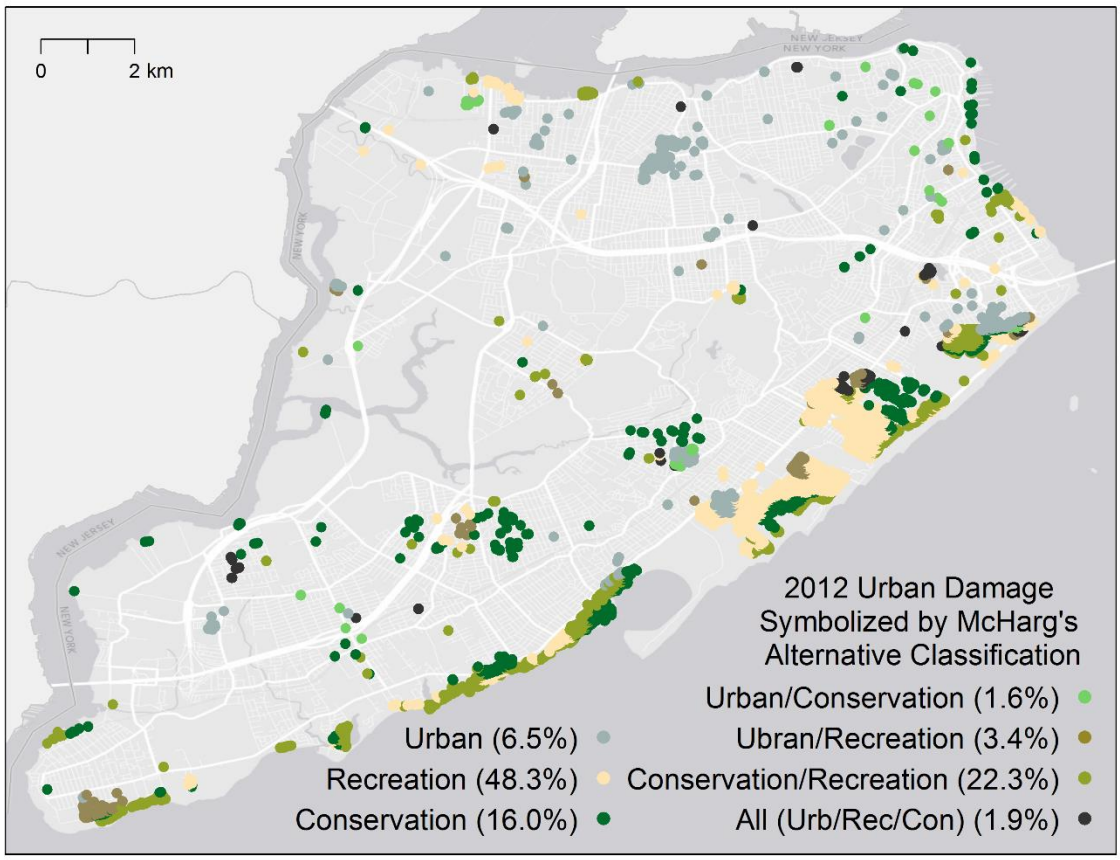


Fig. 3.9. Building Damage Estimates Symbolized by McHarg's Land Use Suitability.

Table 3.5. 1960 and 2012 Zoning for Staten Island, Percent Overlap between 1960 Zoning and McHarg; 2012 Zoning and 2012 Land Use.

	1960 Zoning		Overlap of 1960 Zoning & McHarg		2012 Zoning		Overlap of 2012 Zoning & Land Use	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Urban	139.5	92.5	45.6	30.2	127.9	84.8	97.4	64.6
Parks	11.3	7.5	9.7	6.4	22.9	15.2	22.2	14.7
Total	150.8	100.0			150.8	100.0		

3.4. Results

3.4.1. Land Use Classification

Significant differences were evident between McHarg's land use suitability and the 2012 land use across Staten Island. In McHarg's study, suitable urban land use constituted only 20.4% of the total area, while in the 2012 land use, this land use class was three times greater, dominating 62.4% of the island (see Table 3.2). This finding came mostly at the expense of the conservation and recreation classes in the 2012 land use as these classes were significantly lower than McHarg's study, totaling only 8.4% and 6.6% compared to 25.2% and 18.5%, respectively. The differences between McHarg's study and 2012 land use were statistically significant for the urban class ($p=0.01$), the conservation class ($p=0.05$), and the recreation class ($p=0.01$).

In storm surge areas, similar differences were observed between urban and other land use classes (see Table 3.2). Storm surge covered 39.9% of urban areas in 2012. Had land use patterns followed McHarg's recommendations, storm surge would have impacted only 4.9% of urban areas. In McHarg's study, storm surge would have instead affected 38.6% of recreation areas, which would have resulted in minimal structural damage and lower economic loss. The differences between McHarg's land use suitability and 2012 land use were statistically significant for both urban and recreation classes ($p=0.01$). On the other hand, conservation and conservation-recreation areas did not suffer from this scarcity. While the *amount* of observed and recommended areas were similar, the *locations* of these classes differed, as they were concentrated in the northwest storm surge affected areas in the 2012 land use.

3.4.2. Building Damage Assessment

Examining land use classifications based on building damage data show striking proportional differences between 2012 land use and McHarg's land use suitability. This shows that there would have been a considerable reduction in buildings damaged if these areas were left undeveloped. Only 6.6% of the different land use classifications shared the same suitability with most of the differences observed along the eastern shorelines (see Fig. 3.8). Of 6,817 buildings damaged from storm surge, high winds and heavy rains, most of the damaged buildings (96%) were located in urban areas in the 2012 land use, whereas, those same buildings, according to McHarg's study, should have been located in conservation (16.0%) and recreation areas (48.3%) (see Fig. 3.9; Table 3.3a). Although McHarg's study was strictly a land use suitability analysis and not a master plan for building locations, only 13.3% of damaged buildings were located in any of the urban land classes. Economic losses would have been considerably less in McHarg's scenario.

The role of land use is reinforced when examining the locations of buildings damaged in storm surge area (see Table 3.3b). Approximately 95% of damaged buildings were located within the storm surge in the 2012 urban areas, amounting to 78.1% of the damaged buildings on Staten Island. Moreover, greater economic losses were reported in these areas. While buildings in the destroyed and majorly damaged classes were generally found along the coastlines, the greatest concentration occurred along the eastern shore covering the majority of the storm surge area. McHarg had deemed these sites unsuitable for urbanization and better suited for recreation, conservation and/or

conservation-recreation purposes because of vulnerability to tidal inundation and floodwaters**.**

3.4.3. Zoning

Although zoning only designates the *potential* for a given land use, it is quite clear that the trajectory of urbanization was already set in motion, as the majority of land use was zoned for urban development. The amount of Staten Island zoned as urban in 1960 was 92.5% and decreased slightly to 84.8% in 2012 (see Figs. 3.7a-b; Table 3.4). This decrease correlated with an increase in the amount of area zoned for parks and green spaces, more than doubling from 7.7% in 1960 to 15.2% in 2012. Most of this increase was due to newly established parks along the eastern shore and in the southern and northwest parts of the island. Despite this increase, the majority of the island remained zoned for urban development, especially in vulnerable locations along the shoreline. What McHarg had deemed suitable for urban development only overlapped with 1960 urban zoning by 30.2%. McHarg's study conflicted with NYC planning commission because less than a third of the island was designated appropriate for residential, commercial or industrial development. By 2012, urban development comprised 76.1% of urban zoning, when comparing 2012 land use with 2012 zoning.

3.5. Discussion

The omission of McHarg's recommendations from Staten Island development illustrates a missed opportunity for the application of ecological wisdom and sustainable

planning on Staten Island. By utilizing his idea of intrinsic suitability, McHarg had the foresight to recognize that 86.6% of the buildings damaged by Hurricane Sandy were located in areas inappropriate for urban development. As a result, he designated the most vulnerable areas (i.e. eastern, northwestern and west-central shores) better suited for recreation, conservation or conservation-recreation purposes. Unfortunately, instead of following McHarg's suggestion, developers largely underestimated the environmental constraints in favor of building in vulnerable locations. The resulting development sealed off natural water pathways and eroded shoreline defenses, compounding coastal flooding vulnerability (Steiner et al. 2013; Coch, 2014). Consequently, the greatest concentration of destroyed and major damage was along the eastern shore in the communities of Midland Beach, New Dorp and Oakland. Entire city blocks of houses were washed out to sea resulting in 23 deaths and 1,401 houses severely damaged or destroyed (Benimoff et al. 2015; Wagner et al. 2014; NCDC, 2013). While McHarg's study would not have completely avoided damage, the findings of this study show that losses from Sandy would have been substantially reduced had development followed principles of intrinsic suitability and ecological wisdom instead of being driven by economic decisions.

Mounting urban pressures of decentralization and economically-based planning decisions promoted unsustainable development on Staten Island. Erection of the Verranzo-Narrows bridge facilitated an outmigration from other NYC boroughs to Staten Island, enabling residents to easily commute to and from Brooklyn (McHarg, 1969). This resulted in a 24.9% increase in population from 221,991 in 1960 to 295,443 in 1970 (Minnesota Population Center, 2011). With 92.5% of the island zoned for development,

rapid suburbanization spread beyond areas deemed suitable for development by McHarg resulting in the construction of 2,500 housing units annually along the shorelines from 1964 to 1979 (Danielson and Doing, 1982 :106). Guided by financial prospects, high density suburbs became prevalent as small lot sizes were allocated to maximize profits especially along the eastern shore (Danielson and Doing, 1982). Urban development was also encouraged by city government through the sale of city-owned land to private developers (Danielson and Doing, 1982: 106-107). Without a master plan, suburbanization was mostly unregulated and often sited without consideration of drainage or access to city services (Danielson and Doing, 1982:106). Over the years, development continued to outpace other boroughs despite regulation enforcements and zoning amendments to reduce housing density (Staten Island Growth Task Force, 2003). By 2000, population had almost doubled from 1960 to 443,728 residents, increasing housing stock to 163,341 units (Staten Island Growth Task Force, 2003).

Zoning can have profound implications for development. Although zoning is not a master plan or visionary document for future development, it sets the stage for future development serving as a regulatory document guide for planners, developers and city council. Zoning segregates land use and designates what can be built (e.g., structure type, size and density) and where (e.g., setback distance). Zoning designation, however, may not always be appropriate. In the case of Hurricane Sandy and Staten Island, zoning for urban development along the eastern shore and within other known surge areas ignored the vulnerability to and past history of coastal flooding and tidal inundation with only a 7.7% reduction in urban zoning since 1960. Instead of discouraging development in

vulnerable locations, inappropriate designation for zoning and socioeconomic factors of market distortion of flood insurance, higher land rents along the coast, and cultural perceptions of risk can encourage development in vulnerable coastal areas, creating a false sense of safety (Bin et al. 2008; 2013, Messner et al. 2006; Wagner et al. 2014). With 78.1% of damaged buildings located in storm surge affected areas, our findings illustrate how zoning laws set the stage for unsustainable development in highly vulnerable regions.

Since most of the island was zoned as urban in the 1960s, the potential for urban development was already headed in a direction contrary to McHarg's principle of intrinsic suitability. Only 30.2% of the urban zoning were appropriate for development under McHarg's study (see Table 3.2). Prior to the aforementioned urban pressures, not all areas zoned for urban had been developed, so there could have been an opportunity to amend zoning to align development with ecological planning. Coastal locations are typically valued more economically and socially, so excluding development near the shoreline conflicted with local economic growth (Bagstadt, 2007, Bin et al. 2008). Due to these conflicting economic and social ideals of development, McHarg's study failed to be adopted, and as a result, unsustainable development prevailed in vulnerable locations.

Although some zoning amendments were instituted in an attempt to put limits on growth by 2012, not much had changed in terms of zoning for urban development. Areas zoned for urban development only decreased by 7.7% from 1960 to 2012 with 84.8% of the island still designated suitable for urban development (see Table 3.4). Despite this small change, the potential for development was mostly realized with 76.1% of 2012

urban zoning developed (see Table 3.4). Development in the northwest has recognized environmental constraints and land use suitability to some degree, as this area is predominantly a mixture of industrial and wetland reserves and not zoned for residential use. Consequently, damage from Sandy was considerably less in the northwest than the eastern shore. With approximately 25% of urban zoning undeveloped, the opportunity still exists to follow McHarg's intrinsic suitability.

Some areas McHarg deemed unsuitable for urban development could have been urbanized sustainably. McHarg likely did not consider ecosystem services of stormwater management and residential design, until his later work. In his Woodland, TX design, residential areas were designed specifically to channel stormwater runoff to protect the residential infrastructure. Urban areas could be located in areas outside of his recommendation only if stormwater management and other mitigating strategies are implemented. Sustainable designs should draw upon ecosystem services to optimize human-environment dynamics but can include other ecologically-informed designs such as elevating communities above floodplains. Such designs have had notable success as seen in rebuilding efforts following the 1900 Galveston Hurricane, Hurricane Katrina and flash flooding events in the Southwestern U.S. (Simpson et al. 2003; Wright-Gidley and Marines, 2008; Kates et al. 2012).

Prior to Hurricane Sandy, the State of New York and the NYC Planning Department recognized the importance of intrinsic suitability and ecosystem services in their ongoing transformation of the Fresh Kills. In 2001, NYC planning department had drafted a master plan to transform the Fresh Kills landfill into the Fresh Kills Park. Once

the world's largest landfill at 8.9 square kilometers, the landfill is currently transitioning into a world-class park in three decadal phases that will include wetland restoration, recreation and conservation areas and other social benefit (NYC Dept. of Planning, 2015). Their vision aims to enrich the social-ecological system with the dual purpose of mitigating storm surge and floodwaters once completed (Rabos, 2004, NYC Dept. of Planning, 2015).

The aftermath of Hurricane Sandy presents an opportunity to reflect on the past and rebuild sustainably by incorporating ecological wisdom, land use suitability analysis and other ecologically inspired designs. Post Hurricane Sandy, wise decisions and sustainable solutions are being implemented on Staten Island. Currently, NY State is purchasing 300 homes along the eastern shore to create a 'safer and greener Staten Island' (Crain's New York Business, 2015; NY Daily News, 2015). By designating these areas as unsuitable for urbanization, NY State plans on converting the land to a park and possibly a salt-water marsh, recognizing the environmental constraints of coastal flooding and tidal inundation. In areas further inland, some homes are being rebuilt with flood resistant construction, while others are being elevated out of flood zone as a means of mitigating flood vulnerability (GOSR, 2014).

In addition to rezoning and other sustainable solutions, ecologically inspired designs such as the Living Breakwater design, Tottenville and Great Kills Dunes and New Creek Bluebelt are being implemented and funded by federal and state agencies as part of the NY Rising Community Reconstruction Plans. The Living Breakwater design is composed of a series of offshore breakwaters and a living shoreline in Raritan Bay to

mitigate future flooding along the southern shore (GOSR, 2014). This living shoreline taps into eco-system services by using ecologically inspired designs to 'enhance habitats and maintain shoreline processes' and offer protection from storm surge and coastal flooding (Smith, 2006: 9). The Tottenville and Great Kills Dunes project would help stabilize existing dunes and construct new dunes to protect coastal location from storm surge, while fostering healthy ecosystems along the shore (GOSR, 2014). The New Creek Bluebelt would expand the existing Mid-island Bluebelt to help alleviate flooding issues by utilizing stormwater management wetlands (GOSR, 2014). These projects exemplify how the implementation of ecological wisdom can lead to robust strategies that increase resilience to tidal inundation and coastal flooding in vulnerable locations, while simultaneously protecting fragile habitats and society.

3.6. Conclusion

Urban sustainability is needed now more than ever to address mounting urban pressures of population increase, globalization, and decentralization (Solecki and Leichenko, 2006). These pressures influence patterns of social and economic development in a way that negatively impact the coupled human-environment system (Solecki and Leichenko, 2006). Coastal cities are particularly vulnerable to such negative impacts due to additional stressors of sea level rise and increased coastal flooding threats associated with climate change (Rosenzweig and Solecki, 2001; Rosenzweig et al. 2011; Field, 2012). With billions living in these vulnerable regions, urban sustainability approaches can ameliorate urban pressures and mitigate disaster impacts because they

treat the human-environment as intimately linked, explore tradeoffs and emphasize the importance of environmental services (Turner, 2010; Rosenzweig et al. 2011). Ecological wisdom could advance a more holistic approach to urban sustainability through the principal of interconnectedness and raise awareness of human impact on material reality to inspire innovative designs with long-lasting solutions (Xiang, 2014).

The aftermath of Hurricane Sandy exposes the importance of intrinsic suitability and ecological wisdom based on the differences between McHarg's land use suitability and 2012 land use. By underscoring the environmental limitations and opportunities on Staten Island, McHarg's intrinsic suitability could have substantially reduced the damaging impacts from storm surge. Unfortunately, vulnerable areas that should have been designated as conservation, recreation or conservation-recreation were urbanized and often overdeveloped due to pressures of rapid suburbanization and inappropriate designation of zoning dating back to the 1960s. This development sealed off natural water pathways and eroding natural shoreline defenses, resulting in widespread damage.

The findings of this study identify the critical need for ecological wisdom and urban sustainability to ameliorate urban pressures and mitigate disaster impacts. This can be achieved through the continued use and implementation of suitability analysis with multifunctional landscape and sustainable solutions. Ecologically inspired designs are more likely to attenuate current and future threats of flooding in a sustainable manner by optimizing benefits to the coupled human-environment system (Carpenter et al. 2009). While we focused specifically on McHarg’s methods for Staten Island and damage due to Hurricane Sandy, we conclude that adaptations and improvements to McHarg’s approach

that integrate more detailed land use types, specific ecosystem services, linkages to social vulnerability and cost-benefit analysis provide insight on how to mitigate damage from environmental hazards.

CHAPTER 4

UNPILOTED AERIAL SYSTEMS (UASS) APPLICATION FOR TORNADO DAMAGE SURVEYS

Wagner, M., R. K. Doe, A. Johnson, Z. Chen, J. Das, and R. S. Cerveny, 2019: Unpiloted Aerial Systems (UASs) Application for Tornado Damage Surveys: Benefits and Procedures. Bulletin of the American Meteorological Society, 100(12), 2401-2405.

One of the most exciting frontiers in meteorology in recent years has been the exploratory use of drones, or more accurately "Unpiloted Aerial Systems" (UAS), in meteorological measurement and assessment. In particular, UASs can provide a unique advantage in improving the assessment of tornado intensity and path characteristics. Current storm damage assessments (i.e., ground-truth surveys or satellite imagery analyses) are restricted by available resources, accessibility to damage site, technological limitations, and damage indicators (Doswell et al. 2009; Womble et al. 2018). UAS-led storm damage surveys could improve tornado damage assessments by providing more detailed information, which would also better distinguish between tornadic and straight-line winds. This detailed information coupled with 3D-modeling capabilities of UASs could also lead to better insight into high-wind flow interactions with land cover and topography. In this article, we discuss the benefits, limitations, and procedures of UAS-led tornado damage surveys, which could augment NOAA NWS damage surveys or be used for forensic investigations or learned insight.

We have found via our project Severe Convective Storm Observations Utilizing Unpiloted Aerial Systems (UASs)-based Technologies (SCOUT) that UASs technologies can allow meteorologists to 1) gain access to impassable or remote locations, 2) identify damage not observable by ground or resolvable in satellite imagery, 3) cover large surface areas at high spatial and temporal resolutions, 4) assist with more detailed site investigations. UASs can be deployed almost immediately after a tornado event, can better capture critical damage evidence (see Womble et al. 2018), and are less likely to be affected by atmospheric contaminants (e.g., clouds, haze) due to low altitude collection (less than 400 feet (122 meters) Above Ground Level (AGL)). Their low-flying height coupled with technological advancements of UASs provide affordable hyper-spatial damage information that can be used to better discern damage and estimate EF scale rating, that either would have been difficult to identify or misclassified through traditional ground surveys or satellite analysis. For example, results from our field research show what initially appeared to be denuding north of the reservoir in satellite imagery (Fig. 4.1a) was actually wind-strewn hay captured in UAS imagery (Fig. 4.1b-c). Other findings show the capabilities of UAS technologies to differentiate high-wind impacts (e.g., erosion, scour, soil deposition, and topographic interactions) based on land cover characteristics (e.g., Fig. 4.2).

UAS-based storm damage assessments using visible and multispectral imagery could better capture the extent and variability of damage, especially in rural locations. Storm damage in rural locations is often underestimated due to 1) underreporting

(uninhabited areas) (Alexander and Wurman, 2008), 2) limited damage indicators for vegetation, and 3) ability to detect and rate vegetation stress (Skow and Cogil, 2017).



Fig. 4.1. Section of Tornado Damage Path from the April 30, 2017 Canton, Texas Tornadoes Captured by a) Satellite Imagery Courtesy of RapidEye (5 m Resolution) and b-c) Unpiloted Aerial System (UAS) Imagery (1.2 cm Spatial Resolution).

UAS-based multispectral analysis may better detect vegetation damage, especially at the low end of the EF-scale, because of the hyper-spatial information collected in red and near-infrared bands. For example, our preliminary results reveal a portion of the damage path detectable only in UAS multispectral imagery, providing damage path

information even in areas of low vegetation cover (Fig. 4.3). Such findings highlight the capability to better detect and rate vegetation stress and could lead to the development of more damage indicators for vegetation impacts. More accurate damage assessments and loss analyses would improve hazard sensing and monitoring operations and awareness especially in remote locations and areas of low population density.



Fig. 4.2. Micro-topographical Influences on High-Wind Impacts. A Visible Break in the May 1, 2018 Tescott, KS Tornado Track as Tornado Winds Interact with a Sunken Gully: Limited Erosion and Scour Inside the Gully Versus Increased Intensity Scour with Gain in Elevation.

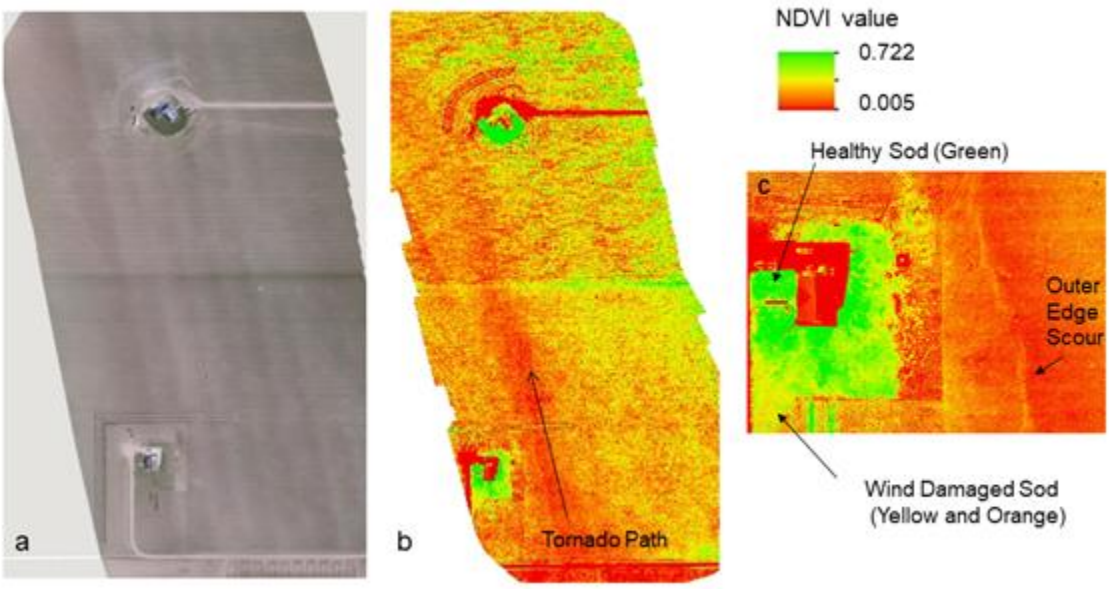


Fig. 4.3. Section of Tornado Damage Path from the June 12, 2017 Carpenter, Wyoming Tornado Captured in a) UAS Visible Imagery and UAS Normalized Difference Index b) Overview and c) Zoomed View of Tornado Damage in Lower Left Corner. Analysis Show Lower NDVI values for Damaged Vegetation and Range of Vegetation Stress (Dead, Damaged (Stressed), Healthy).

UAS-based Structure-from-Motion (SfM) and other three-dimensional (3D) products could provide a better understanding of high wind damage and interactions with land cover. SfM provides a 3D perspective by overlapping photographs obtained from multiple viewpoints and is a cost effective alternative to Light Detection and Ranging (LiDAR), which is used to produce 3D topographical maps of the earth's surface (Johnson et al. 2014). Tornado damage assessments are taking advantage of this technology since UAS-based products provide better views of structural and vegetative

damage than previous aerial methods. For example, analysis of hyper-spatial imagery could lead to a better understanding of structural damage and/or failure due to high winds (see Womble et al. 2016; 2017, Mohammadi et al. 2017). Other 3D products like Digital Surface Models (DSMs) can be used to better understand the influence of topography on tornado winds and inferred damage intensity (e.g., Fig. 4.4) (see Doe and Wagner, 2019). Additionally, machine learning, an application of artificial intelligence (AI), automates damage estimation and could improve damage detection by identifying more storm damage than current methods and at the microscale.

Navigating data collection of UAS tornado damage investigations and policy in the United States can be challenging to those unfamiliar with Federal Aviation Administration (FAA) regulations and post-storm environments. UAS-based tornado damage surveys require pre-flight planning, flight operations (data acquisition), and data processing and sharing. Pre-flight planning necessitates understanding site characteristics of the region being surveyed, operating within specified FAA UAS regulated airspace (i.e., airspace restrictions over military bases, airports, national parks and other locations), assembling the proper personnel and equipment, and obtaining permissions from any citizens within the area surveyed. UASs operations must be overseen by a certified remote pilot that has obtained FAA Part 107 certification (FAA, 2016) and follow FAA guidelines (see FAA, 2018) and any agency specific policies (e.g., NOAA aircraft policy and requirements (see OMAO 2016)).

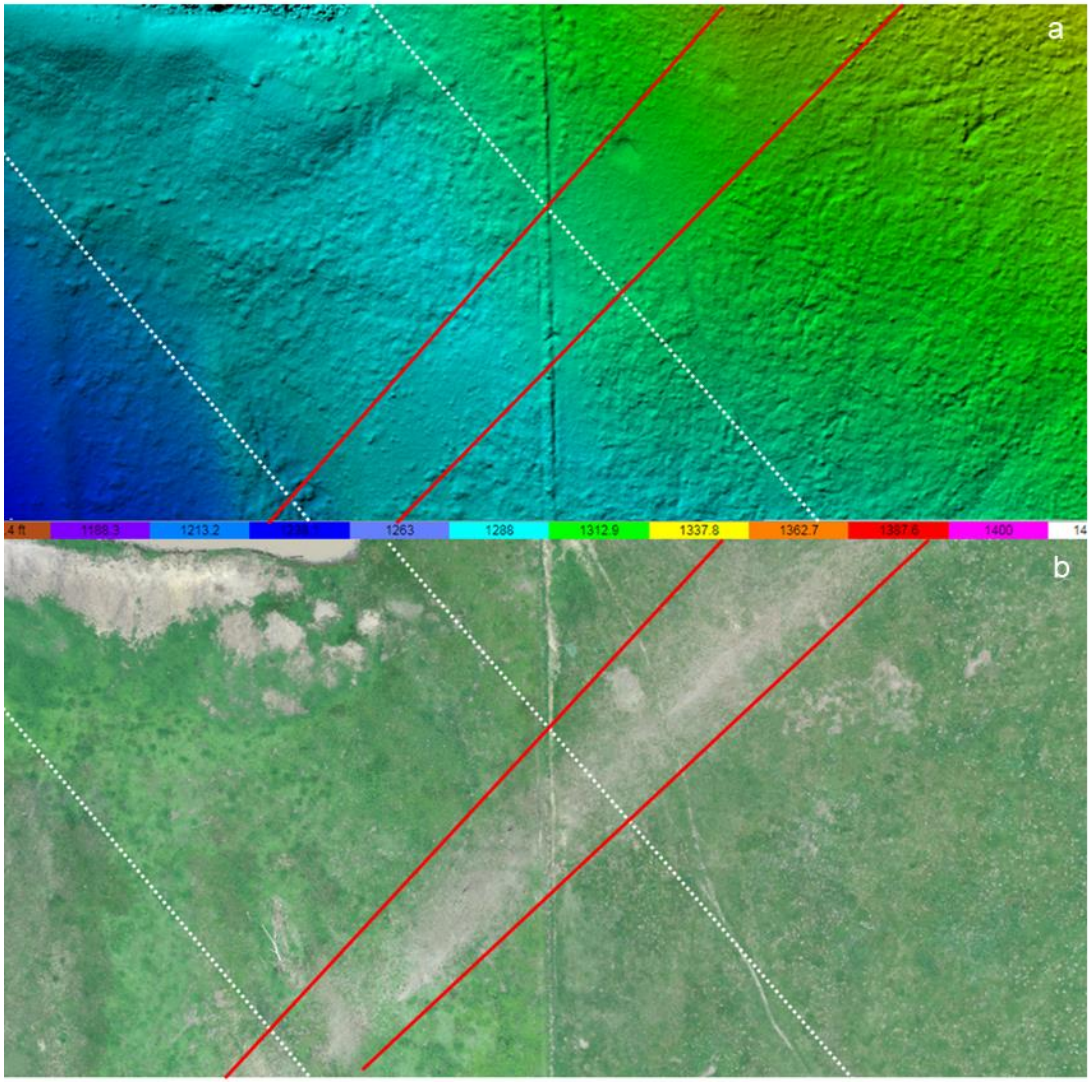


Fig. 4.4. a) Digital Surface Model (DSM) showing Three Areas of Distinct Elevation (Shaded Blue to Green) and Eroded Surface Roughness from the May 1, 2018 Tescott, KS Tornado Track. Smoother Surface within the Red Lines Captures the Tornado Track Scour in the Short Prairie Grasses. b) Progressive Width Increases with Elevation Gain of Approximately 74 feet (22.5 meters) Captured in Unpiloted Aerial System (UAS) Imagery (2.5 cm Spatial Resolution), Suggesting an Increase in Wind Intensity with Increasing Elevation.

In addition to preflight necessities, many aspects of UAS operations, including flight operations and data processing, have been learned from three years of field work. Specifically, flight operations can be conducted and automated using a variety of flights apps (e.g., Pix4D, DroneDeploy) and should be cognizant of lighting conditions to minimize data loss due to shadows. Because flight operations are often limited to a battery life of 30 minutes or less (fixed-wing UASs excluded), it is important to have several batteries and a charging platform onsite. In the case of 3D mapping, photograph overlap (front and side) should be set to a minimum of 70% to achieve parallax needed for 3D modeling and producing orthomosaics. After flight operations, data can be processed using a variety of software from low cost and automated platforms (e.g., MapsMadeEasy) to higher cost and user-controlled packages (e.g., AgiSoft, Pix4D). Processed data should ideally be shared with the appropriate agencies and in data formats tailored to their specific needs and infrastructure.

Specific lessons we have learned with regard to UAS flight operations in tornado damage assessments include 1) engaging stakeholders before and after the assessment, 2) obtaining flight permissions in highly sensitive areas, and 3) constructing accessible data-sharing platforms. Disaster zones are highly sensitive and stressful spaces where emergency managers and local law enforcement are often overloaded with incoming information while executing their operations. Therefore, coordinating with emergency managers, NOAA personnel, and other agencies is key to a) assisting these organizations with regard to their specific needs, b) gaining access in these sensitive areas, and c) staying up-to-date on airspace restrictions and other emergency management operations.

In the United States, UASs can be deployed with the proper authorization (airspace and emergency management regulations) and without obtaining permission from property owners. However, we strongly recommend obtaining permissions from property owners, especially in rural communities to address privacy issues, establish trust, and ensure operations are not impeded. Policies outside the U.S. can be very restrictive making it extremely difficult to operate in some countries (as seen in Europe). Therefore, organizations outside of the U.S. (e.g., TORRO) would need to consult their specific laws. Lastly, data-sharing and decision support platforms should be easily accessible, capable of handling large volumes of data, and ideally would include a collaborative mapping platform for visualizing and sharing large datasets with multiple agencies to facilitate better decision-making.

UAS technologies have the potential to be critical tools in the detection and analysis of tornado and other weather-related damage as demonstrated by recent studies (i.e., engineering analysis (Womble et al. 2016; 2017, Mohammadi et al. 2017), high-wind damage surveys (Walker et al. 2016; Skow, 2017). We foresee two contributions – specialized sensor suites on UAS platforms and state-of-the-art algorithms for optimal data acquisition and analysis of damage information (e.g., deep neural networks, segmentation, object detection training). State-of-the-art algorithms will improve damage detection by enabling precise automated detection of complex morphological features and estimation of optimal probabilistic maps (or semantic maps) of properties of interest such as damage to structures or vegetation. We believe that UASs will ultimately improve damage detection in rural locations (e.g., portions of the Great Plains), which have

experienced well-documented reporting biases due to low population density, relatively inaccessible regions, and limited damage indicators for vegetation (Snyder and Bluestein, 2014). This improvement will be fostered, in part, by UAS-based multispectral analyses, which has the potential to better detect damage to vegetation and could lead to the development of damage indicators for vegetation that are more reflective of tornado strength.

CHAPTER 5

HIGH-RESOLUTION OBSERVATIONS OF MICROSCALE INFLUENCES ON TORNADO TRACKS USING UNPILOTED AERIAL SYSTEMS (UAS) TECHNOLOGIES

Wagner, M., R. K. Doe, C. Wang, and R. S. Cerveny, 2020: High-resolution observations of microscale influences on tornado tracks using Unpiloted Aerial Systems (UAS) technologies. Monthly Weather Review, Manuscript in preparation.

5.1. Introduction

Over recent years, the magnitude and severity of tornado impacts have generated costs into the billions of dollars and loss of live. The challenges of accurate prediction and precise locational impact of tornadoes contributes to these costs by adding a layer of complexity to both tornado forecasting and damage mitigation, especially with regard to human vulnerability assessment. This is due, in part, to important microgeographical concerns associated with varying tornadic intensity, spatial scale and land use. In order to better address some of these challenges, the geotechnological application of Unpiloted Aerial Systems (UASs) can perform enhanced site investigations, especially in locations of complex terrain (Wagner et al. 2019).

UAS aerial enhancements of tornado damage include high resolution (centimeter scale) imagery, local assessment of topographical and micro-topographical features, use of multispectral data and advanced computer modelling and analysis. Each tornado track

has a unique fingerprint. While the atmospheric synoptic conditions leading to the event are relatively known, the surface conditions which might influence the direction and severity along the track must be addressed through special attention in the local environment. Performing high resolution site investigations can lead to a better understanding into how specific surface conditions such as topography can influence tornado behavior.

This study uses high-resolution imagery obtained from Unpiloted Aerial Systems (UAS) and 3D-modeling products to examine topographical influences on tornadoes. We conducted a UAS-based tornado damage assessment following the 01 May 2018 Tescott, Kansas tornado, which was rated an EF-3 on the Enhanced Fujita scale (NOAA, 2020). From this survey, we generated UAS visible and visible difference vegetative index (VDVI) imagery, digital surface models, and point clouds. We analyzed the influence of topography on tornadoes at the microscale using spatial comparisons as well as overlay and transect analysis of UAS visible and VDVI imagery with digital surface models (DSMs). We also performed change detection analysis to quantify the magnitude of high-wind damage. These analyses give new information on the microscale influence of topography on tornadogenesis.

5.2. Background

5.2.1. Topographic Influence on Tornadoes

The history of research involving topographic influence on tornadoes displays a lack of consensus. Some researchers have shown that topography can (a) initiate or

enhance tornadogenesis (Passe-Smith 2006; 2008), (b) affect tornadic intensity (Coleman, 2010; Bosart et al. 2003), and (c) alter path direction (Lewellen and Lewellen, 2007). Forbes (1998) theorized that tornado intensity decreases (increases) on the windward (leeward) side of a ridge/hill due to the vortex compressing (stretching), creating mass convergence (divergence), and consequently, a decrease (increase) in angular momentum (Lewellen, 2012; Cannon et al. 2016). Lewellen (2012) expanded on this theory noting that near-surface flow component would be deflected back into the vortex uphill, increasing near-surface flow and swirl ratio (Sc) and consequently, decreasing tornadic intensity. In addition to changes in damage intensity, Lewellen (2012) also noted tornado path could deviate to the left as it approaches the ridge and then to the right as it climbs the ridge. While Lewellen (2012) and Coleman (2010) observed similar results as Forbes (1998), Lewellen (2012) also found a brief intensification in simulated tornadic intensity near the ridge citing surface roughness, translational velocity, storm velocity, and slope were also important factors in altering near surface flow and Sc.

Conversely, other studies using damage assessments, radar analyses, and numerical modeling have shown mixed results in topographic influences on tornadoes. For example, Houser et al. (2017) noted conflicting results in their radar-based analysis suggesting topographic influences on tornadic intensity were case specific. Cannon et al. (2016) found greater damage intensity on the windward side versus the leeward side in their damage assessments but noted large variability in damage between the windward and leeward sides. They also noted a stronger topographic influence associated with

shallower slopes, suggesting other factors at play. Ahmed (2016) found similar results to Cannon et al. (2016) using damage assessments and numerical simulations observing a zone of protection on the leeward side approximately five times the heights of the hill (elevation gain), suggesting tornado diameter had to be larger than the depression.

5.2.2. Unpiloted Aerial Systems (UASs) in Tornado Damage Assessment and Change Detection

Recently UAS systems have been used in tornado damage assessment (e.g., Skow and Cogil, 2017; Wagner et al. 2019). High resolution damage assessments utilizing UAS technologies can provide better analysis of topographic influences on tornadoes at the microscale. UAS technologies provide centimeter scale information due to their low altitude collection of less than 400 feet (122 meters) Above Ground Level (AGL)) (Womble et al. 2018; Wagner et al. 2019). This detailed information coupled with the three-dimensional (3D) modeling capabilities of UASs via Structure from Motion (SfM) could lead to better insight into high-wind interactions with land cover and topography (Wagner et al. 2019). SfM uses overlapping photographs obtained through multiple angles to produce 3D modeling products (e.g., Digital Surface Models (DSMs), point clouds, orthomosaics (Westoby et al. 2012; Johnson et al. 2014). This approach is a cost-effective alternative to Light Detection and Ranging (LiDAR) (Westoby et al. 2012; Johnson et al. 2014) and has been used in assessing typhoon (Ezequiel, 2014; Chen et al. 2020) and tornado related damage (Wagner et al. 2017; Womble et al. 2018), as well as, fault line movement (Heredia et al. 2009; Johnson et al. 2014).

Change detection, commonly used in land cover change analyses (e.g., Myint et al. 2008), could also provide a better insight into high-wind interactions with topography. Change detection, which quantifies the magnitude of change through the differencing of pre-event and post-event data (Lu et al. 2004), has been successfully used in high-wind damage assessments using optical (satellite) data (Yuan et al. 2001; Myint et al. 2008) as well as radar data (Molthan et al. 2014). Change detection via point cloud differencing using UAS-SfM or LiDAR data has been frequently used in seismic and geomorphological studies to capture microscale changes as a result of geophysical processes (Abellan et al. 2016). While point cloud differencing is gaining traction in assessing structural damage and wind loads (e.g., Xu et al. 2014; Kashani et al. 2014), this technique could also be applied to investigating microtopographical influences on tornadoes as well as land cover interactions with high-wind events. Some caveats to this approach include ground sampling distance, land cover type and characteristics, post-event conditions (e.g., soil moisture), and availability of pre-event data (Kingfield and deBeurs 2014, Womble et al. 2018).

5.3. Methods

5.3.1. Study Area

On 1 May 2018, five supercells affected north-central Kansas, spawning 12 tornadoes. One supercell near Tescott, KS produced an EF-3 rated tornado with a damage path length and width of 23.3 kilometers (14.5 miles) and 0.8 kilometers (0.5 miles), respectively (see Fig. 5.1). Although no injuries or deaths were reported, this tornado

produced isolated severe damage to property and vegetation within this sparsely populated region (NOAA, 2020). Within the damage path, we focus our analysis on where the greatest elevation change (approximately 62 meters (205 feet)) occurred.



Fig. 5.1. 01 May 1998 Tescott, KS Tornado Path a) Overview and b) Survey Site Shown in White Box. Isolines Show Damage Ratings According to the Enhanced Fujita (EF) Scale with the Heaviest Damage (EF-3) Shown in Red and Weakest Damage (EF-0) Shown in Beige.

5.3.2. Data and Data Collection

Following the tornado event, UAS surveys were conducted to obtain post-event visible imagery. A DJI Phantom 4 UAS was flown at a flying height of 200 to 300 meters, yielding 1.69 cm pixel resolution. Visible imagery were collected using near nadir angle and 75% front and side overlap, which is necessary to achieve 3D modeling

capabilities through SfM (e.g., Westoby et al. 2012; Johnson et al. 2014). Approximately 2000 images were collected from 18-20 May 2018 under relatively cloud free skies.

Ground control surveys were conducted to ensure geospatial accuracy of data. Ground control points (GCPs) were collected using a Trimble Geo7x with an accuracy of +/- 0.4 centimeters. Ten points (GCPs) were collected using 1 meter by 1 meter targets, which were distributed throughout the study area and at varying elevation heights. Horizontal positions were referenced to 1984 World Geodetic Datum Universal Transverse Mercator and vertical positions were referenced to World Geodetic System 1984.

In addition to post-event data, Aerial-based Light Detection and Ranging (LiDAR) data were acquired for change detection. LiDAR data were acquired from the United States Geological Survey (USGS) with a 5 meter spatial resolution (USGS, 2020).

5.3.3. Data Preprocessing

UAS imagery were processed using Agisoft Photoscan to generate post-event imagery and 3D-modeling products. UAS imagery were co-registered to GCPs to remove positional distortions of 1 to 10 cm, resulting from errors in camera GPS location (Johnson et al. 2014). Color calibrations were applied to balance color differences due to different lighting conditions. Data products included dense point clouds, digital elevation models, and orthomosaics. UAS point cloud data were resampled to 5 meters to match the spatial resolution of USGS LiDAR data.

We calculated visible-band difference vegetation index (VDVI) to better identify high wind damage. VDVI can be used to assess vegetation health and identify land cover types (e.g., bare soil, vegetation) based on the spectral response of features and information obtained in the visible bands (blue, green, red) (Wang et al. 2015). We calculated the visible-band difference vegetation index (VDVI) using the following equation:

VDVI = (2*Green - Red - Blue)/(2*Green + Red + Blue) (Eqn. 1)

where Blue, Red, and Green correspond to wavelength bands in the visible spectrum.

5.3.4. Assessments of Microscale Influences on Tornadoes

First, we used spatial comparisons, as well as, overlay and transect analyses to examine topographic influences on tornadoes. Specifically, we compared UAS-based orthomosaics to elevation information to examine high wind interactions with microtopographic features. UAS-based orthomosaics were compared to digital surface models (DSMs) to assess high wind damage relative to elevation.

In addition to spatial comparisons, we performed overlay analysis to assess the location and extent of scour relative to changes in elevation. Using a Geographic Information System (GIS) platform and the UAS DSM, we generated and overlaid 2 meter contours onto the VDVI image to assess the location and extent of scour relative to elevation changes. We also calculated slope (defined here as the maximum rate of elevation change) to quantify changes in elevation gradient as well as hillshade to assess terrain effects.

To evaluate the variability of damage relative to elevation, we analyzed a series of transects oriented perpendicular to the centerline of the damage path (see Fig. 5.2). We selected three transects at key elevation profiles: the gully (group A), near areas of local maxima (groups B and C), and at the top of the hill (group D) (see Fig. 5.2b) to assess changes in damage relative to the gully, local elevation maxima, steep elevation gradient, and flat terrain, respectively. Along these twelve transects, we extracted VDVI and elevation values to assess changes in damage intensity and path width relative to elevation, as measured by VDVI values.

Transects were drawn at 20 meter intervals along the centerline of the damage path (area of intense scour) (see Fig. 5.2), totaling to 36 transects. We created buffers of 50 meters width for transects in and around boxes A and D, 75 meters width from transects in and round box B, and 100 meter widths from the centerline of the tornado track (area of intense scour). The length of these transects were drawn to include damaged and non-damaged areas with transects of 200 meters long at the widest part (Box C) of the tornado path and 100 meters long at the narrowest part (Boxes A and D) of the tornado path. For transects in boxes A-D, we extracted VDVI and elevation values at one-meter intervals along each transect.

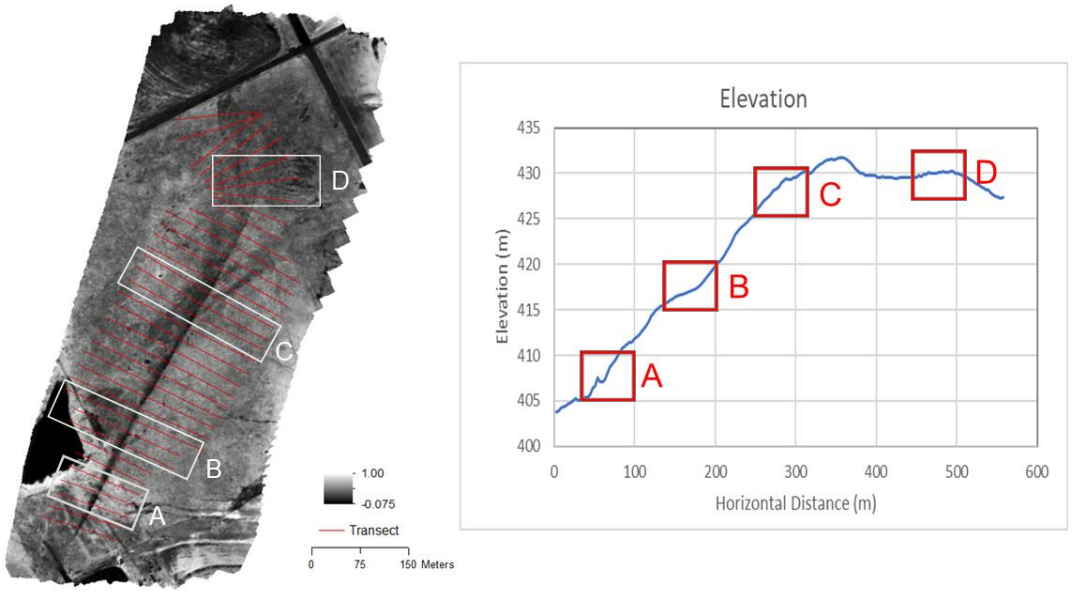


Fig. 5.2. a) Visible Difference Vegetation Index (VDVI) image of the 01 May 2018 Tescott, KS Tornado with Transects (Shown in Red) Oriented Perpendicular to the Tornado Track. White boxes Show Specific Transects Discussed in Text. b) Vertical Elevation Profile along the Center of Damage Path (Area of Greatest Scour). Red Boxes on the Graph Correspond to Selected Transects Labeled in Respective White Boxes.

Changed detection via point cloud differencing was used to examine microtopographical influences from tornadic winds. We used CloudCompare, an open source program for 3D visualizations and point cloud analysis, to conduct point cloud differencing. For the pre-tornado event point cloud, we used the USGS aerial-based LiDAR. For the post-event point cloud, we used the resampled UAS-based point cloud. The pre-event point cloud (reference model) was registered and aligned to the post-event point cloud using iterative closest point (ICP) fine alignment with a root mean square

error (rmse) difference of 0.5x10-5. After registration, the point clouds were differenced to calculate the change in XYZ between point clouds using the MC3C2 differencing tool.

5.4. Results

UAS-based imagery and DSM provide very high-resolution (centimeter-scale) information of the tornado track and elevation. Visible and VDVI imagery (Fig. 5.3a,c) show an area of intense scour starting at the inception point (bottom of the image), continuing through the center of the image, then decreasing in intensity as the track visibly fans out. In the imagery, the track measures approximately 550 meters long and 75 meters at its widest point. Examination of the DSM (Fig. 5.3b) indicates that the track passed through an area of complex terrain with an elevation increase of approximately 40 meters. Additionally, the resolution of the DSM is so high that even small surface features (such as minor gullies) can be easily identified and used for microscale analysis.

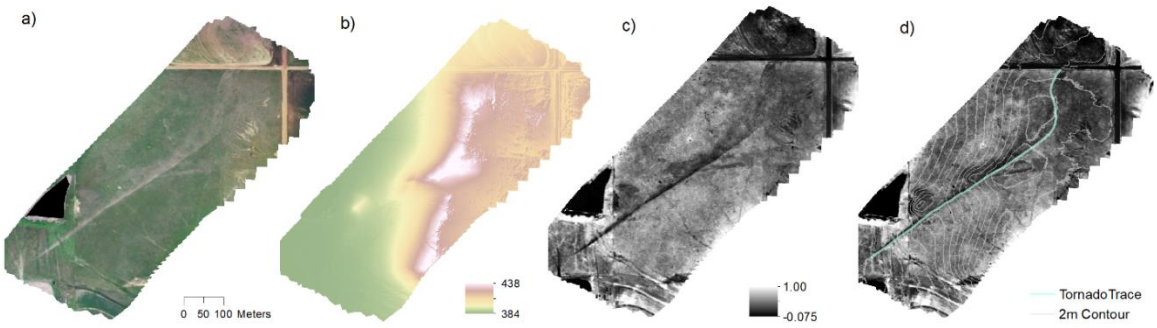


Fig. 5.3. Unpiloted Aerial System (UAS) Derived Information: a) Visible Image b) Digital Surface model (DSM) c) Visible Difference Vegetation Index (VDVI) Image of the 01 May 2018 Tescott, KS Tornado Site Survey. d) VDVI Image with 2 Meter Contours and Tornado trace.

Analysis of the VDVI image better highlights the range of damage relative to topography as well as vegetative health over the survey site. Overall VDVI values are relatively low in the image with some higher values (close to 0.40) towards the bottom of the image, indicative of healthier and denser vegetation. Within the area of intense scour, VDVI values are similar to those of bare soil or water with values close to zero (shown in black in Fig. 5.3). Areas of enhanced scour can also be seen along the trace in areas of local maxima elevation (see Figs. 5.3b-d). Interestingly, the VDVI image depicts more clearly that as the track weakens in intensity, the path becomes trochoidal. In this area, the path traverses between two local maxima. Fig. 5.3d shows the damage path appears to follow the area of maximum elevation change as the tornado trace passes through the steepest elevation gradient.

When examining the track in finer detail, there is evidence of microtopographic influences within the signature (see Figs. 5.4 and 5.5). Figs. 5.4a-b displays a visible break in the track corresponding with tornadic winds interacting with a gully. Inside the gully, VDVI values are higher (Fig. 5.4b) and surface erosion is limited as evidenced by increased surface roughness/texture (Fig. 5.4d). Outside the gully, Figs. 5.4c-d depict visible surface smoothing within the highlighted track (white dashed lines), showing that vegetation has been completely removed. Additionally, VDVI values are close to zero (Fig. 5.4b), also indicative of denuded vegetation. Looking at the top of end of the track, trochoidal marks are identified, suggesting changing wind dynamics. The distinct swirl pattern is more noticeable in the VDVI image (Fig. 5.5b). Interestingly, the track appears to follow the local maxima contour, suggesting further topographical influence.

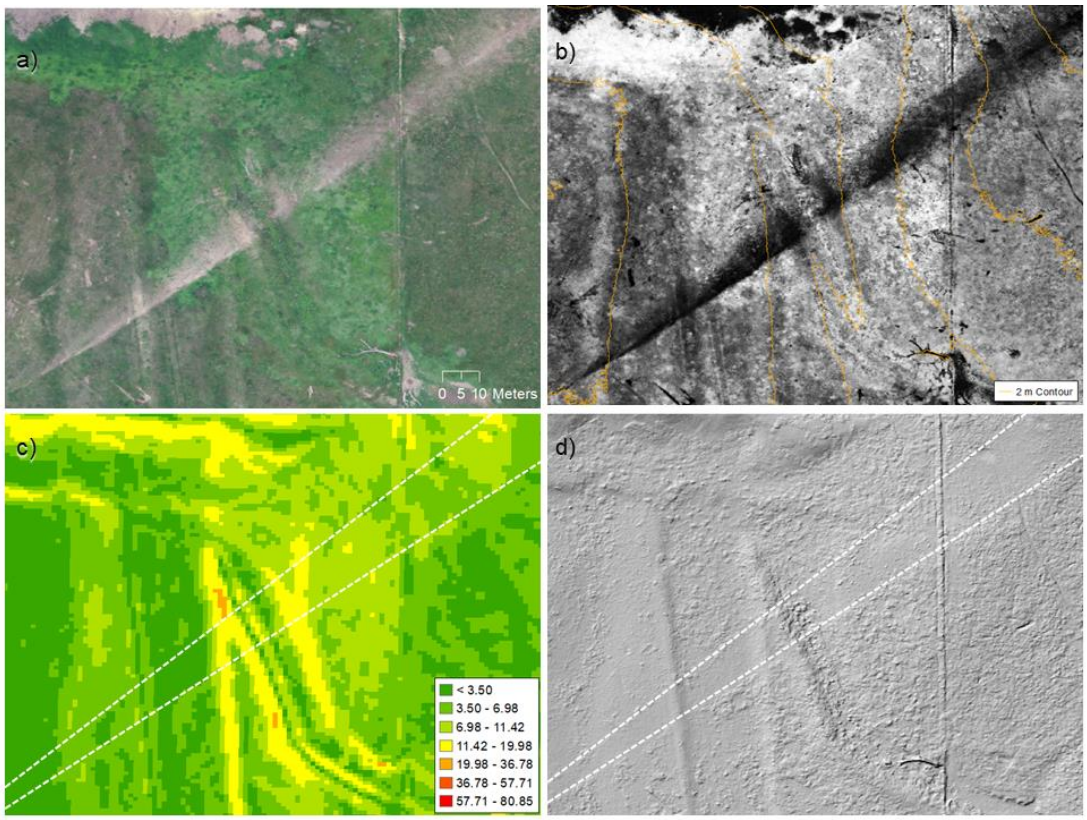


Fig. 5.4. Microtopographical Influences of High-Wind Impacts Captured in a) Visible Imagery b) Visible Difference Vegetation Index (VDVI) c) Slope and d) Hillshade of the 01 May 2018 Tescott, KS Tornado. Visible Break in Damage Path due to Limited Surface Erosion (Increased Texture) with Sunken Gully. Smoothed Surfaces within White Dashed Lines (Tornado Track) Show Areas of Increased Scour within Shortgrass Prairies.

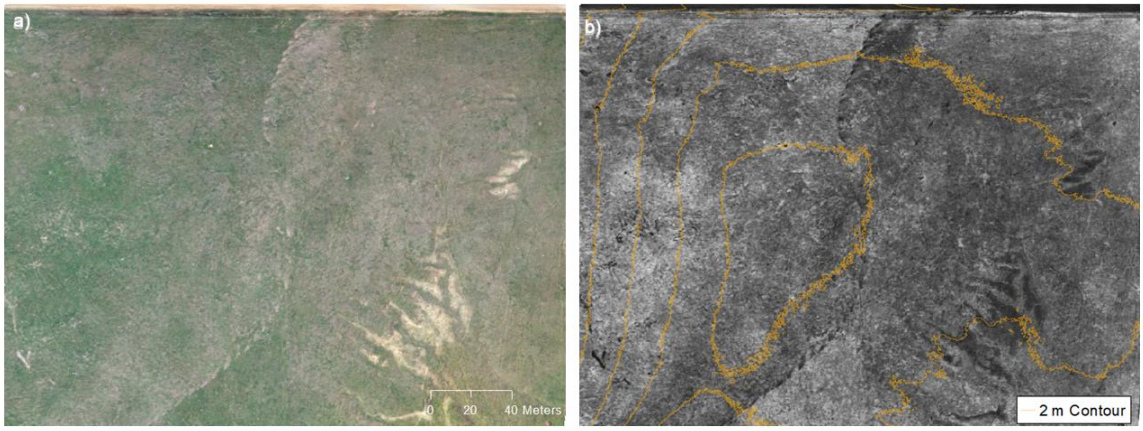


Fig. 5.5. Trochoidal Marking Captured in a) Visible and b) Visible Difference Vegetation Index (VDVI) Imagery of the 01 May 2018 Tescott, KS Tornado near the End of the Survey Site. Dashed Line is Evidence of High Impact Marks (Individual Pitted Effect) in Shortgrass Prairies.

Transect analyses (Figs. 5.2, 5.6) show changes in damage intensity and path width relative to elevation, as measured by VDVI values. In the case of the gully, transects are oriented roughly parallel to the gully where transect A1 is downslope of the gully, transect A2 is inside in the gully, and transect A3 upslope of the gully. Fig. 5.2b (red box A) displays an approximate gain of five (5) meters in vertical elevation along the centerline of the damage path (area of intense scour) with a slight dip in vertical elevation corresponding to the gully. Transects A1 and A3 show VDVI values close to zero within the area of intense scour (center of the track) bounded by blue vertical lines, whereas, transect A2 shows VDVI values of 0.1 to 0.30 in the center of track (see Fig. 5.6). This finding illustrates how tornadic winds can produce varying degrees of damage even relative to microscale changes in elevation. Tornado path width decreases between

transect A1 to A2 by 2 meters and then increases from transect A2 to A3 by 3 meters. These findings (the differences in VDVI values and changes in track width) suggest elevation changes at the microscale may play a role in tornado track dynamics.

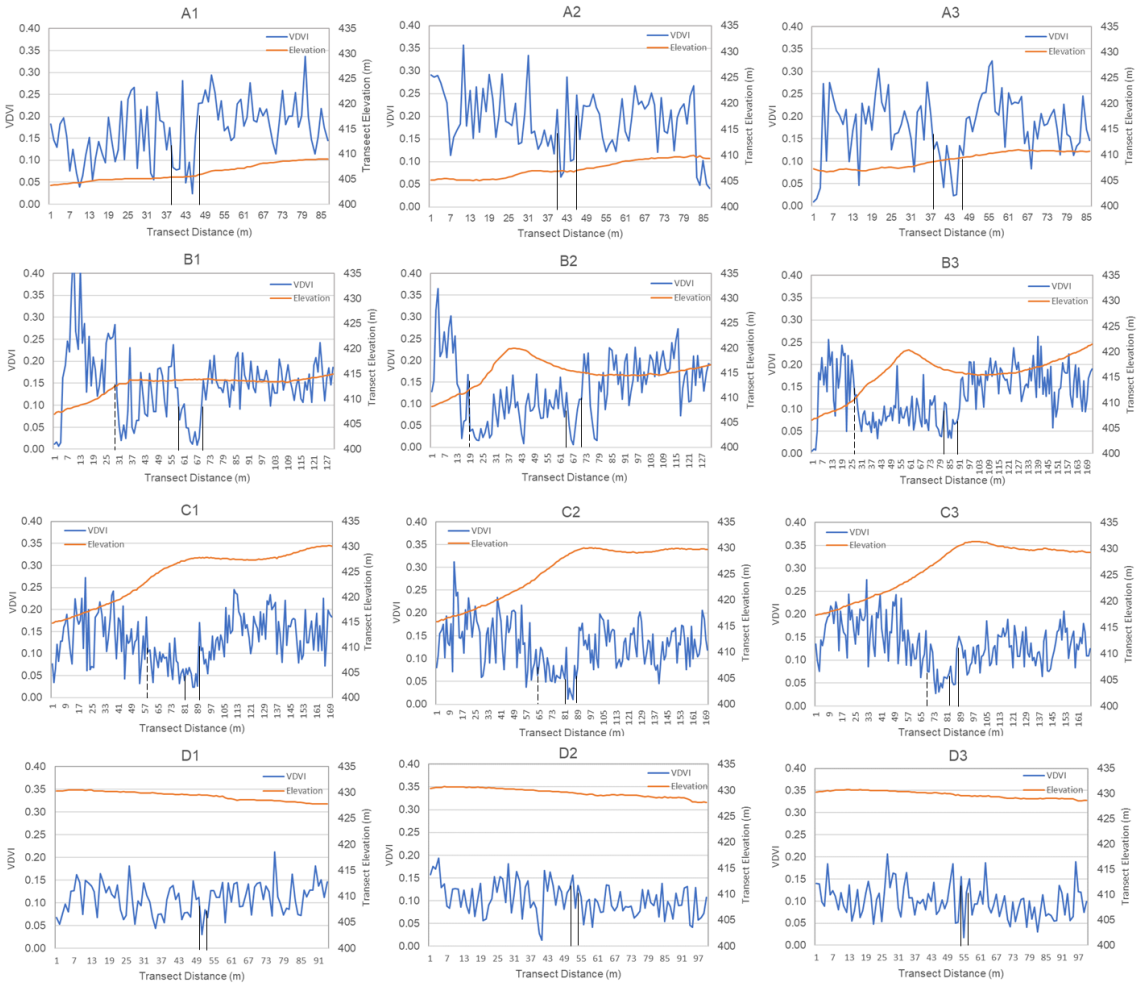


Fig. 5.6. Visible Difference Vegetation Index (VDVI) Values of the 01 May 2018 Tescott, KS Tornado at Selected Transects Perpendicular to the Center of the Damage Path (Area of Intense Scour) shown in White Boxes in Fig. 5.5a. Transects are Ordered Beginning at the Bottom of the Box in Ascending Order (e.g., A1) to the Top of the Box

(e.g., A3). VDVI values Shown in Blue and Elevation Information Shown in Orange along these Transects.

Transects B1-B3 (Figs. 5.2, 5.6) show even more of a topographical influence as the tornado path widens considerably from transects A1-A3 (see box A in 5.2) to transects B1-B3 (see box B in 5.2) with increasing elevation. In transect B1, the scour width widens to approximately 40 meters with the most intense scour width increasing to 10 meters as the track begins to interact with a local elevation maxima along the transect. Corresponding to these elevation changes, VDVI values decrease to an average of 0.1 and 0.03 in the areas of enhanced scour and intense scour, respectively. Tornado path width progressively increases by 10 meters for transects B2 (~53 meters) and B3 (~63 meters) over the local elevation maxima (420 meters). Despite the increase in overall scour, the width of the intense scour decreases by a few meters from transect B1 to B3.

Transects C1-D3 (Fig. 5.6) also highlight how landscape and microscale elevation relationships can influence tornado track. Near the elevation maxima in the survey site (transects C1-C3), vertical elevation increases from 425 meters to 430 meters (Fig 5.2b) with horizontal elevation changes of approximately 15 meters (Fig. 5.6). In this area, VDVI values also rapidly decrease from 0.2 to less than 0.05 in response to the steep? microscale elevation gradient (see Fig. 5.6). In the area of intense scour (center of the track), VDVI values dip close to zero near the area of maximum elevation for the survey site. These findings highlight how damage increases in the most prominent part of the landscape. As elevation levels out (see transects D1-D3 in Figs. 5.2, 5.6), microtopography plays less of an influence in track dynamics. At 430 meters in the flat

terrain (Box D in Fig 5.2), the tornado track becomes less defined and changes from linear to trochoidal (see Fig. 5.2).

Point cloud differencing using USGS LiDAR data and UAS-based point cloud data (Fig. 5.7) shows the amount of land cover change relative to wind interactions with topography and landscape features. In this figure, the geographic extent of the track can be seen as a long thin linear feature crossing from the lower left to the upper right of the image. While overall land cover changes are relatively small (0.10 meters or less), there are some areas of maximum change ranging from 0.28 to 0.40 meters. In fact, these areas of maximum erosion and scour coincide with transects A1-A3 and B1-B3. Additionally, the greatest amount of land cover change can be seen in areas of local maximum elevation, pointing to greater damage in elevated areas and with exposed features.

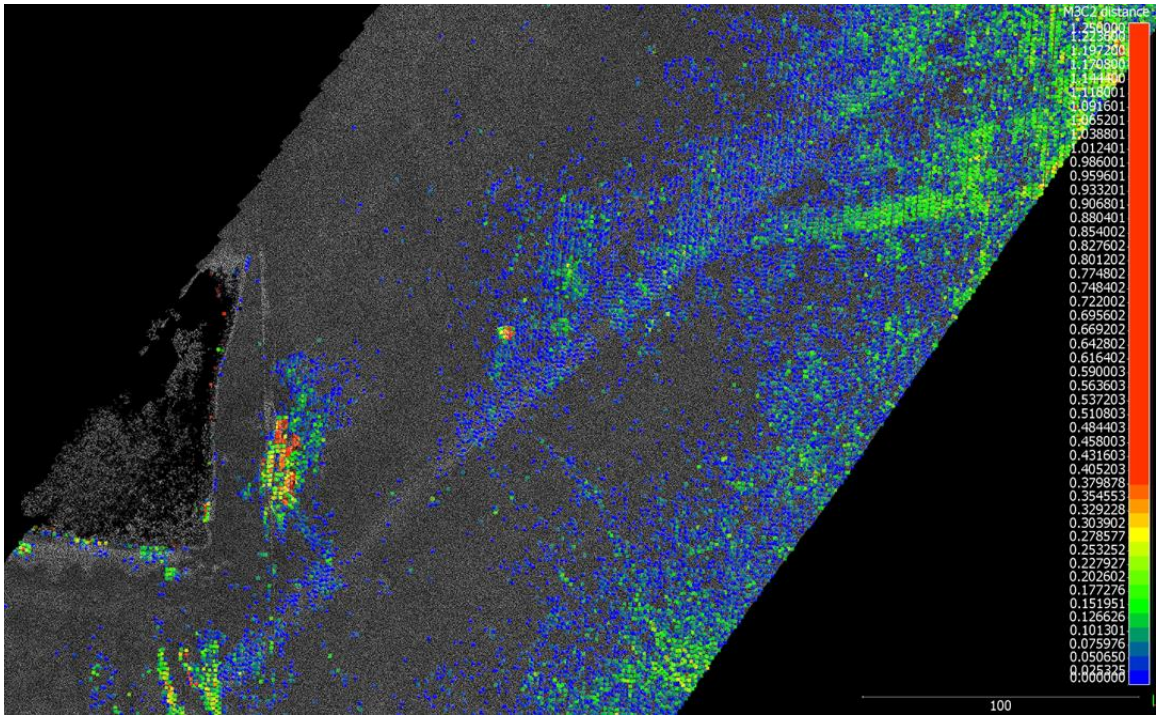


Fig. 5.7. Point Cloud Differencing of the 01 May 2018 Tescott KS Tornado using USGS Light Detection and Ranging (LiDAR) data and resampled Unpiloted Aerial System (UAS) point cloud data. Small Land Cover Change Displayed in Blue Hues, while Larger Changes Shown in Red Hues.

5.5. Discussion

The 1 May 2018 Tescott, KS EF-3 tornado provided a unique opportunity to examine the influence of microtopographical features on tornado behavior (damage path and variability) using UAS technologies and geospatial techniques. Our analyses provide high-resolution observations of microtopographical interactions based on damage variability related to elevation changes. The gully landform illustrates how tornadic winds can produce varying degrees of damage relative to even small changes in elevation with little to no damage observed inside the gully and areas of denuded vegetation outside the gully. Damage also increased in areas of local elevation maxima and near the elevation maximum (~430 meters) as evidenced by enhanced scour (lower VDVI values) and increasing track width. Where elevation plateaued, damage decreased considerably with the damage path becoming less defined and changing from linear to trochoidal. These findings highlight how topography can play a major role in tornado behavior (damage intensity and path deviation).

While tornado interactions with the local environment can be site specific, our findings differ from the predominant theory on the influence of topography on tornadoes. Current theory notes that tornadoes can form or intensify as elevation decreases (Forbes,

1998; Coleman, 2010). Although some observational studies have noted decreased in tornadic intensity with increasing elevation, our results show increases in elevation and slope can have a notable influence on the intensity and width of the track, similar to the findings of Ahmed et al. (2016) and Cannon et al. (2016). Our findings could be corroborated by Lewellen (2012) that noted the effects can vary considerably with tornado type, translation speed, topography, scale, alignment, and surface roughness. Vortices can be deflected by or attracted to slopes or stall over topographic features, sometimes detached from the surface (Lewellen 2012). Therefore, more than one complex dynamic can affect tornadic intensity, highlighting the need for comprehensive assessments to determine site specific topographical interactions and influences.

This study also presents an interesting case study into the complicated kinematics of tornadoes as the damage path changes from linear to trochoidal. In the linear segment, we hypothesize that a kinematic feature of fast moving intense flow was located at or near the axis of tornado and moving with the mesocyclone as the tornado moved up the hill (Rasmussen, 2020, pers. comm). During the intense scour, the tornado was probably single-celled at the ground with very high wind speeds and an intense upward jet (Rasmussen, 2020, pers. comm). This could explain the linear segment of denuded vegetation (deep scour) as non-trochoidal track segments have been noted to occur when the tornado is located near or at the center of the mesocyclone (e.g., Wakimoto et al. 2003). It is hypothesized that the tornado then transitioned into a two-celled vortex as the tornado moved to the top of the hill with the kinematic feature of intense flow moving out in front of the axis and the path becoming trochoidal.

As seen in this study, geospatial techniques (i.e., VDVI analysis and change detection) prove especially useful in assessing damage variability within the track and relative to elevation. In particular, VDVI analysis better captured the range of damage variability by assessing vegetative health over the survey site. Overall, VDVI values were generally low (an average of 0.2) due to the land cover type consisting of predominantly shortgrass prairies. In areas affected by tornadic winds, VDVI values generally dropped to an average of 0.10, indicating areas of stressed vegetation. In areas of intense scour, VDVI values dropped close to 0, similar to those of bare soil and water, pointing to areas of denuded vegetation. These findings indicate the ability to detect vegetation damage based on the spectral response of vegetation in the red and green bands, even when near-infrared information is unavailable. Additionally, relating changes in VDVI values relative to changes in elevation can provide insight into distribution of damage within the track.

Change detection via point cloud differencing results also show more damage in areas of higher elevation and to exposed features. While land cover changes are relatively small over most of the track, there are some noticeable land cover changes with the greatest land cover change (0.28 to 0.40 meters) observed near areas of local maxima. These areas of change also coincide with areas of maximum scour and erosion in the VDVI analysis (i.e., transects A1-A3 and B1-B3 in Fig. 5.6), providing an additional measure of topographic influence. However, some of this land cover change could be attributed to normal erosion processes based on wind patterns.

Assessing the amount of land cover change relative to a specific event depends on the timing of data collection (i.e., pre-event and post-data) as well as the spatial resolution of the data. Ideally, pre-event and post-event data should be collected close to the time of the event so that land cover changes observed are the result of the event assessed. In this study, the two year time difference between pre-event and post-event data likely captured land cover changes occurring outside of the tornado event (e.g., wind erosion). Additionally, some changes associated with the tornado could have gone undetected due to the coarse spatial resolution of the pre-event data (5 meters). This approach demonstrates the ability to quantify the magnitude of land cover change, which could be used to assess the amount of land cover relative to a tornado event should timely and high-resolution data become available.

This study also demonstrates the benefits of utilizing UAS technologies and geospatial techniques in site surveys (tornado damage assessments) (e.g., Wagner et al. 2019). UAS high resolution imagery provides centimeter scale damage information that can be used to easily identify small-scale features such as local elevation maxima and minima (i.e., the gully shown) as well as debris marks. The 3D modeling capabilities also provide high-resolution (centimeter scale) elevation information, which can used to examine topographic influences on tornado behavior as well as other land cover interactions at the microscale. Using UAS-based information in conjunction with geospatial techniques can also refine damage path through additional damage information (e.g., surface roughness, change detection) and more precise measurements (track width and length) as shown in this study.

Future work should examine additional case examples to assess/validate the findings of this study, given site-specific characteristics of tornado events. Additional analyses should be performed to assess the statistical significance of changes in damage intensity relative to elevation. Additional studies are also needed to investigate high wind interactions with other landforms and land cover features (e.g., land use, vegetation type). Specifically, comprehensive assessments involving multiple observation datasets (e.g., in situ measurements, radar data, damage information) could improve our understanding of wind dynamics and land cover influences by relating changes in kinematic structures to observed damage. Such assessments would improve our understanding on how site-specific characteristics (e.g., land cover, terrain) can influence tornadogenesis, which could lead to better planning and/or adoption of robust resiliency measures.

CHAPTER 6

CONCLUSION

6.1. Introduction

Recent extreme weather events such the Nashville, TN tornado and Hurricanes Maria and Harvey highlight the devastating economic losses and loss of life associated with weather-related disasters. Disaster losses are rising in part because more people are relocating to hazard-prone areas. increasing their vulnerability to these events in terms of exposure. Additionally, society is lowering their resiliency to extreme weather events due to changing demographics (Bouwer, 2010; Chang and Franczyk, 2008; IPCC, 2012; McPhillips et al. 2018; Klotzbach et al. 2018), increases in population growth and urbanization (Kunkel et al. 1999; Klotzbach et al. 2018; Broska et al. 2020), and rise in wealth (Klotzbach et al. 2018). Disaster losses will likely continue to rise as extreme weather events are projected to increase under climate change. Therefore, understanding the impacts of extreme weather events is critical to mitigating disaster losses and increasing our resiliency to future events.

Improving our knowledge of extreme event impacts requires examining social and ecological (biophysical) components. Social factors (e.g., resource availability, institutions, governance, technology) can amplify the damaging impacts of extreme weather events, whereas, ecological factors are related to the biophysical characteristics of the impact such as storm characteristics (e.g., hurricane strength, tornadic wind speeds, storm surge heights), land cover interactions, and extent of impact. These factors can be

intricately linked, as extreme weather event impacts can be affected by both components (Adger, 2000; Walker et al. 2004; McGinnis and Ostrom, 2014).

Geographical approaches are best suited to examine both social and ecological factors in extreme weather event impacts because they systematically examine the spatial interactions (e.g., flows, processes, impacts) of the earth's system as well as human-environment relationships (Clifford et al. 2016). Geographical approaches can be applied to assess the social and ecological components in extreme weather event impacts in two distinct ways. First, geographical approaches can be used to examine social factors in extreme weather event impacts. This approach can be quantitative or qualitative depending on the nature of the data and research question. Second, geographical approaches can quantify the impact of the extreme weather event as well as measuring or modeling the biophysical characteristics and dynamics of the event.

This research has demonstrated the utility of geographical approaches in assessing social and ecological components of extreme weather event impacts. Specifically, this research goal was divided into two distinct components:

c) Assessment of the social factors of extreme weather events impacts through application of geographical approaches
d) Assessment of the ecological (biophysical) effects of extreme weather events impacts through application of geographical approaches

in which four papers were produced. Chapters 2 and 3 addressed social factors of extreme weather event impacts of goal (a). Chapters 4 and 5 addressed the ecological

factors of extreme weather event impacts of goal (b). Their fundamental conclusions/findings are summarized below.

6.2. Summary of Dissertation Findings

My first study examined how knowledge disconnect between experts (climatologists, urban planners, civil engineers) and policy-makers contributed to the damaging impacts of Hurricane Sandy. In this paper (published in *Applied Geography)*, we argue that social ecological resiliency is governed by four adaptive pathways in which 1) resources are determined by institutional arrangements and knowledge, 2) knowledge gap (connection) permits (precludes) societies from designing appropriate disaster responses, 3) institutions shape social vulnerability by setting formal and informal rules for how actors and stakeholders interrelate, and 4) adoption of appropriate technologies determines societal adaptation to impending change.

In the case of Hurricane Sandy, perceptions of risk and issues of willingness to invest led to maladaptive strategies, amplifying the impacts of coastal flooding and storm surge. Policy-makers and other actors did not 1) perceive the climatological risk of tropical storms and hurricane occurrences along the Northeastern seaboard communicated by climatologists, 2) understand the role of land use suitability in coastal flooding as urban planners had advised against development in areas susceptible to coastal flooding as well as in barrier islands, and 3) support erecting storm surge barriers as recommended by engineers to mitigate the risk of storm surge and coastal flooding.

Willingness to invest in robust resiliency measures is a function of 1) discursive knowledge, 2) institutional collaboration, and 3) innovation of technologies as demonstrated by the example of the Dutch Flood policy. Risk is framed using narratives and communicated through multiple channels/media platforms. Knowledge is constructed through plurality of stakeholders including the public, which facilitates institutional collaboration and the willingness to invest in innovative technologies as seen in the Dutch Deltaworks program. This work highlights the importance of mobilizing knowledge to facilitate consensual decision-making, foster institutional collaboration, and invest in appropriate measures to mitigate extreme weather event impacts.

My second study examined the role of land use suitability as suggested by Ian McHarg in 1969 and unsustainable planning in the impact of Hurricane Sandy. This paper was published in *Landscape and Urban Planning.* Significant differences were observed between McHarg's land use suitability and 2012 land use with urban areas in the 2012 land use three times higher than McHarg's land use suitability. Storm surge areas would have only impacted 4.9% of urban areas in McHarg's land use suitability instead of the 39.9% urban observed in the 2012 land use. These differences were statistically significant ($p=0.01$) and would have led to minimal structural damage and economic loss.

Damaged building assessments show that economic losses would have considerably less in McHarg's scenario. Of the 6,817 building affected by storm surge, winds, and heavy rains, most of the buildings (96%) were located within urban areas in the 2012 land use, whereas, those same buildings, according to McHarg, should have

been located in conservation (16.0%) and recreation areas (48.3%). In storm surge affected areas, approximately 95% of damaged buildings located in 2012 urban areas, amounting to 78.1% of the damaged buildings in Staten Island. In fact, the greatest economic losses (destroyed or major damage) were observed in areas that McHarg deemed unsuitable for urbanization and better suited for recreation and/or conservation due to vulnerability to tidal inundation and coastal flooding.

While zoning only designates the potential for land use, zoning sets the stage for future development, segregating land use and designating what can be built. Results from zoning analysis show that McHarg's suggestions would likely have not been realized as 92.5% of the island was zoned for urban areas. With the trajectory for urbanization underway, economic pressures and incentives allowed development in areas vulnerable to tidal inundation and coastal flooding. This study highlights a missed opportunity for sustainable planning, in part, due to the gap in knowledge between policy-makers and urban planners and lack for institutional support discussed in paper 1.

The third paper discussed the benefits, limitations, and procedures of using Unpiloted Aerial Systems (UASs) in tornado damage surveys and was published in the *Bulletin of the American Meteorological Society*. It is important that the meteorological community understands both the benefits and limitations of these technologies as these technologies are becoming an integral part of meteorological measurements and assessments.

Benefits of UAS-based damage surveys include the ability to 1) access remote or impassable locations, 2) better capture perishable data (Womble et al. 2018), and 3)

provide more detailed information to better discern damage and estimate EF-scale rating than traditional methods (i.e., ground surveys, satellite imagery analysis. Our findings show that UAS-based damage assessments can better differentiate high-wind impacts based on land cover characteristics and identify damage, especially when using a multispectral camera. UAS-based multispectral analysis could better detect vegetation especially at the low end of the Enhanced-Fujita (EF) scale, which would improve damage detection in rural area that have well-documented population biases and could lead to the development of damage indicators that area more reflective of tornado strength.

Equipment limitations, scale of operations, navigating FAA and other agency specific policy, and working in disaster zones must be considered to successfully collect, analyze, and disseminate UAS-based damage information. Equipment limitations include limited battery life of approximately 30 minutes (non-fixed wing UAS), requiring multiple batteries and a charging station. Flight operations must adhere to Federal Aviation Administration (FAA) guidelines as well as other agency specific regulations. When operating in disaster sensitive spaces, one should work with emergency managers to 1) assist these organizations with their specific needs, 2) gain access in these sensitive areas, and 3) stay up to date on air space restrictions and other emergency management operations. Lastly, data sharing and infrastructure should easily accessible, capable of handling large volumes of data, and include a collaborative platform for visualization and data sharing between multiple agencies.

Finally, the fourth paper linked the UAS work described in the third paper to a specific research question: examine topographical influences on tornadoes using UAS technologies and geospatial methods. This paper will be submitted in April 2020 to the American Meteorological Society journal *Monthly Weather Review*.

The findings of this work highlight how topography can play a major role in tornado behavior (damage intensity and path deviation). The gully landform illustrated how tornadic winds can produce varying degrees of damage relative to even small elevation changes with little to no damage observed inside the gully and areas of denuded vegetation outside the gully. Damage also increased in areas of local elevation maxima and near the elevation maximum (~430 meters) as evidenced by enhanced scour (lower VDVI values) and increasing track width. Change detection via point cloud differencing results also showed more damage in areas of higher elevation and to exposed features. Where elevation plateaued, damage decreased considerably with the damage path becoming less defined and changing from linear to trochoidal.

Geospatial techniques (i.e., VDVI analysis and change detection) proved useful in assessing damage variability within the track and relative to elevation. The VDVI image better depicted the range of damage variability relative to topography and with vegetative health over the survey site. In areas affected by tornadic winds, VDVI values dropped to an average of 0.10, indicating areas of stressed vegetation. In areas of intense scour, VDVI values dropped close to 0, similar to those of bare soil and water, pointing to areas of denuded vegetation. These findings indicate the ability to detect vegetation damage based on the spectral response of vegetation in the red and green bands, even when near-

infrared information is unavailable. Additionally, relating changes in VDVI values relative to changes in elevation can provide insight into distribution of damage within the track.

This research also illustrates the importance of using UASs in obtaining high resolution data for analysis. UAS high resolution imagery provides centimeter scale damage information that can be used to easily identify small-scale features such as local elevation maxima and minima (i.e., the gully shown) as well as debris marks. The 3D modeling capabilities provide high-resolution (centimeter scale) elevation information, which can used to examine topographic influences on tornado behavior as well as other land cover interactions at the microscale. Using UAS-based information in conjunction with geospatial techniques can also refine damage path through additional damage information (e.g., surface roughness, change detection) and more precise measurements (track width and length) as shown in this study.

6.3. Conclusion and Significance of Work

These four papers presented aptly demonstrate the utility of geographical approaches in assessing social and ecological components in extreme weather event impacts. This work 1) identifies significantly important tools (i.e., geographical approaches) with regard to extreme weather event impacts and 2) demonstrates the effectiveness of those tools for both researchers and others (first responders, policy-managers, etc.). Geographical approaches provide a deeper and more comprehensive understanding of extreme weather event impacts by recognizing the multiple dimensions

and role of human-environment relationships in disaster impacts. Together, the four papers in this dissertation highlight the role of human-environmental relationships, scale of impacts regarding hurricanes and tornadoes, and range the spectrum of research from basic data collection using state-of-the art UAS technologies and analyses of these data to policy implications and recommendations for in extreme weather event impacts.

The first two papers analyzed the social components in the impact of Hurricane Sandy through the application of social geographical approaches. These papers illustrate how social components of knowledge disconnect between experts and policy-makers and unsustainable planning (land use suitability) amplified the impact of Hurricane Sandy, resulting in devastating damage in New York and New Jersey and to Staten Island. Bridging this gap in knowledge is critical for both social and ecological systems, because of the intricate linkage between social and ecological factors and implications on the system as a whole. Developing sustainably and devising robust adaptation strategies necessitates discursive knowledge to induce the necessary behavioral change to redesign policy and invest in innovative technologies to increase our resiliency to future extreme weather events.

The role of policy and land use highlighted in those two papers have led to significant contributions to the literature with additional work citing this research. Since publication, Papers 1 (Chapter 2) and 2 (Chapter 3) have been cited 45 and 13 times, respectively. Paper 1 (Chapter 2) has been used to support/validate/justify research on: 1) resiliency, 2) hurricane and other extreme weather event impacts, 3) risk perceptions of extreme weather events and climate change, 4) co-production of knowledge with

implication for disaster preparedness and recovery, 5) policy opportunities ('windows') following extreme events, and 6) role of institutions in extreme weather events and climate change. Paper 2 (Chapter 3) has been cited by research focusing on sustainable development, ecological wisdom, and natural resource management.

The last two papers (Chapters 4 and 5) examined the benefits, utility, and limitations of UAS technologies in tornado damage surveys. Understanding the benefits and limitations of these technologies is critical to the meteorological community as these new technologies are being implemented in meteorological measurements and assessments. This research demonstrates how UASs and geospatial methods (ecological geographical approaches) provide a more accurate and complete damage information compared to current damage assessments (e.g., ground surveys and satellite imagery analysis). In particular, UAS-based damage survey information can better 1) identify of damage and severe straight-line winds unidentifiable from current methods, 2) refine of tornado damage paths, and 3) lead to a better assignment of damage ratings, especially in rural locations. The final paper (Chapter 5) demonstrates how UASs and geospatial methods (ecological geographical approaches) can improve our understanding of severe storm dynamics regarding tornadic wind interactions with topography. Utilizing UAS-based high resolution imagery and 3D products like Digital Surface Models (DSMs) show the ability to detect even microscale changes in elevation with important implications to society: validating sheltering in low-lying areas in open areas and land use planning in tornado risk areas.

The research in Chapters 4 and 5 has the potential to improve severe weather forecasts and warnings through better documentation of severe weather events, leading to better understanding of the relationship of identifiable storm structures and storm hazards. The detailed UAS information will likely 1) improve the accuracy of severe storm report database, 2) reduce bias in the climatological record, and consequently, 3) improve tornado climatology. This research will connect with other NOAA projects such as VORTEX-SE, which will focus on understanding tornado impacts in the Southeast US. In particular, part of my work as a post-doctoral researcher will examine how we can improve damage surveys of VORTEX-SE events in collaboration with local National Weather Service Weather Forecast Offices (NWS WFOs).

The fundamental contribution of this research is twofold: 1) using new technologies (i.e., UASs) to detect land cover changes as a result of extreme weather event impacts and 2) connects extreme weather event impact assessments to policy. Firstly, the use of UAS technologies and geospatial methods improves our understanding of land cover interactions with high-wind event as demonstrated by the work in Chapter 5 by detecting and linking fine scale damage information with 3D models. Connecting more accurate and complete damage information with in-situ observations (e.g. radar data) provides more information on land cover interactions in high-wind events and improves our understanding of severe convective weather events and associated earth system processes. Secondly, this research connects extreme weather event impacts to policy, recognizing the role it can play in disaster impacts and potential to mitigate future losses. Understanding the social and ecological components in extreme weather event

impacts gives us the ability to recognize what is sustainable and unsustainable and what factors we can control in the outcome of these impacts. Integrating this knowledge into policy is essential to developing sustainably, investing in innovative technologies, and devising robust adaptation strategies that mitigate our risk to future extreme weather events.

Overall, this research demonstrates our potential to improve our resiliency to future extreme weather events and mitigate future losses by better understanding the social and ecological components in extreme weather event impacts through geographical approaches. Knowledge from these assessments can provide researchers, first responders, and the public valuable information to develop robust policies and mitigation strategies that save lives and protect property.

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