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THE SIGNIFICANCE OF A HIGH RESOLUTION 2D HYDRAULIC MODEL INCLUDING GREEN INFRASTRUCTURE FOR ASSESSMENT OF COASTAL COMMUNITY VULNERABILITY AND RESILIENCE

by

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A Thesis

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Thesis Chair: Dr. Rouzbeh Nazari

Dedications

I dedicate this thesis to my father, mother, sister and brother. They have encouraged me to continue to strive to be the best I can be and not let anything get in the way of my success. The hard work presented in this paper is a product of the unconditional love and support from my family, and I wouldn't have been able to do it without them.

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Finally, to those who have conquered so much more than a master's degree, I applaud your accomplishments. Thank you for dedicating so much time and energy into research and learning. Without you, the world would never reach advancement.

Abstract

Katie M. Miller
THE SIGNIFICANCE OFAN ENHANCED FINE-SCALE HYDRAULIC MODEL
INCLUDING GREEN INFRASTRUCTURE FOR COMMUNITY RESILIENCY

2016-2017
Dr. Rouzbeh Nazari
Master of Science in Civil Engineering

This paper outlines the development of an enhanced hydraulic flood model that uses a fine-scale grid to analyze significant areas of flooding for improved flood predictions and resiliency planning. This study modeled the extent of Atlantic City and Camden, New Jersey. The capabilities of the model were compared to coarser national models, HAZUS-MH and SLOSH, to understand the significance of fine-scale hydraulic modeling. The results illustrated that the HAZUS and SLOSH models showed gaps in some areas and lacked accuracy due to lower resolution. This paper also describes how these developed models show the impacts of severe storms, and the effects of Green Infrastructure (GI) implementation as resiliency methods using SWMM. Overall, the models with GI show a decrease of peak runoff and decreased flow due to the GI implementation. The results and benefits from this study's simulation and modeling techniques support modeling storms using high-resolution hydraulic programs due to their precision. This research will allow coastal community members to understand the significance of fine-scale flood modeling and green infrastructure implementation with more advanced techniques in the future for resiliency planning.

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Chapter 1

Introduction

1.1 Statement of the Problem

The rising levels of the ocean and the potential increase in storm and hurricane frequency due to climate change are putting coastal and riverine communities of New Jersey in danger. There is an immense amount of inundation that vulnerable communities receive during a storm event; therefore a plan of resilience against the destruction is highly necessary. The bayside along New Jersey's barrier island communities is one of the nine high-risk areas for flooding along the Atlantic Coast according to the U.S. Army Corps of Engineers (Degener, R. 2015). It was also indicated that the sea level may rise approximately 1.5 meters by 2100 in Atlantic City (Degener, R. 2015). This high risk for Atlantic City creates the need for adaptive measures to be implemented to reduce the community's vulnerability to extreme storm events and increase resilience in response to such threats.

Camden, New Jersey, along the Delaware River, is a highly threatened community as well. Camden is an urban community, with a combined sewer system and poor water management services that overflow continuously during a storm (Van Abs, Daniel J. 2014). Climate Central has projected a 1.28 meter rise above the local high tide line locally near Camden by 2100, from a 1992 baseline (Climate Central, 2016). The probability of the surrounding communities to be washed-out the next time a heavy storm presents itself is high, and advanced protective tactics need to be acknowledged.

1.2 Scope of Study

1. Develop a fine-scale hydrologic and hydraulic flood model to simulate past flooding events in subjected areas.
2. Compare the fine-scale model to currently used national models that are coarser in resolution, to show the significance of fine-scale modeling for such climatic problems.
3. Analyze a simple resiliency method of levee implementation along the study areas of Atlantic City.
4. Simulate the existing urban drainage system in a Camden neighborhood to illustrate the benefits of green infrastructure as a resiliency method against flooding.

1.3 Study Objectives

The focus of this study was to illustrate the benefits of fine-scale hydraulic modeling for resiliency planning prior to the implementation of mitigation techniques in Atlantic City and Camden, New Jersey. A high-resolution hydraulic model was used to simulate the spatial extent of flooding for a specified region in both communities and compared to the output of the coarse resolution models HAZUS-MH and SLOSH. This paper illustrates how high-resolution simulations are capable of showing fine-scale differences in inundation levels, which will enable communities to focus on reliable resiliency measures with the potential of significant economic savings as compared to the use of coarser models. The dual focus of this paper is to understand the importance of flooding and illustrate how flood mitigation techniques, such as green infrastructure, in SWMM can benefit areas threatened by flooding.

Chapter 2

Literature Review

Sea level has been rising over the past century due primarily to the climate change (Bindoff et al 2007). A warming climate has led to increased rates of melting of glaciers and thermal expansion of the ocean's water. This has increased the risk of coastal and inland flooding throughout much of the world. In the US, sea-level rise threatens infrastructure (i.e. bridges, transportation, dams, buildings, docks, etc.) and the economy. The Atlantic seaboard is highly prone to coastal flooding and has received billions of dollars in damage all along the coast due to tropical storms and hurricanes (NOAA 2014). A large portion of industry and commerce are vulnerable due to their location within the low-lying areas along the coast. Hurricane Sandy damaged hundreds of power lines, affecting more than 8 million residents in the United States (LiveScience, 2013). New York City's Metropolitan Transportation Authority received about 5 billion dollars for damages (Toro 2013) to maritime facilities (Smythe 2013) caused by Hurricane Sandy. Additionally, coastal counties contribute $6.6 trillion, or just under half of the country's gross domestic product, to the U.S. economy and are home to almost 40% of the U.S population (National Ocean Service 2014). This makes coastal communities extremely valuable to the country, meaning they need to be protected well and greatly managed.

An extreme sea level rise event along the northeast coast of the United States, was recorded to be around 12 cm from 2009 to 2010 (Goddard, 2015), and it is evident that the coastal flood zone is becoming wider and deeper with the potential for more damage from storm surge and flooding. Specifically, the southern New Jersey coast is at high risk of flooding, economic loss, and land depletion due to sea level rise caused by climate change and the isostatic rebound of the land after the retreat of glaciers from the last Ice Age. The bayside along New Jersey's barrier island communities are one of the nine high-risk areas for flooding along the North Atlantic Coast according to the U.S. Army Corps of Engineers (Gurnian, S. 2015)**.** and a study done resulted in Atlantic City's sea level rise to about 1.5 meters by 2100 (Degener, R 2015). Additionally, an analysis done by Strauss et al (2014) projected a sea level rise of 0.39 meters in Atlantic City by 2050. Atlantic City is at high risk and needs resiliency planning methods to help reduce vulnerability to potential loss and destruction. Therefore, there is a need for information and analyses on the hazardous flooding issues that the city faces.

Cutter (1996) has identified vulnerability as the combination of the physical risk and social response due to a hazard within a specific geographical area- 'vulnerability by places.' Using the spatial distribution of flood risk, land use and people within the different flood-risk zones, Wu et al (2002) found that due to Cape May County's geographical location and its elevation of only 3 m above mean sea level, storm surges and sea level rise were major issues that have to be dealt with immediately. It was also found that the increase in sea level due to climatic change will increase the vulnerability of the county to coastal storms.

One tool to evaluate the threatening conditions of a potential storm is the Sea Lake and Overland Surges from Hurricane (SLOSH) model. The SLOSH model estimates storm surge heights and winds from historical and predicted hurricanes (NHC 1999b). Wu used the SLOSH model with a Digital Elevation Model (DEM) of Cape May County to depict what areas of the county would be inundated for a projected storm surge height, identifying risk areas. Riverine and inland flooding was also taken into account based on Q3 flood data provided by FEMA (1996). Combining these major threats of destruction allowed the team to depict a more accurate physical characterization of the flood risk in the area. Not only was the physical exposure of flooding examined, but the social vulnerability of the community was identified as well. Variables such as population, housing units, number of females and other factors were examined within the study area. An overall flood vulnerability map was developed by dividing the overall vulnerability index into low, moderate, high and very high. It was concluded that climate change would have substantial impacts on the coastal communities and sea level rise would increase the risk in areas that were already at higher risk. These studies signify the need for more research to help mitigate such flooding hazards. Solutions need to be readily available to be implemented for all coastal communities that are at a potential for loss.

While an understanding of the vulnerability of a community is crucial, it is also important to understand the fundamentals of community resilience. Resilience is the ability of a system to respond and recover from disasters and allows that system to absorb the impacts and cope with an event (Cutter et al., 2008). It has been suggested that resilience can be defined as a system’s capacity to absorb disturbance and reorganize into a fully functioning system (Adger et al., 2005; Klein et al., 2003; Folke 2006). This includes a system’s capacity to return to its original state as well as advancing the system’s resilient capabilities through learning and adaptation. Other resilience models often include the robustness, redundancy, resourcefulness and rapidity of resilient infrastructure (Tierney, 2003), but none have succeeded to include the antecedent social factors that occur at the local levels or to account the resilience of the natural environment. Challenges remain in the development of consistent factors that can be used to evaluate the disaster resilience of communities. Since it is difficult to quantify resilience and get a solid measurement of caution or awareness, there are indicators used to compare relative levels of resilience between places or analyze trends over time. These indicators are very useful and important when trying to reduce complexity, measure progress, map the impacts and set priorities for decision making. A society can be considered resilient in different ways that have to be measured on different scales. For example, social resilience is influenced and can be increased by improvements in communication, risk awareness and preparedness. Economic resilience is influenced based on the mitigation strategies that aim to lessen the probability of failure of the community (Rose, 2006).

Goddard et al (2015) have developed the Disaster Resilience of Place (DROP) model, which includes a conceptual basis for establishing baselines of measuring resilience, and is designed to present the relationship between vulnerability and resilience. This model was created specifically to address natural hazards. It focuses on resilience at the community level, and the model emphasizes the social resilience of place (Cutter, 2008). Within the DROP framework, recovery is an ongoing process within a community until it is fully back to its original or better state, where preparedness and mitigation including social learning can be improved. The DROP model provides a basis for all communities to learn from the hazardous events that are experienced and gives them an opportunity to improve their mitigation techniques. For example, if a community experiences a 10-year flood once, their absorptive capacity probably would not be exceeded, however, if they experience a 10-year flood every year in several consecutive years, then their resources will not be sufficient for effective coping responses.

While vulnerability and resiliency are crucial to developing a framework for understanding climatic hazards, it is also important to have the modeling capability for climate projections and predictions of the potential for future impacts. There are existing models, such as HAZUS-MH (Hazards US) and SLOSH (Sea, Lake, and Overland Surges from Hurricanes) provided by The Federal Emergency Management Agency (FEMA) and the National Oceanic and Atmospheric Administration (NOAA), respectively. The HAZUS model calculates the exposure for selected areas and then characterizes the intensity or level of the hazard (flood level) using the return period of a flood, (e.g. a 100-year return period is a flood that only occurs every one hundred years). HAZUS can calculate the potential losses such as structural damage, economic loss, etc. SLOSH estimates the level of storm surges resulting from historical, hypothetical or predicted hurricanes. However, these models are applicable for relatively large scales beyond the focus of local communities. The ability to focus on local impacts and potential mitigation techniques can help to focus efforts to reduce vulnerability, increase resilience, and direct economic investment to where it will be most effective.

Additionally, there is a need for the use of high-resolution flood models in advance of implementation of any stormwater management system. The overall goal of this study was to compare national flood assessment models to an enhanced regional flood model and to illustrate how flood mitigation techniques can benefit areas threatened by flooding.

A study done in Belgium along the lower part of the Ourthe River illustrated how micro-scale analyses for protective measures of threatened coastal communities, along rivers and oceans, is extremely important (Ernst et al. 2010.) The refined analysis allows focus to be set on assets such as structures, buildings and facilities and shows the effectiveness of potential local measures for inundated areas in the community. This study took advantage of available data that characterized each building's vulnerability and used a two-dimensional flow model to provide high-resolution maps of flooding.

The availability of high resolution and highly accurate topographic datasets in several countries have allowed the researchers in Belgium to collect significant data from airborne laser altimetry (LIDAR) and echo-sonar techniques. Using this exceptional quality of topographic data and a fine-scale grid as fine as 2-m by 2-m enables modeling at such a scale to individually pinpoint streets and houses rather than a larger grid that generalizes a vast area used by existing national models. This study's fine-scale model was so precise that when compared to historic flood events, observed data and numerical predictions from the simulation were in agreement, validating the uniqueness and consistency of high-resolution modeling. This study showed by using a fine-scale approach, the deduction of flood impacts and destruction could be made and there was an understanding about the level of effects a potential storm scenario will bring. This study used hydrological data from a statistical analysis of discharges measured at a nearby tide gauge for the hydraulic boundary conditions and found inundation depths and velocity components for each considered discharge. The researchers were also able to apply their exposure evaluation equation to the analysis and determine exclusive results. The data shows a detailed spatial distribution of affected residential and non-residential buildings for a 154-year flood, with the water depth in each area, where each type of building is located. The results also showed that for discharge values lower than the 100-year flood, not many houses undergo flooding with a water depth higher than 1.3 m but there is an increase in the number of houses flooded by less than 0.3 m and even more of an increase in houses flooded with a water depth in between 0.3 m and 1.3 m. In contrast, for discharge values higher than 1000 m3/s, the number of houses flooded by less than 1.3 m decreased, revealing that for such extreme storm events, even buildings located at the edge of the inundation extent undergo flooding with significantly greater water depths (Ernst et al. 2010). This crucial information that was found validates the importance and impending reputation that fine-scaled hydraulic modeling has.

Another study done by the same researchers also endorsed the need for fine-scale hydraulic modeling to make accurate predictions and forecasts. This study took place along the Dendre River in Belgium (Ernst et al. 2010.) The hydraulic model provided the user with great detail and precision, due to the quality of scale and topography using laser altimetry. This type of modeling takes current configuration to a higher level, in displaying the exact depth of flood that a house will endure. The spatial resolution of this model ranges from 4 m to 1 m and is coupled with supreme high-resolution digital elevation models (DEMs), which provides the user with a very impressive layout. For example, for validation purposes, the flood of January 28th, 1995 was modeled in the fine-scaled hydraulic modeling software. The peak discharge of the storm evaluated at 180 m3/s. After pertinent parameters were set in place, that same peak discharge value was inputted into the model corresponding to a 15-year return period. The predicted spatial pattern of the flood using the modeling software matched the observational pattern flawlessly. Another comparison was done for a different reach of the river. To take advantage of such fine DEM information, the grid cells were able to downsize from 4 m to 1 m resolution. The flood on January 3rd, 2003 was used to compare to the new simulation. This flood had a peak discharge of 150 m3/s. Six survey points were used to validate the accuracy of the fine-scale flood model. The observation and calculation values in centimeters were extremely similar. Point 1 had an observation value of 82 and a calculation value of 86. Point 2 had an observation value of 5 and calculation value of 15-30 at the center of the street. Point 3 had an observation value of 25 and calculated value of 5 along the houses. Point 4 had an observation value of 20 and calculation value of 30. Point 5 had an observation value of 80, calculated value of 90 and Point 6 had an observation value of 94, and the calculated value was 90 cm (Erpicum, S. et al, 2009). The computation of this particular study also shows the flow regime, which was compared to authentic pictures of the event. The flow path in the simulation matched the flow path in the aerial photograph. These results are prime for decision makers and policy makers in locating priority areas where mitigation techniques are needed to reduce flood risk.

These studies are only a small illustration of why there is a need for the use of high-resolution flood models in advance of implementation of any stormwater management system. These flood models can help reduce risk as well as minimize over/ under engineering design costs because of the precision these detailed models provide. A dollar spent on mitigation is repaid four times over in dollars not spent on response and recovery (Rose et al. 2007; FEMA 2011). With such highly accurate DEMs and flow simulations using a grid size as small as 1 m, these models succeed in the expectations of true flood depths and flows. The precision of these models is what is needed in order to keep threatened communities from being devastated by sea level rise, storm surge and severe flooding.

The frequency of hurricanes and storm surges seems to be increasing due to the climate changing and sea level rising as coastal communities are becoming extremely vulnerable to the flooding produced by these heavy storms. Camden, New Jersey, an underprivileged urban community with a combined sewer system needs resiliency plans set in place to mitigate the potential for damage due to the vulnerability of the community. Based on the National Climate Assessment intermediate high sea level rise scenario, Climate Central has projected a 1.28 meter rise above the local high tide line locally near Camden by 2100, from a 1992 baseline (Climate Central, 2016). The Assessment analysis concluded that there is a 33% risk of at least one flood exceeding 4 feet by 2030, an 84% risk by midcentury and a 100% risk by 2100 that a flood will reach and exceed 4 feet. Even the slightest increase in sea level rise makes rare floods more common because it adds to the tides and storm surges. The increase in sea level will essentially cause more sustained extreme storm surges and increased coastal erosion, damaging and affecting many parts of local communities along a waterbody.

The city of Camden contains a combined sewer system in an urbanized area and is parallel to the Delaware River, both causing problems during severe storm events. The combined sewer system carries sanitary sewage and stormwater through the same system to a treatment facility. When there is a rainfall event, it’s likely that total wastewater flows will exceed the capacity of the system, which then overflows into nearby streams, lakes, and roads. Any rainfall event affects the Delaware River for two reasons, water quality and flooding. If the event is large enough, contaminants will be discharged into the river as well as the water level will rise onto the surface and flood a particular area within the city. For example, a slow moving system dropped about four to six inches of rainfall on portions of the south-central New Jersey area on July 12-13 in 2004 (DRBC, 2015). More than a foot of rainfall was measured in some locations and as a result, 25 roads were closed and hundreds of residents had to evacuate. In the south central New Jersey area, a total of 17 dams were either partially or totally breached and countless numbers of streams flooded their banks. Being a county flood disaster zone, Camden County was made eligible for federal aid. Events like these are on a continuous climb for the future and preventative measures are crucial.

Due to the climate changing which is affecting water levels, communities need to be prepared and increase their resilience towards climatic disasters. Urban communities like Camden are at higher risk for flood damage because of their infrastructure, increased impervious surfaces that do not allow stormwater to drain, and its economic status. It is one of the poorest cities in the United States (MetroFocus, 2012) and because of this, storm preparation and resiliency has not been a priority for the community. This is a problem due to the probable increase in frequency of severe storms, which will cause more damage to the city.

There was a case study done on the Caribbean island of St Maarten where key elements of disaster management planning were used. The concept of a 'digital city' was explored, which is a way to improve the preparation for natural disasters. Resiliency is a quick recovery characteristic of a city or community. Preparation for a natural disaster, prevention for hazards from developing and reducing the effects of a disaster are all key components to resiliency planning. The 'digital city' method includes the application of hydroinformatic technologies in urban water systems (Vojinovic and van Teeffelen 2007). Hydroinformatic technologies use simulation modeling and information technology to better water management. The 'digital city' concept is comprised of city administrators collecting and analyzing data for their urban areas through Geographic Information systems (GIS). The information and communication provided by these maps allow them to delineate floodplains, zone areas for protection for flooding and identify plans for different types of land use (Yang and Tsai 2000). With this information presented properly, natural disaster public meetings can be achieved. The idea also includes the measurements of sewerage water levels and flows, groundwater levels, etc. These measurements associated with the remote sensing of the land use and terrain levels, rainfall predictions, and routine asset inspections can help provide a digital overview of the risks associated with potential disasters (Price, R. K. and Vojinovic, Z. 2008).

Decision making support systems can be combined with data and modeling systems to increase resiliency and provide warnings of hindering disasters (Price, R.K and Vojinovic, Z. 2008). The monitoring system combined with an effective modeling system can form a basis for a reliable decision support system which has a few major functions. These functions include improved ways of determining risks and implementing mitigation techniques, the compilation of all data and modeling systems being used as reliable forecasts for a warning system and another function is system to be used as a tool for education programs to intrigue the public. These functions make it very obvious that there is a need for such technological advances and digital data to develop effective plans and communicate accurate information to the public.

The main focus of the ‘digital city’ concept is creating an environment in which users responsible for various aspects of the disaster management plan are permitted to appreciate various flood-related problems and as a result to make better judgements, improved decisions and efficient action plans through the decision support tools provided (Price, R. K. and Vojinovic, Z. 2008).

This paper used The Associated Programme on Flood Management (2004) as insight on lessons learned from urban flood disasters across the world. A few lessons that are suitable for the study presented in “The Significance of a High Resolution 2D Hydraulic Model including Green Infrastructure for Assessment of Coastal Community Vulnerability and Resiliency” are as follows:

- Integrate urban planning and water management, bringing together city planners and water engineers to craft a more viable and sustainable urban environment
- Adopt a sound mix of structural and non-structural strategies for mitigating urban flooding, taking into account the uniqueness of the area and analyzing the associated problems and opportunities.
- Break the poverty cycle through improved risk management that recognizes the vulnerability of the poor.

These three points are the true basis of what needs to be done in order for resiliency in threatened areas to succeed. Urban planning and water management are crucial for a more sustainable environment to handle such climatic stresses. More importantly in this case, in order to decrease the poverty of Camden, New Jersey, improved risk management needs to be achieved so the disaster cycle discontinues. Once the city is at a steady state and less vulnerable, it won’t be seen as such a deficient community.

The case study done on the Caribbean Island of St. Maarten can be used to further the development of the Green Infrastructure resiliency method, combining physical information with social interaction. The case study started with modeling different scenarios for different rainfall events. The hazards were evaluated and the extent of the flood damages were quantified using Average Recurrence Interval (ARI) flood events and corresponding hazards and damages were calculated. Then the impacts of the flood disaster were identified and immediate assistance to the affected sections of the community are initiated using a decision tree created by the authors. Then, guidelines on how to assess the causes and effects of the flood are produced. This process can be explained in detail in Urban Flood Disaster Management (Price, R.K and Vojinovic, Z. 2008).

This case study provides a complete framework for managing urban flood disaster, combining hydroinformatics and city concepts. With the development of new information and communication technologies, the possibility of reducing risk associated with disasters, communication improvement and proactive communities assisting recovery from a disaster event can be achieved, which is highlighted in the study. Many communities need to adopt this type of framework, in order to increase resiliency and risk management practices.

A method to mitigate flooding is the implementation of Green Infrastructure. Green Infrastructure (GI) is very beneficial for building resilience to protect urban communities against climate change such as warmer temperatures, increased flooding and changed rainfall patterns. GI practices like bio infiltration basins, green roofs and rain gardens are integral elements of water management that have the potential to prevent major flooding in areas that are prone to water damage. Green Infrastructure is a cost-effective, resilient approach to managing wet weather impacts that provides many community benefits (EPA 2015). Green Infrastructure is a natural design that reduces and treats stormwater as well as provides environmental, social and economic benefits to a city or community. In urban areas, rainwater falls and puddles onto building roofs, streets and parking lots, where the water is unable to seep into the ground due to the increase of impermeable surfaces. Due to this occurrence, stormwater is a major cause of pollution in urban areas. The runoff and its discharge into nearby water bodies contains trash, bacteria, heavy metals and other pollutants from the urban landscape (EPA 2015). Heavier storms increase the flow of the stormwater system, causing erosion and flooding, essentially damaging the natural habitat, property and infrastructure of the city. GI practices are highly beneficial and use vegetation, native soils and other elements to capture the stormwater, treat it, store it and then filter it through the ground. These are BMP (best management practices) that manage water, mitigates flooding and creates a healthy urban environment as well as increased the resiliency of the community.

The South Australian Green Infrastructure Project was developed to illustrate the effectiveness of GI practices and support the case to invest in Green Infrastructure (Pitman, S.D., Daniels, C.B. & Ely, M.E. 2015). The following information provided verifies the importance and efficiency of green infrastructure, making it an operative decision to implement green infrastructure in vulnerable urban areas, if not everywhere.

In 2010, cities held 3.5 billion people, 50.5% of the world's population, and by 2050 these urban environments will need to accommodate an additional 2.6 billion people (Potter, 2013.) The idea of green infrastructure has escalated due to the positive outcomes that have been demonstrated, as well as the professional research that has been done by planners, designers and engineers. Green infrastructure provides shade, clean water, diffused light, filtered air, and many more benefits (Daniels & Roetman, 2014). The botanic gardens on the roofs and walls of buildings capture hazardous particulates, keeping towns and cities healthy, while also providing aesthetics, attracting more people to the area. These practices greatly build resiliency in urban communities, protecting them from natural disasters such as heavy rainfall and flooding. Water Sensitive Urban Design (WSUD) practices are an approach to green infrastructure such as bio infiltration basins, stormwater harvesting, and the use of porous surfaces (Wong, 2011). These practices serve as a mitigation technique for frequent flooding in urban areas and supports the green space initiative in many cities, networking water systems and these spaces to deliver environmental, social and economic value (Ely & Pitman, 2014.)

Resiliency planning is pertinent for communities who are vulnerable to considerable flooding associated with such rain storms, hurricanes and storm surges. Urban flooding has been an ongoing problem due to the vast amount of impermeable surfaces associated with these areas. Green infrastructure suggests a great alternative approach for greater resiliency by using the WSUD practices as well as other designs that are very effective in reducing the likelihood and consequences of damage and risk (Maunsell, 2009). The benefits of using green infrastructure for mitigation and resiliency planning are infinite and the review in *Green Infrastructure as life support: urban nature and climate change* has demonstrated such success in the natural modification. These designs will help not only the common population in threatened communities but it will also help the natural environment as well. This type of flood mitigation is a new, innovative plan for building. The environment is extremely important and with these strategies, many problems can be solved.

One of the main objectives of this paper is assessing the effectiveness of green infrastructure to mitigate the impacts due to severe storm events. Likewise, Versini et al (2015) have completed research to assess green roofs from building scale to basin scale; to understand if similar implementation of green roofs will affect the entire basin in such a way. Green roof coverage is expanding; so much, that 10 km2 of green roof coverage is starting to happen in Germany (Lassalle,2012). Green roofs are specific elements to the urban city where there is nowhere left for infrastructure. Green roofs contribute to the aesthetic worth of a building, they reduce the heat island effect, protect biodiversity, and manage urban runoff. There are numerous beneficial effects of green roofs, let alone the whole umbrella of green infrastructure. The main performance of green roofs is stormwater management, reducing annual runoff and peak volume, as well as managing the rainfall intensity and water quality. During a yearlong experiment in New Zealand, where six different areas from 10 to 50m^2 were placed with green roofs on Auckland University. The results found 66% of precipitation was retained and a peak flow reduction ranged from 31%-100% within six of the different areas. Another surface in Genoa, Italy was covered, 350 m^2 was divided into two plots, and after 6 months, the results shows volume retained of 10%-100% and a peak flow reduction ranging from 80%-100%. These studies illustrate the effectiveness of green roofs alone, supporting research to go one step further and explore the success of green roofs at a basin scale as well.

Versini et al used SWMM 5.0 to conduct their research. For their case study, Hats-de-Seine, France was modeled. It is a highly populated and urbanized area with 1.5 million inhabitants within a 176 km2 area. Their stormwater system is extremely sensitive due to the rapid growth in the early 90’s and is prone to local flooding. The Chatillon basin was split into several sub-basins, each sub-basin having an infiltration area and then an impervious area where a green-roof was implemented. The impacts of the green roof scale showed an expected reduction in the hydrological response; the higher the covering, the higher the reductions of peak discharge and volume. Results showed that at the roof scale, reductions of peak discharge and runoff volume are of the same order of magnitude; 12.5% covering of the roof resulted in about 10% reduction, 25% covering resulted in about 20% reduction, 50% of covering resulted in about 40% reduction and 100% of green roof covering resulted in about 85% reduction of hydrologic responses. At a basin scale, from a green roof covering of 12.5%, there was an average of 4.9% runoff reduction, and a 25% covering of green roof showed an average increase in reduction of 9%. With 50% green roof covering, there was an average peak discharge of 18.6% and 100% green roof covering averaged a reduction of 35.6%. This supports the suggestion that the more green-covering on eligible buildings, the more reduction there will be. The conclusions of this study show that the amount of precipitation is a limiting factor for the workability of the green roof, both at a building and basin scale. The higher the precipitation, the less of a hydrological impact there will be from the green roofs, but overall the green roofs are successful in their purpose.

Camden has already initiated a plan of action to help support its current and future flooding issues. The Camden SMART Initiative (Stormwater Management and Resource Training) was formed to improve the quality of life and environmental and economic health of the City of Camden (CCMUA, 2011). They support a green stormwater infrastructure approach, which will be environmentally and economically beneficial to remediate the urban community and its waterways. This initiative is a collaboration between the City of Camden, Camden County Municipal Utilities Authority (CCMUA), Rutgers Cooperative Extension Water Resources Program, New Jersey Tree Foundation (NJTF), Cooper's Ferry Partnership (CFP), New Jersey Department of Environmental Protection (NJDEP), public-private partners, community organizations, and Camden residents. This collaboration between so many individuals has helped revitalize the community with green infrastructure projects and programs. These programs are benefiting the city by preventing neighborhood flooding, reducing combined sewer overflows, improving air and water quality, and much more. There have been forty-five completed projects since 2011, capturing 61.2 MG of stormwater each year. There are no projects in the process currently, but continued research will prove that green infrastructure will help the community for the future environmentally and economically.

Chapter 3

Methodology

3.1 Context of the Study

A fine scale hydraulic modeling interface and program, Surface-water Modeling System (SMS) and TUFLOW, were used to show the significance of high-resolution flood mapping in Atlantic City and Camden, New Jersey. This fine scale hydraulic model was then compared to national coarse-resolution models, HAZUS and SLOSH, to defend the argument more substantially, of how fine-scale modeling is significant in the preliminary stages of resiliency planning. The study area of Camden was also modeled in a program provided by the USEPA, Storm Water Management Model (SWMM), which illustrated the effects of flooding and the benefits of green infrastructure implementation.

3.2 Study Areas

3.2.1 Study area, Atlantic City. Atlantic City, New Jersey is in Atlantic County, about 150 km south of New York City and lies at the north end of Absecon Beach, a barrier island along the coast of New Jersey (Figure 1). Bridges connecting the mainland to the city span the Intracoastal Waterway and the shallow bays. Atlantic City is a resort town, including hotels, casinos and beaches along a stretch of more than five miles of boardwalk. The area consists of 44 square km and 16 square km of water. According to Census Bureau 2010, Atlantic City had a population estimate of 40,000 people.

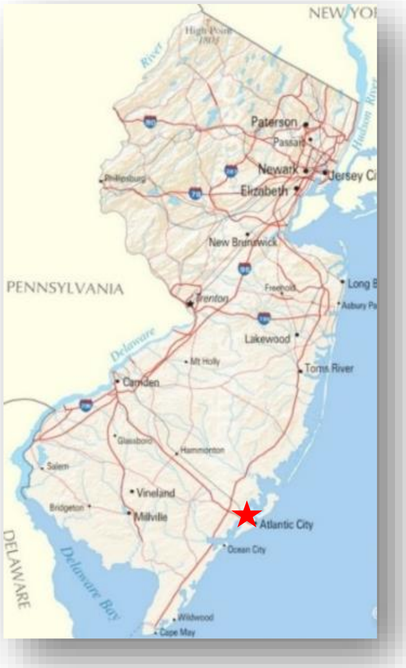


Figure 1. Study Area- Atlantic City.

This study selected a small portion of the city to analyze, allowing for a more detailed and precise result. This specific area was chosen to analyze due to the constant damage it suffers. Atlantic City has had their boards ripped up from the coastline, resident cars turned over, power lines cut, basements flooded and businesses shut down due to hurricanes, and severe weather events that are increasingly inevitable as sea level rise and climate continue to be a concern. Additionally, this area was chosen for analyzation due to the high volume in tourist activity and conventions in this area. This city offers the public vast amounts of opportunity and recreation, creating a vulnerable area that needs to be protected.

Three areas were analyzed in Atlantic City. One area is a vacant lot next to the channel, with homes and docks located further up the channel. This area was specifically chosen due to the high flooding that it receives when a storm hits, and because of the risk in the area for potential sea level rise. The second area that was analyzed consists of a strip of two-story homes right along the channel with ownership of boats. This area is highly vulnerable due to its low resilient characteristics of little to no flood barrier implementation or green infrastructure. The third area of Atlantic City that was analyzed, like the previous area, is highly prone to flooding, which has been shown on sea level rise risk maps provided by Climate Central and NOAA as well. The third area has been chosen due to the high risk of inundation in the area during severe storms. Figure 2 shows these three areas of interested showcased in this study.

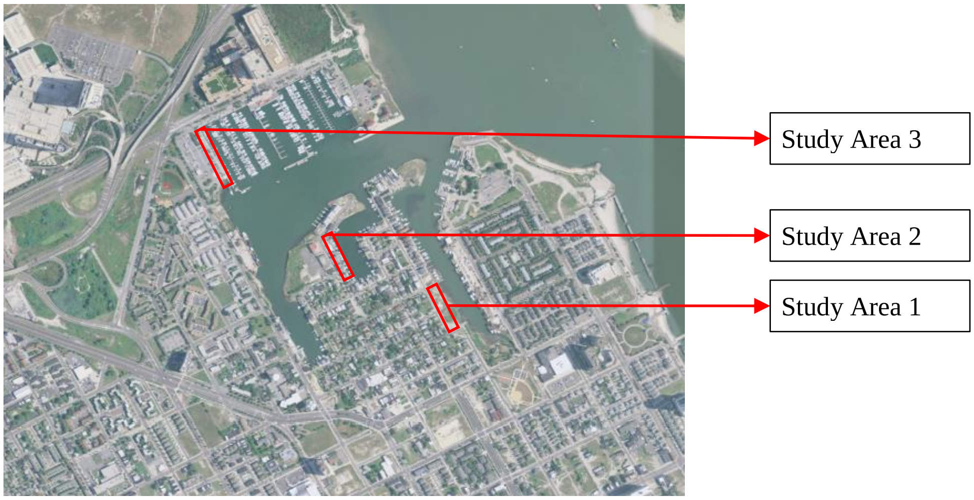


Figure 2. Study Areas of Atlantic City.

Figure 3 shows three points in each study area. Three points were analyzed due to the different possibilities of inundation depths at different points in one area. The three points in the first study area are about 20m apart, the points in the second study area are about 5m apart and the third set of points in the third study area are about 40m apart. The reason for the different distances of points is to show that even with points 40m apart to as close as 5m apart, there will be a different depth of inundation and fine-scale modeling is precise enough to illustrate that characteristic.

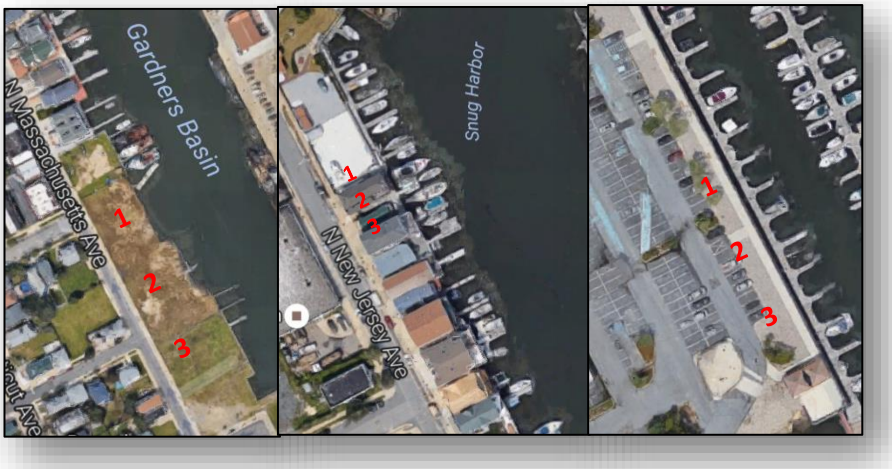


Figure 3. Specific Points Analyzed.

3.2.2 Study area, Camden. Camden is a city in Camden County on the west side of southern New Jersey. According to the Census Bureau population estimate for 2015, there is an estimated population of 76,119 people living in this urban community. Camden is 4.7 miles southeast of Philadelphia, Pennsylvania and parallels the Delaware River covering 8.82 square miles of land. The estimated median household income in 2013 was about $22,043, compared to all of New Jersey with $70,165. Camden is a very poor community, where help and planning is needed directly. Figure 4 depicts the extent of Camden City, showing the study area for the analysis.

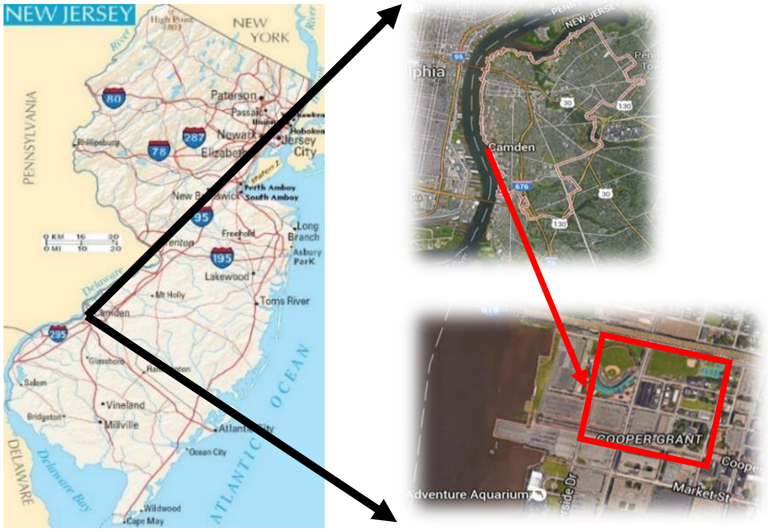


Figure 4. Study Area in Camden, New Jersey.

Only a few blocks were analyzed for the purpose of this study, allowing for a more detailed and precise result. Camden City has had numerous road and bridge closures, severe car accidents, heavy flooding and much more because of past hurricanes and severe weather events that are increasing in frequency due to climate changes. The hazards are considerably alarming and with the city offering the Adventure Aquarium, Campbell's Stadium, Rutgers University, Cooper Hospital and many other attractions that could be beneficial to the community, the continuous cycle of destruction needs to end with proper care, planning and resiliency methodology.

This portion of the large city was chosen due to the high level of flooding that occurs in this area, as shown in Figure 5, which illustrates the hotspots of Camden.

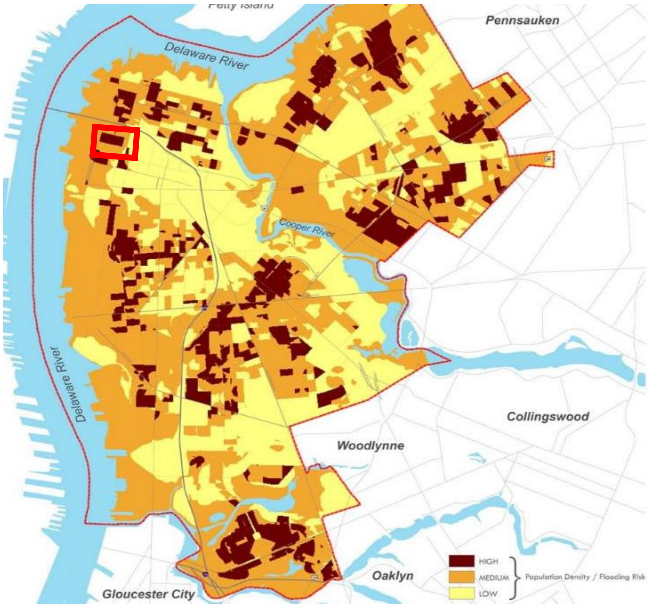


Figure 5. Camden Hotspots (Camden Smart Initiative).

3.3Modeling Instrumentation

3.3.1 Programs. Surface-water Modeling System (SMS) is a program for building and simulating water surface models. SMS allows the input of scatter set data and imagery to model potential flooding. SMS helps to predict flood location due to certain flow patterns from inland and coastal flooding. It also allows the representation of possible flooding scenarios due to rainfall, storm surge or potential sea level rise. TUFLOW (Two-dimensional Unsteady Flow) is the engine used for this study that is supported through the graphical user interface (GUI) SMS to simulate the free-surface water flow for urban waterways, rivers, coastlines, etc. This computer program simulates flood and tidal flow through an area of interest and shows the impacts that it has on that area. The fully 2D solution algorithm of TUFLOW is based on Stelling (1984) and solves the full two-dimensional, depth averaged, momentum and continuity equations for free-surface flow

(TUFLOW 2007). TUFLOW is specifically oriented towards establishing flow patterns in coastal waters, estuaries, rivers, floodplains and urban areas where the flow patterns are essentially 2D in nature.

The functions of this dual component were compared to the functions of two national models, SLOSH (NOAA) and HAZUS (FEMA), currently used for predictions. SLOSH (Sea, Lake, and Overland Surges from Hurricanes) provides a compilation of data gathered by the NWS (National Weather Service) in regards to the tidal surges resulting from hurricanes of increasing intensities (Jelesnianski, 1992). The model uses historical hurricane data as well as weather patterns to predict the maximum of maximum (MOM) or worst-case- scenario effects that will be produced during each hurricane scenario (Glahn, 2009). The program also provides this data for coastal regions all around the United States and even for some foreign countries. To synthesize and manipulate the data, ESRI ArcMap is used. HAZUS is a GIS-based modeling program used for estimating losses from flooding, hurricane, and earthquake scenarios (FEMA, 2007). HAZUS produces graphic illustrations of high-risk locations and areas affected by different disaster scenarios as well as economic loss estimates in thousands of dollars. Additionally, it uses internal data to estimate the functionality of infrastructural elements following earthquakes and storms of different return periods.

Another program, Storm Water Management Model (SWMM) by the EPA, was used to input green infrastructure into the system to analyze the effects of green roofs and rain gardens in a high risk area of Camden. SWMM is a dynamic hydrologic-hydraulic water quality simulation model that is used for the simulation of runoff quantity and quality from primarily urban areas (EPA 2016). It tracks flow rate, flow depths and quality of water in each pipe, as well as models hydrologic performances of low impact development controls such as rain gardens, green roofs, bio swales, etc.

3.3.2 SMS/TUFLOW model development - Atlantic City.

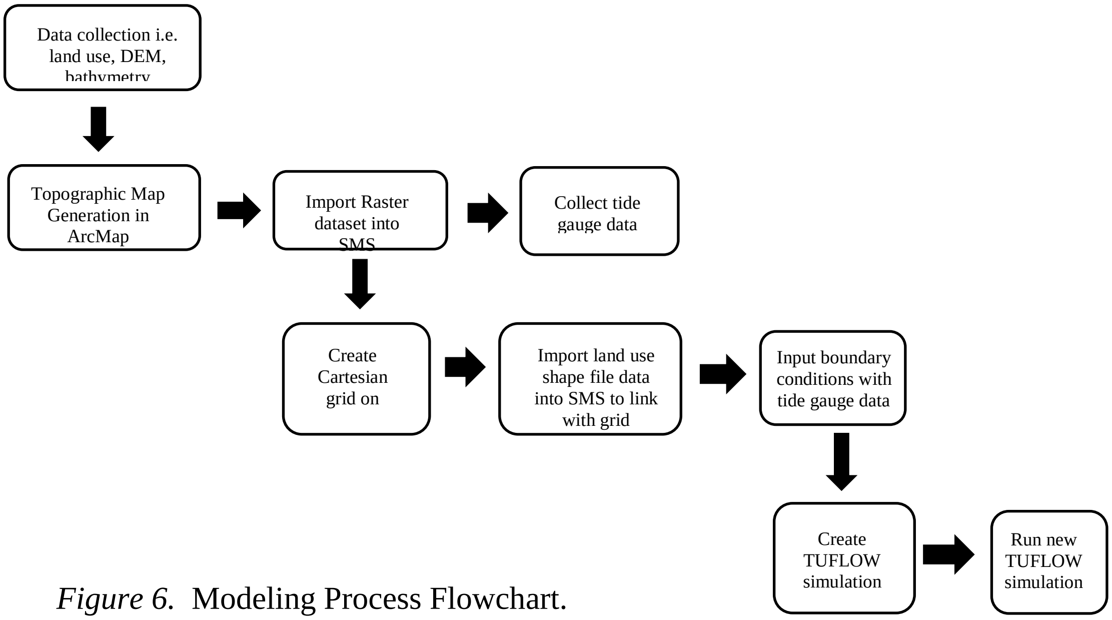


Figure 6. Modeling Process Flowchart.

Figure 6 briefly simplifies the fine-scale modeling process in nine comprehensible steps. To understand the details of the process, the firm basics had to be acknowledged first. Before the modeling process could begin, the subject area needed to be displayed in ArcMap. The creation for a full extensive map was needed to begin the modeling process for flood detection and mitigation. It was a detailed process where Table 1 includes the numerous steps taken to complete the map.

Table 1

Map Generation Steps

Step	Process
1	Land use, elevation, and bathymetry data were downloaded from the state sites NJDEP and NOAA, and merged into one data file
2	LIDAR (Light Detection and Ranging) data were downloaded from USGS Earth Explorer to create a dataset of the city
3	LIDAR data and surface features contained in the downloaded LAS files were generated using the Create LAS Dataset tool in ArcMap to generate a DEM (Digital Elevation Model)
4	Estuarine and coastal bathymetry had to be downloaded
5	Bathymetric Digital Elevation Grids offshore of NJ were downloaded as .e00 files. These files had to be exported to a GRID file in order to receive all the physical data
6	Once all of the files were inputted into ArcMap, the Mosaic tool was used to combine the land topography of Atlantic City, with the bathymetry data
7	This created a raster dataset prepared to be imported into SMS for modeling purposes

The DEM of the study was obtained from LIDAR data downloaded from NJDEP (New Jersey Department of Environmental Protection), NOAA and USGS. Figure 7 illustrates the finalized DEM and all of the parts that had to be combined together to create such a large dataset. Once the creation of the DEM was finalized, it was transferred into a raster file to import into Surface-water Modeling System (SMS). Surface-water Modeling System (SMS) allows the input of scatter set data and imagery to model potential flooding. SMS helps to predict flood location due to certain flow patterns from inland and coastal flooding. It also allows the representation of possible flooding scenarios due to rainfall, storm surge or potential sea level rise. Once this very crucial modeling step is complete, strategic planning and processing is next.

Figure 7. ArcMap Raster Dataset of Atlantic City.

Once the large file as shown in Figure 7 was imported into SMS, the creation of the mesh and Cartesian grid began. Figure 8 shows the generation of the grid. This mesh allows for the data of elevations and material properties to coincide, implementing a large grid within the data file. This grid contains a great deal of single cells that have different volume capacities, elevations and areas. The cells in the case are 10 m by 10 m.

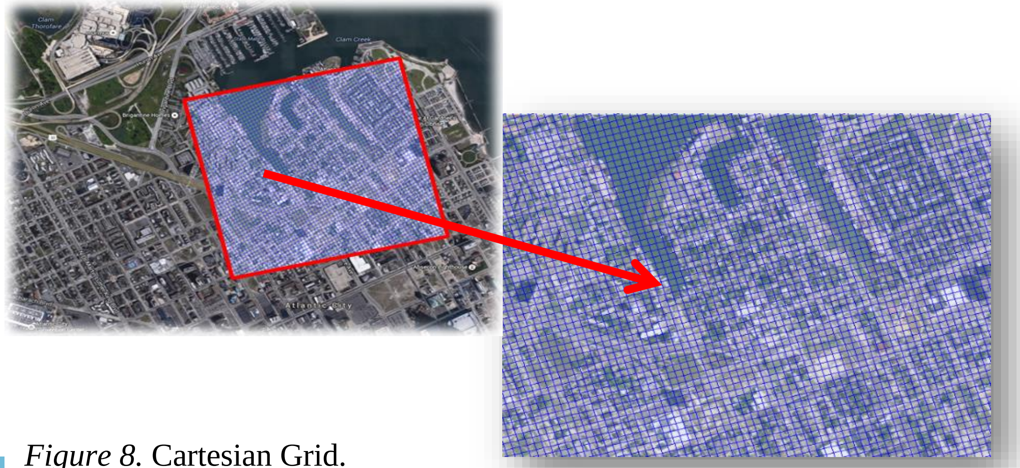


Figure 8. Cartesian Grid.

The extents of the ‘2D domain’ are defined based on the general land topography, which includes the low- lying areas that are prone to flooding. The model also uses upstream and downstream boundaries represented as a flow-time and flow-head boundary, respectively, to estimate peak flow. The grid is very sensitive and needs to be precisely built based on available information on topography and DEM in order for the simulation of a flood to run properly.

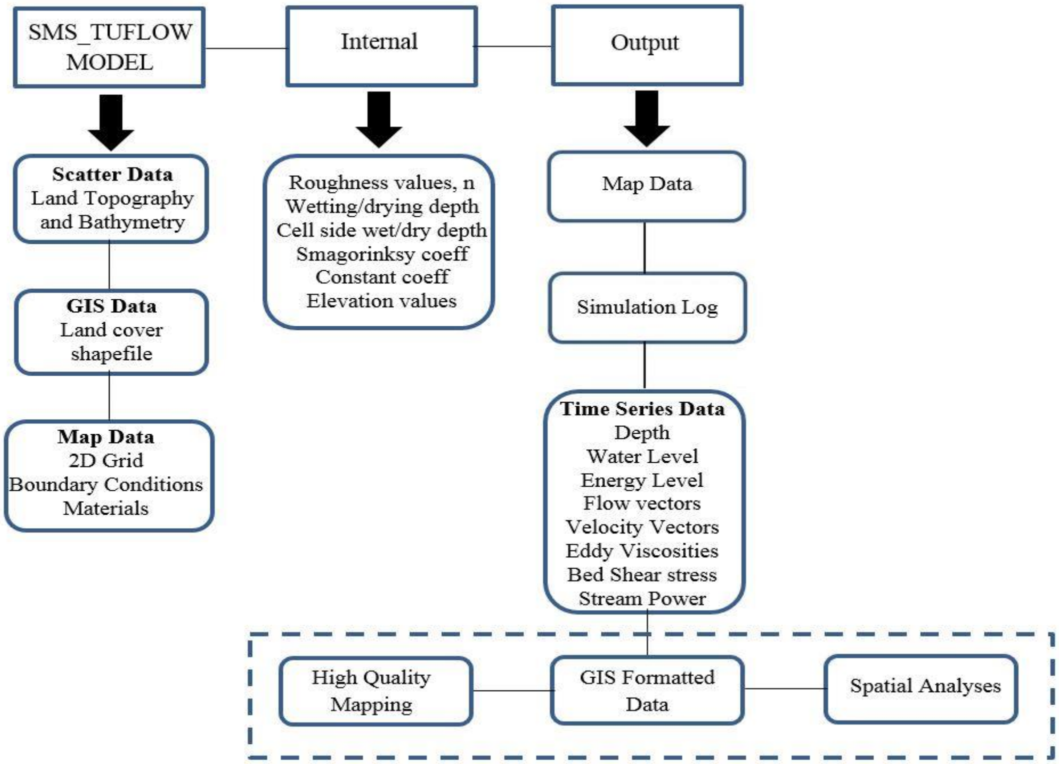


Figure 9. SMS_TUFLOW Model Characteristics.

Figure 9 displays the inputs and outputs of the fine-scale model as a flowchart. Once all the Scatter Data, GIS Data and Map Data are inputted, and the simulation has run properly, there are many outputs and results that are used for analysis.

The boundary conditions displayed in Figure 10 contain data that were provided by USGS National Water Information System, Web Interface. Two storms were chosen to be analyzed and the data from the two appropriate tide gauges were inputted into the corresponding boundaries. Data on land-use were used with surface elevation data to estimate roughness values for channels and overland areas. The model used inland and ocean boundaries represented as water surface elevation over a specified time. However, observed data for the ocean boundary were not available, therefore model calibration was done using tide data available from two USGS tidal gages. One tidal gage, USGS gage 01410600 (Gage 1) Absecon Channel at Atlantic City, NJ (39°22'40", 74°25’25”), was located near the ocean boundary, and the second tidal gage, USGS gage 01410510 (Gage 2) Absecon Creek at Absecon, NJ (39°25'23", 74°30’00”), was located at the inland boundary, where the locations are shown in Figure 10. The ocean boundary was a water surface elevation that was calibrated using observed data from Gage 1 for a storm event on April 30, 2014. The ocean boundary water surface elevation was adjusted to the obtained simulated water surface elevations that fit the observed water surface elevations at Gage 1. A regression equation was developed relating the ocean boundary water surface elevation to observed water surface elevation at Gage 1, where the relationship is shown in Figure 17.

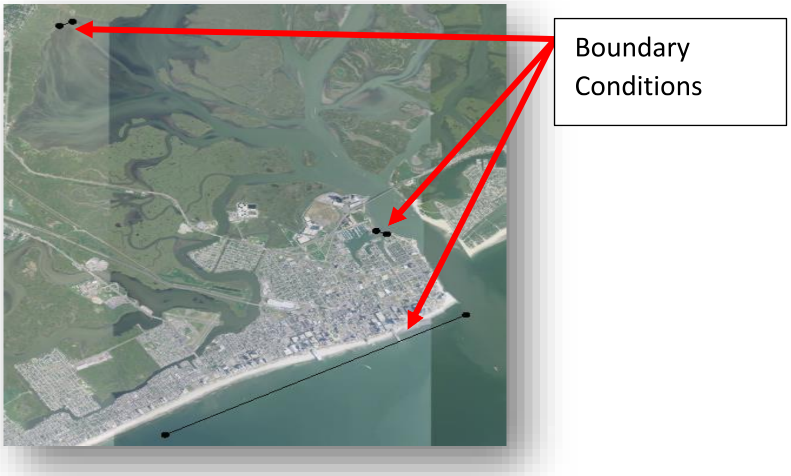


Figure 10. Atlantic City Boundary Conditions.

Once the boundary conditions were set in place, rainfall data had to be collected and inputted into the SMS model. Rainfall data for a general rainstorm on April 30, 3014 was downloaded from Weather Underground provided by The Weather Company, where hourly precipitation data was retrieved. Rainfall data during the Hurricane Irene event was downloaded from NOAA Climate data online files. Table 2 shows the precipitation data inputted into the system. This was done by using a set of tools in the program, first creating a feature arc around the entire system in SMS. Then, a polygon was created so the data could be inputted into the system as a boundary condition, but rather than Flow vs. Time for previous boundary conditions, the condition was set to Rainfall vs. Time.

Table 2

Precipitation Data

April 30, 2014 Storm Event		**Hurricane Irene Event**	
Time (hrs)	**Precipitation (mm)**	**Time (hrs)**	**Precipitation (mm)**
0	0	**0**	0
1	0.254	**1**	1.27
2	1.016	**2**	6.1
3	0.508	**3**	13.97
4	3.81	**4**	7.62
5	1.27	**5**	7.87
6	1.016	**6**	8.64
7	0.508	**7**	36.58
8	1.778	**8**	7.11
9	1.112	**9**	5.33
10	7.366	**10**	1.78
11	16.002	**11**	6.86
12	3.302	**12**	4.83

Table 3 shows more of the input parameters used for the TUFLOW simulation. Time step, duration and output information were needed to complete the model setup. Once all the appropriate components were set into the modeling software, the TUFLOW simulation was able to be launched.

Table 3

TUFLOW 2D Model Control

Map Output: Interval	900 seconds (15 minutes)
Screen/log Output: Display Interval	6 time steps
Start Time	0 hours
End Time	14 hours
Time Step	5.0 seconds
Output Datasets	Depth, Water Level, Flow vectors

Once the simulation was finished, various amounts of information were produced such as flood depth, location of flooding, flow path and flood animation. Chapter 4 lays out the results and analysis, describing what each simulation conveyed and the significance of each simulation.

3.3.3 SMS/TUFLOW modeling process- Camden. The extent of Camden was gridded and digitized in an interactive GIS map. Table 4 includes the numerous steps taken to complete the map in ArcGIS. The steps on how the full extensive model was created from start to finish is shown in the flowchart in Figure 6. This flow chart breaks down the process in simplistic steps, to show how the model was developed, illustrating the numerous components involved to emphasize the extensive procedure.

Table 4

Map Generation Steps

Step	**Process**
1	Land use, elevation, and bathymetry data were downloaded from the state sites NJDEP and NOAA, and merged into one data file
2	LIDAR (Light Detection and Ranging) data were downloaded from USGS Earth Explorer to create a dataset of the city.
3	LIDAR data and surface features contained in the downloaded LAS files were generated using the Create LAS Dataset tool in ArcMap to generate a DEM (Digital Elevation Model.)
4	Bathymetry data were downloaded from NOAA.
5	Once all of the files were inputted into ArcMap, the Mosaic tool was used to combine the land topography of Camden City, with the bathymetry data.
6	This created a raster dataset prepared to be imported into SMS for modeling purposes.

The DEM of the study was obtained from data downloaded from NJDEP (http://www.nj.gov/dep/gis/lulcshp.html), NOAA (https://maps.ngdc.noaa.gov/ viewers/ bathymetry/.) and USGS (https://earthexplorer.usgs.gov/). Figure 11 illustrates the finalized DEM that is comprised of a few different datasets. Once the creation of the DEM was finalized, it was transferred into a raster file to import into a Surface-water Modeling System (SMS).

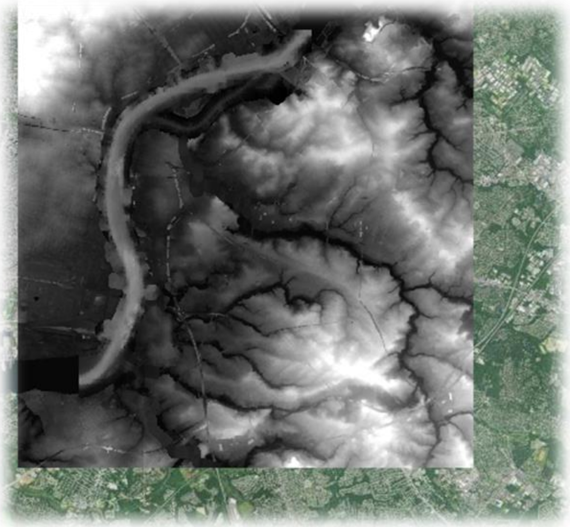


Figure 11. Raster Dataset of Camden.

Just like in Section 3.3.1, once this large dataset shown in Figure 11 was imported into SMS, the Cartesian grid was formed, shown in Figure 12. All the steps described in Section 3.3.1 were also used for the creation of the grid and model in SMS for the Camden study area. It is the same process, with different data and the grid was built using 10m by 10m cells.

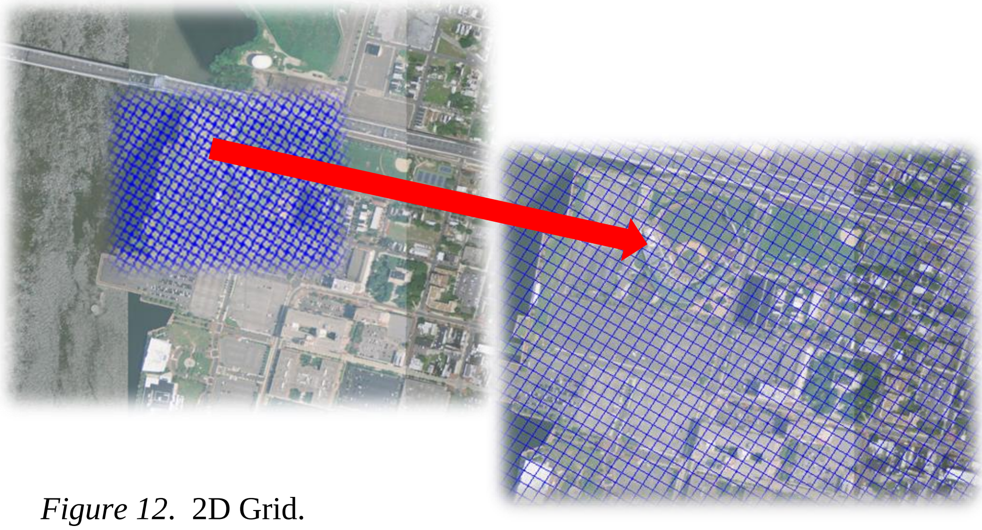


Figure 12. 2D Grid.

Before the flood simulation was run, scatter data, GIS data and map data were imported and inputted into the SMS model. Then, the 2D Geometry Components, Boundary Conditions and Material Sets were added to the model for finalization. The boundary conditions displayed in Figure 13 contain data that were provided by the NOAA tides and currents website. Hurricane Irene hit New Jersey on August 28, 2011. This date was chosen to analyze due to the destruction and such increase in tide levels. The data from the two appropriate tide gauges were inputted into the corresponding boundaries (Figure 13).

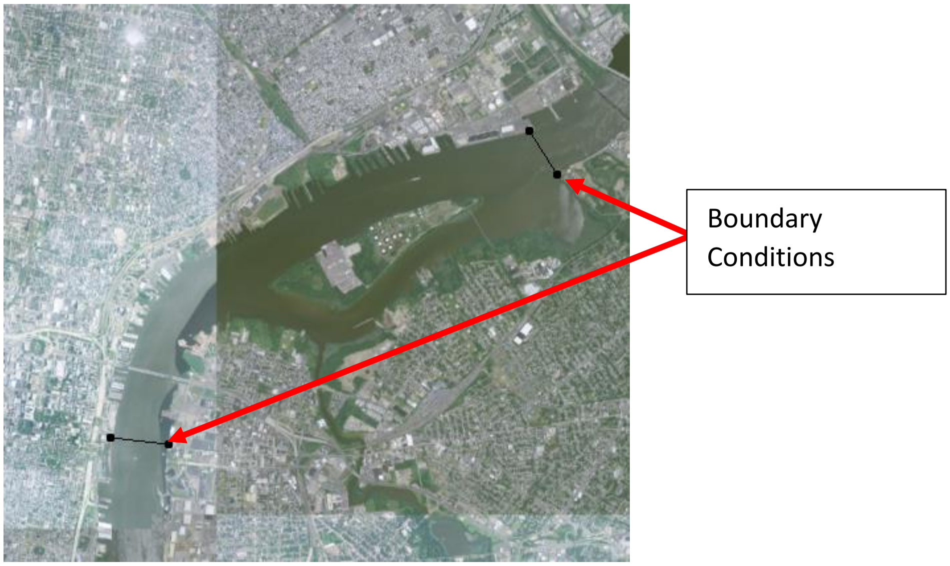


Figure 13. Camden Boundary Conditions.

Table 5 consists of the rainfall data in Camden for the Hurricane Irene storm event provided by NOAA. This rainfall data was implemented into the model. This was done by first creating a feature arc around the entire system in SMS. Then, creating a polygon so the data could be inputted into the system as a boundary condition, but rather than Flow vs. Time, the condition was set to Rainfall vs. Time.

Table 5

Hurricane Irene Precipitation for Camden

Time (hrs)	Precipitation (mm)
0	0
1	7.62
2	4.318
3	3.048
4	8.382
5	10.668
6	9.398
7	5.08
8	19.812
9	30.48
10	9.906
11	2.286
12	7.874

For the model developed here, there were two boundaries to show the flow hydraulics and the extent of flooding due to a hurricane event that was simulated. However, observed data for the upstream boundary was not available, therefore model calibration was done using tide data available from two NOAA tidal gauges and using a linear interpolation equation to define the actual upstream boundary condition. One tidal gauge, NOAA gage 8539094 (gauge 1) Burlington, Delaware River, NJ (40° 4.8' N, 74° 52.4' W), was located upstream, which is the gauge that was out of range. The second tidal gage, NOAA gage 8545240 (gauge 2) Philadelphia, PA (39° 56' N, 75° 8.5' W), was located at the downstream boundary; the locations are shown in Figure 13. Assuming a linear relationship between the two tidal gages, new values were estimated for the theoretical gauge by connecting the two adjacent known values with a straight line, where:

$$y = y_1 + (x - x_1)\frac{y_2 - y_1}{x_2 - x_1}$$

Since the tidal gauge data retrieved for the TUFLOW model were for every two hours, over a 12-hour time span, six different y values were calculated. Table 6 shows sample calculations at time zero for the new upstream boundary, using the linear interpolation equation. The constant x was given a value of zero and since the two known tide gauges were 27359 meters apart, x_1 was given a value of 27359 meters. The imaginary (new) gauge location was given a value of 8530 meters away from the Philadelphia gauge. The y_1 and y_2 values varied, y_1 being the value of the Burlington gauge and y_2 being the value of the Philadelphia gauge. After the new boundary condition was created, simulations were run to show flooding patterns.

Table 6

New Boundary Condition

	Burlington	Philadelphia	New Boundary
Water Level (m)	1.189	1.73	1.41
Location (m)	0	27359	8530
Time (hours)	0	0	0

Sample calculation: $1.189 + (1.73 - 1.189) * \frac{8530}{(27359-0)} = 1.41$

3.3.4 SWMM modeling process- Camden. The second part of this research was using EPA SWMM 5.1 (Storm Water Management Model) to generate green infrastructure propositions in the vulnerable study area of Camden. SWMM has many hydraulic capabilities that can route runoff and external inflows through the drainage system network of pipes, channels, etc. For the purpose of this study, default parameters were used for simplification and a small segment of Camden's stormwater infrastructure was modeled in SWMM. The piping network information was provided by Camden County Municipal Utility Authority (CCMUA).

Within the model, the SCS (Soil Conservation Service) Curve Number method was used for computing runoff. This method is commonly used and consists of three runoff computations. One computes total runoff volume for any given rainfall event while the other two estimate a peak discharge and a runoff hydrograph. Details about how each method within SWMM is computed can be obtained from the Storm Water Management Model Reference Manual- Volume 1 Hydrology (Revised). Sample equations and descriptions can also be found below:

In its classic form, the Curve Number model uses the following equation to relate total event runoff Q (in) to total event precipitation P (in) (Haan et al., 1994; McCuen, 1998; Bedient et al., 2013; NRCS, 2004b):

$Q = \frac{P^2}{P + S_{max}}$, where Smax = the soil's maximum moisture storage capacity (inches).

Smax is derived from a tabulated "curve number" CN that varies with soil type and antecedent conditions:

$$S_{max} = \frac{1000}{CN} - 10$$

Curve numbers for various soil types and land covers are tabulated in the NRCS's National Engineering Handbook (NRCS, 2004a) and in many text books. Assuming all rainfall that does not run off is lost to infiltration (i.e., P – Q = F), Equation 1 can be extended to predict total (cumulative) infiltration F (in) as:

$$F = P - \frac{P^2}{P + S_{max}}$$

The study area was chosen due to the hot spots of Camden already recognized by the city, being one of the many areas that is prone to flooding. The localized area that was modeled in SWMM was 0.148 km^2, divided into 26 subcatchments. Once proper information was collected, the modeling of the network was done. Measurements of the lengths of the pipes were implemented as well as the maximum depths for each junction and each subcatchment drained into its appropriate inlet. Units were set to CMS for uniformity. Figure 14 depicts a small portion of Camden's piping network drawn in the SWMM module.

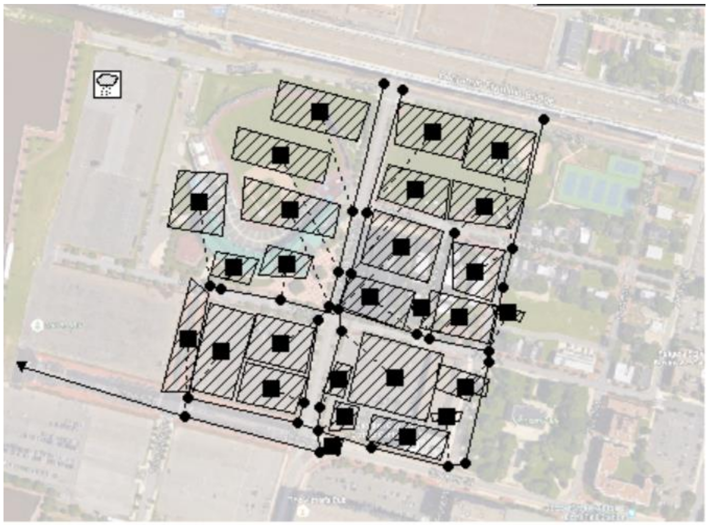
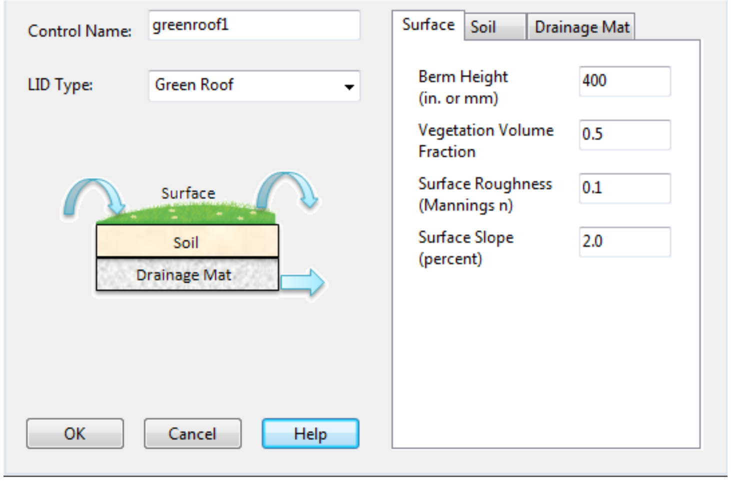


Figure 14. A Portion of Stormwater Sewer System in Camden, New Jersey Modeled in SWMM.

After all the parameters were implemented, two low impact development (LID) controls were then implemented into the program as well. A green roof control and a bio-swale control were each created. Figures 15 and 16 shows the parameters for each control. The units are in millimeters, and the parameters were chosen due to examples through literature.



Control Name: greenroof1

LID Type: Green Roof

Berm Height (in. or mm) 400

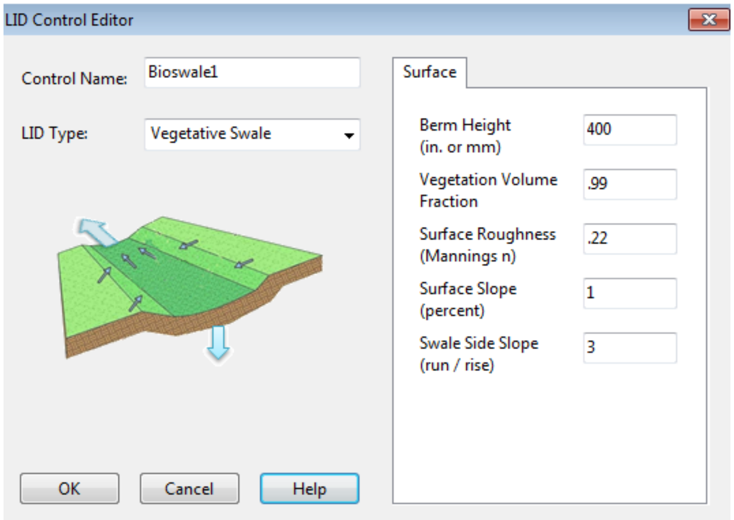
Vegetation Volume Fraction 0.5

Surface Roughness (Mannings n) 0.1

Surface Slope (percent) 2.0

Figure 15. Green Roof LID Control with Parameters.

These controls were applied after simulations were run without green infrastructure implementation to see the nature of the area first. Then, the green roof control was added to the system to see its effects during a storm. After the simulation was run with the green roof control, the bio-swale control was used to see the significance of implementing a bio-swale in an appropriate area. After both controls were used separately, the entire system was analyzed using both LID controls at the same time to show the effects of numerous green infrastructure mechanisms.



Control Name: Bioswale1

LID Type: Vegetative Swale

Berm Height (in. or mm)	400
Vegetation Volume Fraction	.99
Surface Roughness (Mannings n)	.22
Surface Slope (percent)	1
Swale Side Slope (run / rise)	3

Figure 16. Green Roof LID Control with Parameters.

Chapter 4

Results and Discussion

4.1 Atlantic City

As mentioned above (Section 3.3.2), an ocean boundary was required for the model simulation. Since observed data for the ocean boundary were not available, model calibration was done using tide data available at Gage 1. Random values were inputted into the ocean boundary, and then a simulation was run. Once the data and water level presented at Gage 1 (location of Gage 1 shown in Figure 7) matched the observed data at Gage 1 from the USGS database, then the linear relationship was successfully formed between the two boundaries and an equation could be created for any type of event. A regression equation was developed relating the ocean boundary water surface elevation to observed water surface elevation at Gage 1. Figure 17 shows this linear relationship, which allows the ocean boundary condition to be set to simulate different events, within a reasonable range of values for storm surge simulations to simulate the potential impacts of flooding.

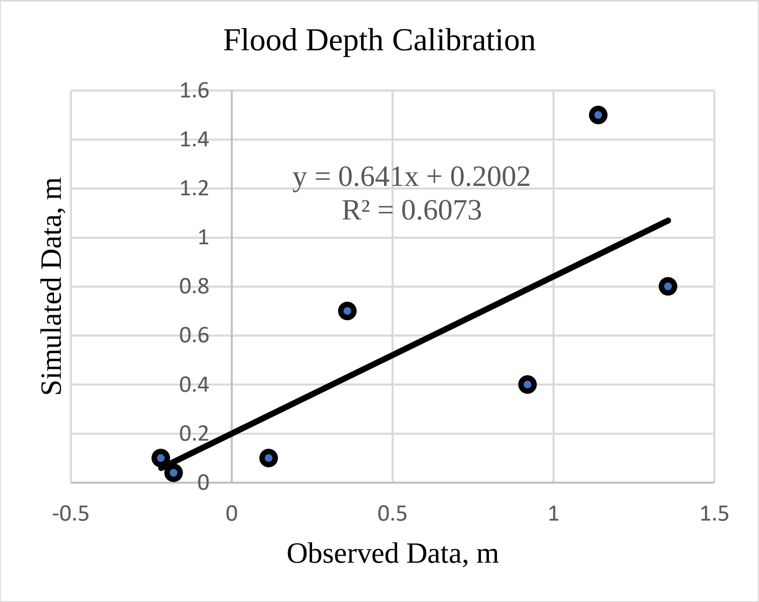


Figure 17. Model Calibration Curve.

A simulation was run using the April 30, 2014 storm data in the boundary conditions to validate that the results being analyzed are accurate.

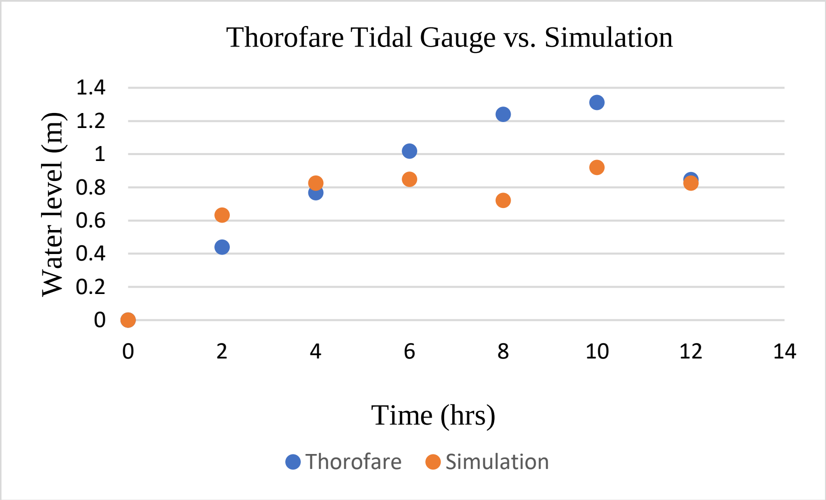


Figure 18. Inside Thorofare at Atlantic City.

Another tide gauge within Atlantic City was used for this validation (Inside Thorofare at Atlantic City, Lat 39°21'13", Long 74°27'25"). The simulation was run and the location of the tide gauge was pin pointed within SMS. The results of the simulation were compared to the tide data provided by the USGS tidal gauge on April 30, 2014. The simulation data and real data seem to be very similar (Figure 18), concluding that the calibration curve and simulations are accurately depicting the flooding patterns within the study areas in Atlantic City.

4.1.1 TUFLOW, HAZUS and SLOSH comparison. To exemplify the significance of fine-scale modeling compared to current national models, a comparison was done. TUFLOW, HAZUS-MH and SLOSH flood models were compared to one another. The effects of Hurricane Irene have been studied using HAZUS-MH and SLOSH software, depicting the damage and losses due to each return period of a storm and the type of Category storm, respectively. Using HAZUS-MH, the representation of flooding for a 100-year return period is illustrated as shown in Figure 19. This shows that a storm like Hurricane Irene, with a 100-year return period, will completely flood the entire city of Atlantic City, from its coast to land to the back bay areas. With this, are estimated losses as well, which have been predicted in the State of NJ 2014 Hazard Mitigation Plan.

Figure 19. HAZUS 100 Year Return Period Flood Map.

Figure 19 illustrates the prediction through previous hurricane and flood information programmed into the software. Instead of pinpointing a single area for a certain kind of storm, HAZUS only generates a flood model at a large scale. The study area shown in Figure 1 is the study area used for the comparison between HAZUS and TUFLOW capabilities as well as the rest of the comparisons between all three models. Figure 20 shows HAZUS and TUFLOW evaluating the same points during Hurricane Irene.

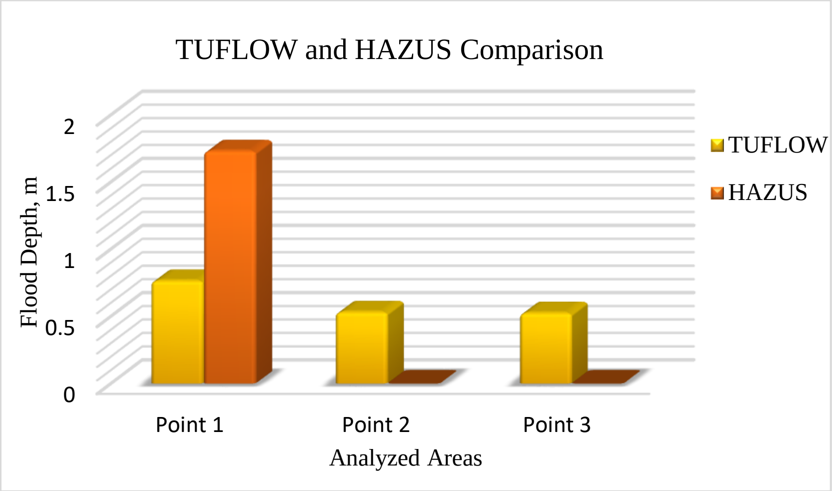


Figure 20. Graph of Flood level comparison between TUFLOW and HAZUS of Hurricane Irene.

Figure 20 shows the points analyzed by TUFLOW and HAZUS have over a meter in value difference at one point. This graph also shows that HAZUS does not have available data for the other two points chosen in Study Area 1. This illustrates that no other interpretation can be made except for the fact that having no available data hinders accuracy, where TUFLOW has data at every point that flooded. A reason why there is discrepancy between the two models is the actual purpose of using fine-scale modeling; that HAZUS information is given at a larger scale where TUFLOW has finer capabilities. The different flood depths are not equated to a certain point but a large area that covers too many different points to be able to get a specific outcome. TUFLOW analyzes data on a point-to-point basis, allowing the flood to simulate a pattern at each point, instead of an only a large area.

Since there were no data available for a couple of the points selected, the second study area was compared using HAZUS and TUFLOW. These points are about 5 m apart.

As shown in Figure 21, the HAZUS grid is large enough to include three different points in the same depth of inundation, whereas TUFLOW allows for a separate depth to be apparent.

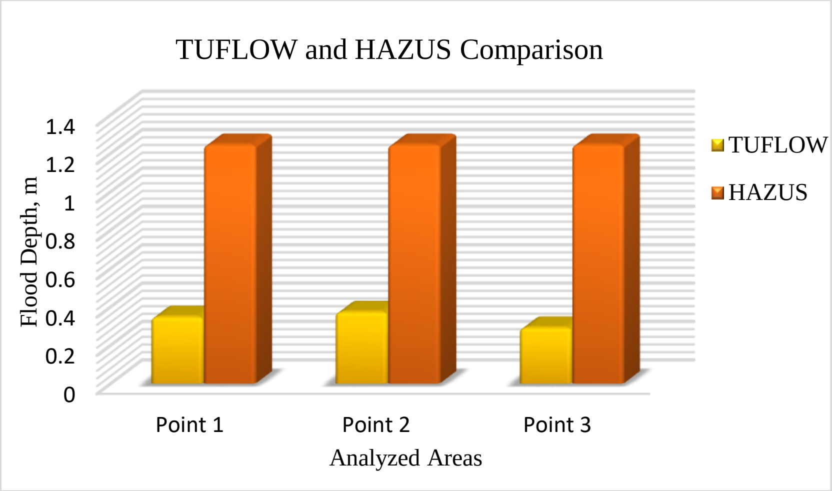


Figure 21. Graph of Flood level comparison between TUFLOW and HAZUS of Hurricane Irene in Study Area 2.

A comparison was made with SLOSH and TUFLOW as well. The SLOSH model creates inundation maps at a large scale like HAZUS, using the worst-case scenario combining the direction of the hurricane, speed, landfall point and high tide. A problem with SLOSH is that it does not include riverine flooding caused by hurricane surge or inland freshwater flooding. The resulting inundation areas are grouped into Category 1 and 2 (dangerous), Category 3 (devastating), and Category 4 (catastrophic) classifications. FEMA Region IV Risk Analysis Team developed storm surge inundation grids for the State and represented the worst-case storm surge scenarios for each category. To assess the exposure to the hurricane surge, a spatial analysis was conducted using the SLOSH model.

Figure 22. SLOSH Category 1 Storm Flood Map.

As you can see in Figure 22, Atlantic City seems to be completely inundated with little to no variable in depth values along the city, using SLOSH analysis. The grid cell size is very large, which covers a great span of land where each parcel has completely different flood characteristics. This coarse model generalizes a large area with having the same depth of flooding, when in reality, those different neighborhoods in each cell have fairly different values of inundation.

Figure 23 illustrates SLOSH results of a Category 1 storm, which is a hurricane with winds up to 74 mph, with a storm surge about 4-5 feet above normal (Hurricane Irene), compared to TUFLOW results for Hurricane Irene’s data at the Atlantic City boundaries.

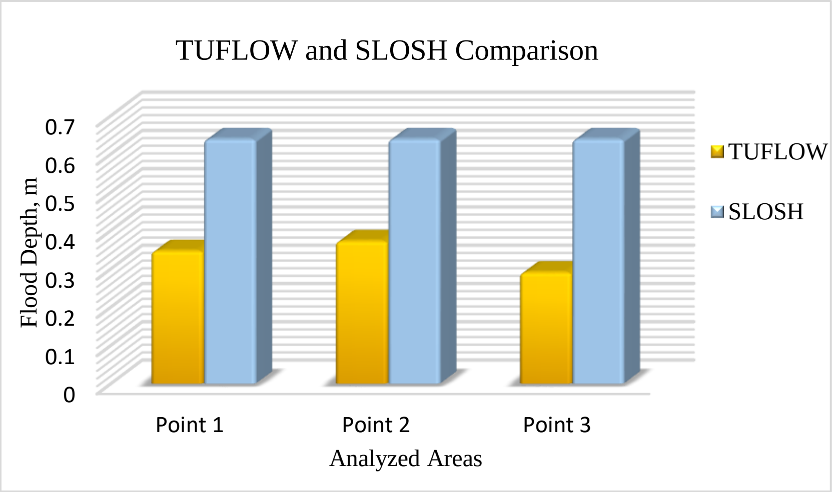


Figure 23. Graph of Flood level comparison using TUFLOW and SLOSH of Hurricane Irene.

These data show comparable results like the HAZUS results. The difference between TUFLOW and SLOSH models is the level of estimation and the model only generates storm data at a large scale. This graph shows that SLOSH has such a large grid size or resolution, that every single point that was analyzed have the same level of inundation. This shows, just like HAZUS, that this software generalizes the points, creating a false representation of what is actually happening. It seems that SLOSH over estimates, using the worst-case scenario statistics. TUFLOW includes a high-resolution grid where the entire DEM is taken into account and flooding values are resulted at a finer scale, where SLOSH uses such a low-resolution DEM that points are combined. Also, due to SLOSH generating a simulation of a general storm, and not a specific one, there are also discrepancies between each model's data. TUFLOW uses specific tide gauge data so the values will be different from general models like SLOSH but presumably more accurate.

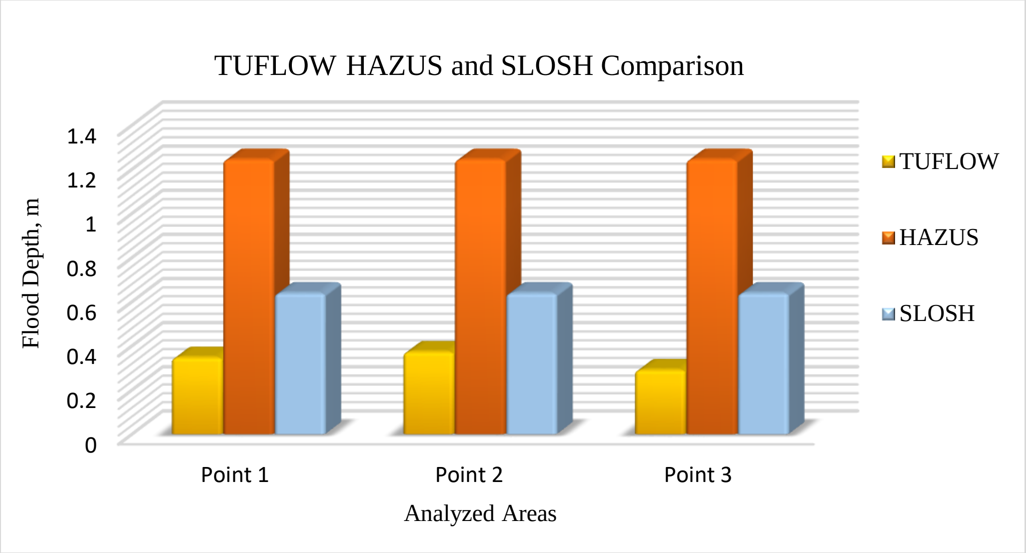


Figure 24. Comparing Flood levels of Hurricane Irene in proposed area using TUFLOW, HAZUS and SLOSH.

Three different flood models were compared to each other in Study Area 2, comparing three of the same points (Figure 24). The results show how SLOSH and HAZUS have such limited resources and such a low-resolution grid, that the worst-case scenarios presented seem to overestimate more than enough for decent results. These results can also be discussed in reference to a study performed by Katehis (2015) where Superstorm Sandy was analyzed and the map clearly shows the places missed on the East shoreline by HAZUS that shows flooding using the other models presented. These varied results are due to miscalculations of flood surface geometry, resulting in “gaps” in the flood data.

This determination of gaps is supported in this current study, where gaps within HAZUS and SLOSH data are shown (Figure 25). These gaps come to show that it is important to have real data and true simulation data to create an accurate prediction of storm behavior. Even with such a large grid to predict storm values, depending on topographic data and the default settings within the program, important information still may not be conveyed.

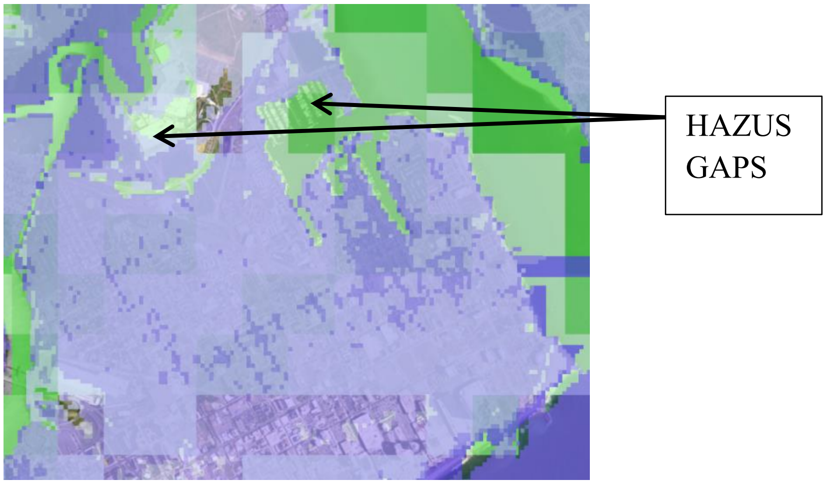


Figure 25. HAZUS and SLOSH Comparison for Hurricane Irene.

4.1.2 TUFLOW capabilities.

4.1.2.1 First Analysis. Figure 26 shows a basic simulation for a rainstorm event that happened on April 30, 2014. Boundary conditions highlighted in red were set in the Absecon Creek, Absecon Channel and Atlantic Ocean using the tide gauge data provided.

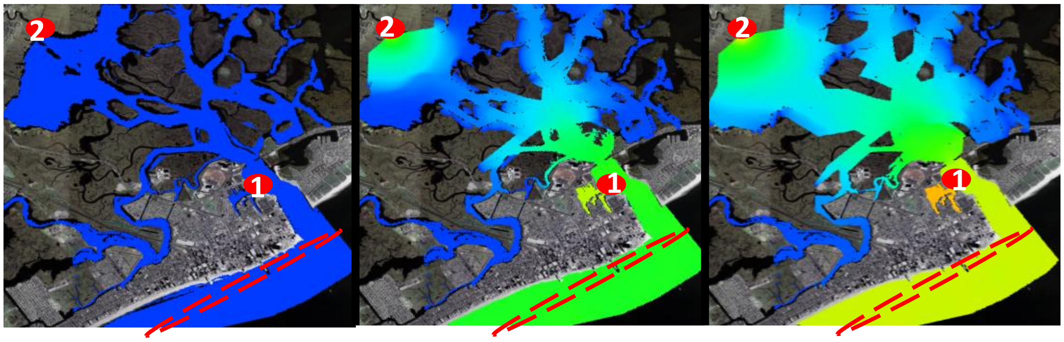


Figure 26. Hourly TUFLOW Simulation of Flooding in Atlantic City; Blue represents lower flood depth where Orange represents a higher flood depth; Red circles represent the location of the boundary conditions.

As shown, the left picture in Figure 26 depicts the flood level at time 0:00, where there is no flooding represented. The middle picture shows flooding within the next hour of the storm and the picture on the right illustrates an increase in water level as the storm goes on. The color scheme from Blue to Orange, correlates with depth. The lowest depth is blue and the highest depth is shown as the orange hue. Figure 26 shows an increase in flood depth as well as an increase in spatial distribution of water throughout the simulated storm.

Figure 27 shows that same area, more localized and at a finer scale to show the details of the simulation. Figure 27 on the left shows the area before the storm event occurred. Figure 27 on the right shows the same area during the storm event, showing flooding in places that depicted no water before. There is a 1, 2 and 3 placed on the certain points of the grid to analyze.

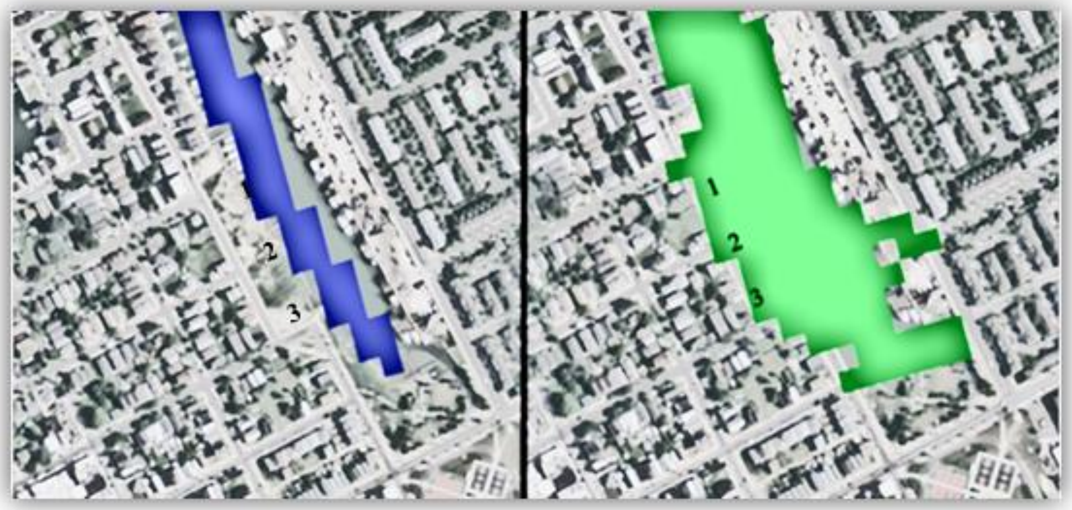


Figure 27. Pre-flood Area (left), Post Flood Area (right).

Three points rather than just one point on the map were chosen to be analyzed due to the vast possibilities of flood patterns that can happen within the same vicinity. The three points are shown to give a better visual of the possible effects in more than one area at a time. Flood depth at each point shown in Figure 27 was very different despite the proximity of the locations to each other (Figure 28). The storm event on April 30, 2014 generated the tides from the bays and ocean to rise and increase the depth of the water to flood onto land, with a maximum depth of 0.647 meters of water on the surface (Figure 28). The three different points were at three different elevations of .67 m above sea level, 0.806 and 1.17 respectively. Where the water is flowing from and how high the elevation is, affects the inundation at these points. For example, Point 1 is at a higher elevation than Point 2, but had a higher maximum flood depth. Many factors can cause this to happen such as the type of land cover before that point, possibly slowing down flow and mitigating flooding conditions before it gets to the point being analyzed. When studying the area, Point 2 has taller grasses that can infiltrate more water as well as a dock resisting some water flow to that point, whereas Point 1 has low grasses and no structures in the path of water flow. This causes Point 1 to have a higher flood depth level than Point 2. Even though the three points are very close in proximity, they still hold different characteristics, where flood features will be different in each particular position.

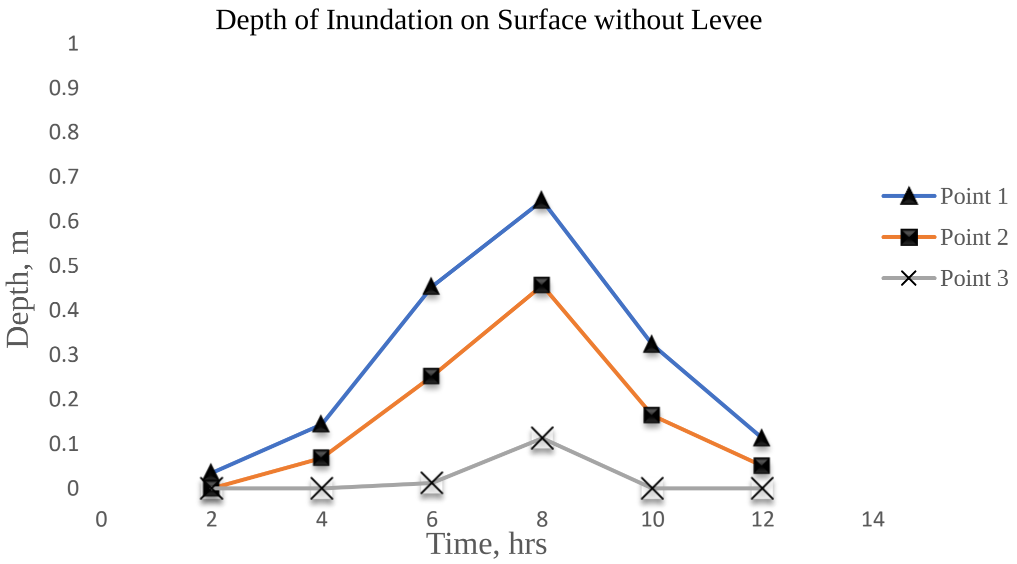


Figure 28. Flood Depth of April 30, 2014 Storm.

This is important to understand because without such a fine scale model, local variation of flood depths at nearby locations would not be able to be determined. National models such as HAZUS and SLOSH use a coarse grid, which lump local areas into one datum point, assigning them a flood depth of the same value; which is incorrect. The accuracy from fine-scale hydraulic models allows for estimates and predictions at a lot scales, which helps community members to understand more precisely the risk of a particular storm. They would be able to know if the waters of that storm were going to encroach on their land or not, and have a better description than other existing models. This model gives precise numbers in high resolution so predictions are more clear and accurate.

These results validate the argument to use fine-scale modeling as a stepping-stone towards resiliency planning. Without such localized models, predictions and estimations will not be correct or beneficial for future preparation.

This area was also analyzed with a levee with rainfall and a levee with no rainfall, to examine if creating a levee in the study areas would help mitigate flooding from such storm.

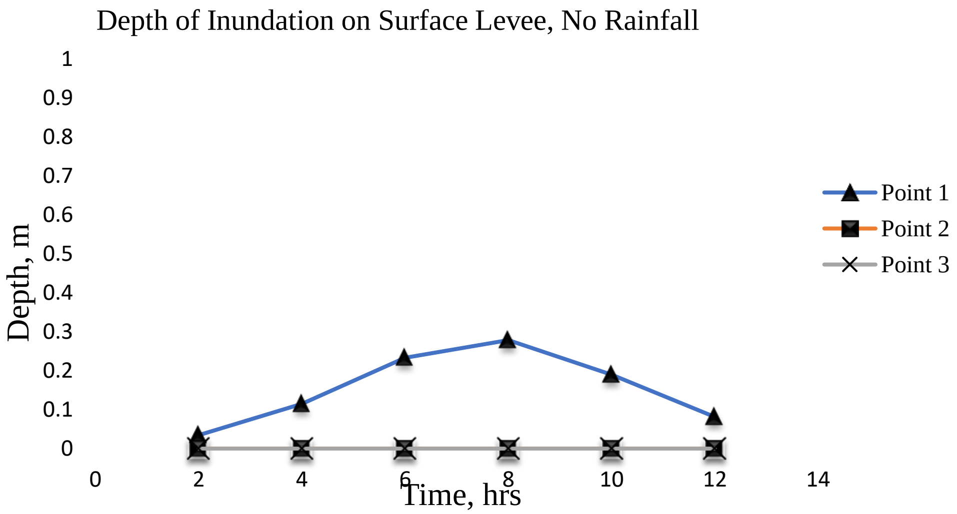


Figure 29. Flood Depth with Levee and No Rainfall.

Figure 29 shows a definite decrease in flooding when implementing a levee. Figure 30 shows a decrease as well, but only a slight decrease with rainfall included. This is due to drainage in the area. These figures show that a levee will protect from storm surge, and will also work during rain events, but there needs to be a good drainage system set in place to be able to get optimum results from the levee. The levee is essentially blocking the rainfall to flow into the ocean, creating a backflow of slight flooding since the drainage for rainwater isn’t optimal. These results are important for future planning purposes and when deciding which mitigation techniques work best for a community.

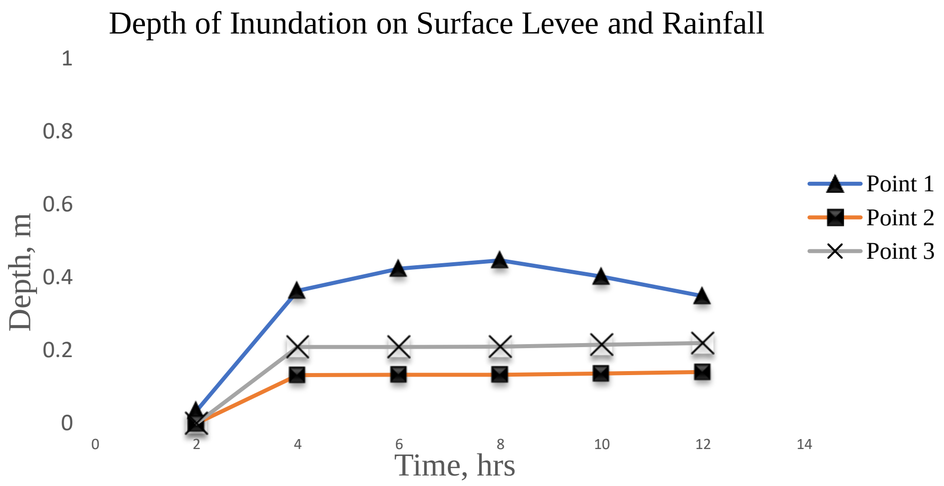


Figure 30. Flood Depth with Levee and Rainfall.

4.1.2.2 Second Analysis. Another area was analyzed to show how different areas in the same city can have totally different effects. Figure 31 shows the same rainstorm event previously illustrated in section 4.1.2.2, but in Study Area 2.

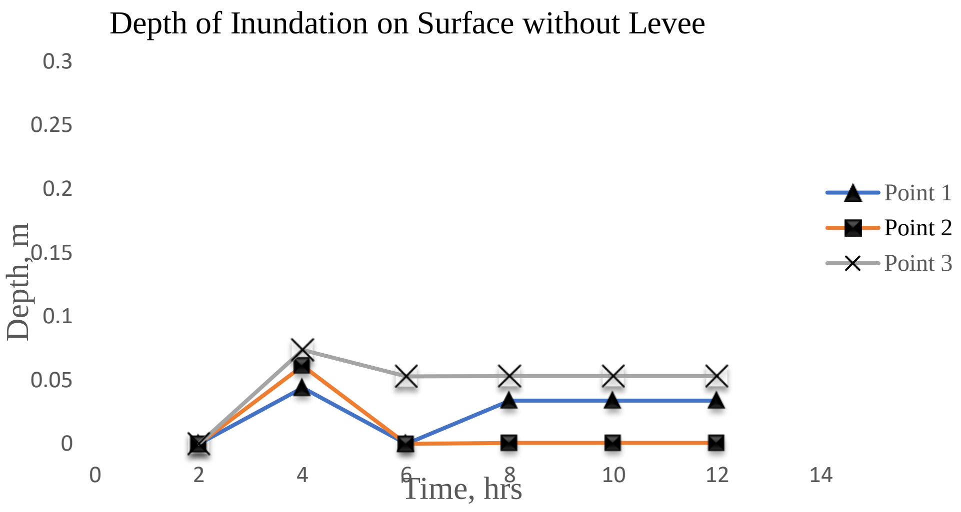


Figure 31. Flood Depth of April 30, 2014 Storm.

Figure 31 shows the same rainfall event, in a different location. The flooding in this location is minimal even without a levee. Figure 32 shows this area with a levee and no rainfall, two of the three points receive no inundation at all, and Point 1 has a maximum depth of .0168 m. This is a significant decrease from the previous graph of a .053 m maximum depth of inundation.

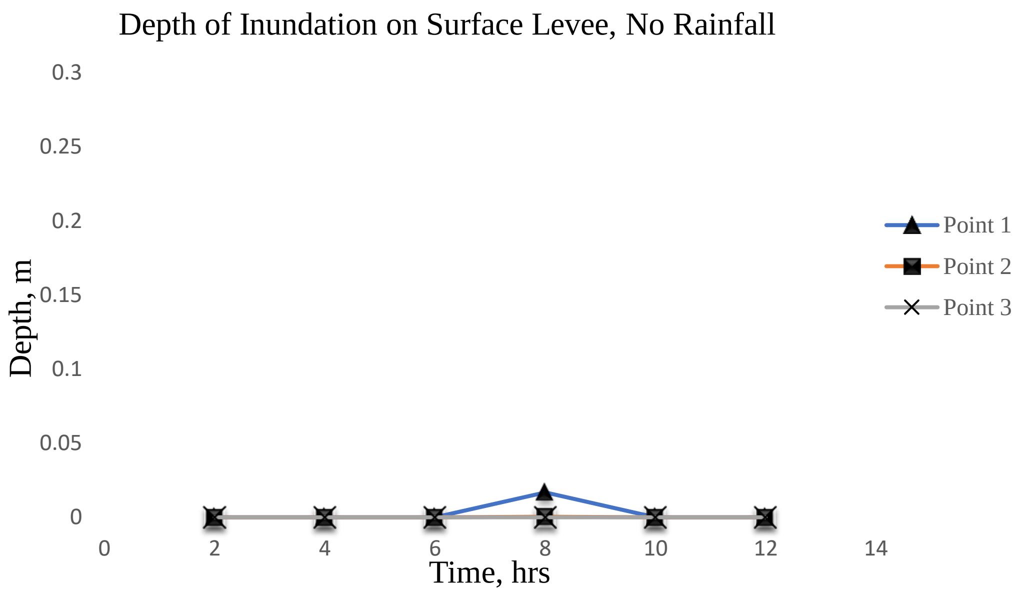


Figure 32. Flood Depth with Levee and No Rainfall.

Figure 33 shows this same event, in the same location, but with a levee and rainfall inputted into the system. This drastically increases the flooding in the area, which shows that a levee wouldn't be an appropriate resiliency method for this area of Atlantic City. The maximum depth of inundation increased to 0.6008, which means the water is not draining due to poor drainage in the area and a blockage from the levee.

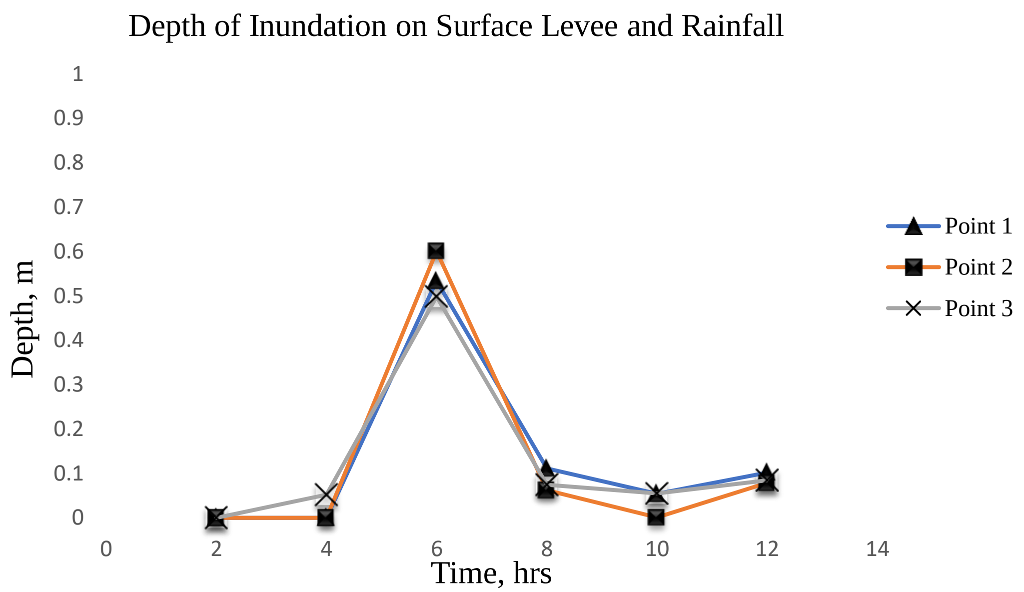


Figure 33. Flood Depth with Levee and Rainfall.

4.1.2.3 Third Analysis. Another event (Hurricane Irene) was analyzed in TUFLOW that was recorded to be the seventh-costliest hurricane in the United States. It hit the eastern shoreline on August 28, 2011. Figure 34 shows the results from the simulation due to Hurricane Irene at the previous points analyzed from the standard storm in April 2014 (Study Area 1). The maximum depth of inundation at these three points was 0.732 meters. This graph shows that at a certain point in time, at location Point 1, the water depth was 0.732 meters on the surface, equivalent to being a little bit higher than knee deep on an average person. These results show how damaging Hurricane Irene was, just at one point on the surface. With rushing, continuous water on land, the damage of flooding was immense with no protection.

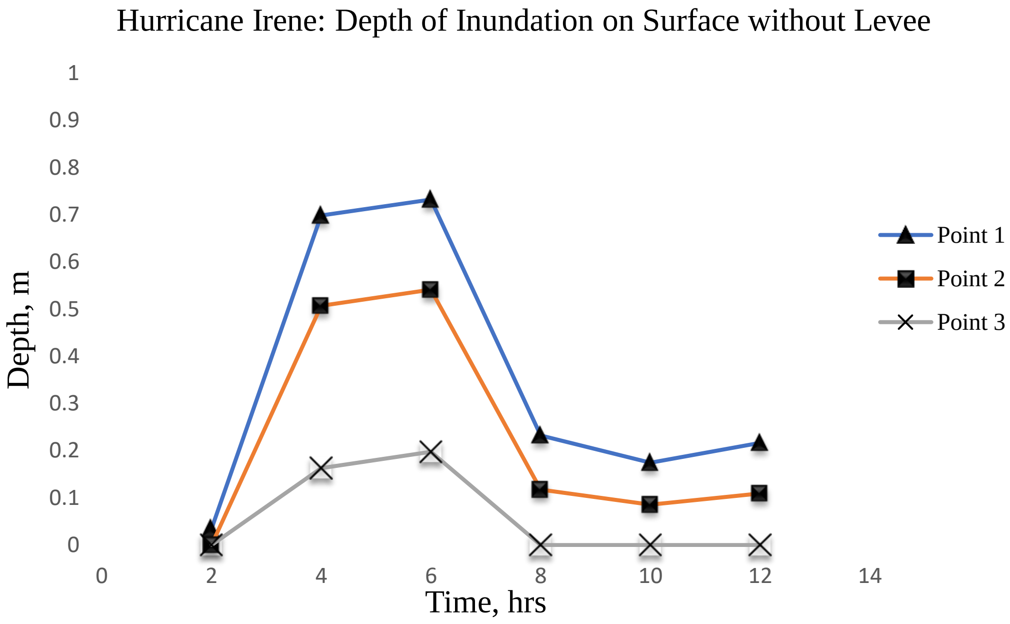


Figure 34. Flood Depth of Hurricane Irene.

The results show how effective flood barriers and mitigation techniques are needed in these areas prone to flooding, especially during a severe hurricane. Figure 34 illustrates, as previously (Figure 31), that even though these three points analyzed are in close proximity, about 20 meters from each other, the level of flooding is variable between the three points. These results validate the argument to use fine-scale modeling as a stepping-stone towards resiliency planning. Without such localized models, predictions and estimations will not be correct or beneficial for future preparation.

Figure 35 illustrates the impact that Hurricane Irene would most likely have had at the same locations without rainfall, but with a levee set in place. As the graph shows, the 3-meter levee does its intended purpose of minimizing flood in those areas. The maximum depth of water along the three points was at Point 3, with a depth of 0.29 m at Point 1, but the rest of the points are at 0.00 m. The depth of water at those locations dropped tremendously, about a half of a meter of water would not have been in that area if protective measures were set in place.

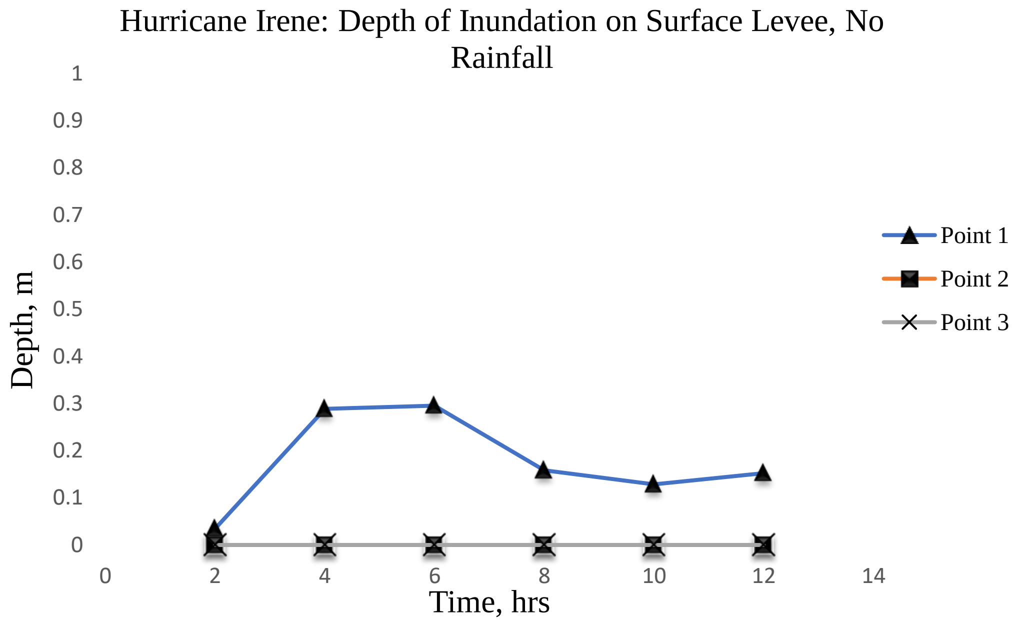


Figure 35. Flood Depth of Hurricane Irene with Levee and No Rainfall.

Figure 35 shows that the levee helps tremendously for a storm surge, blocking a significant amount of water from the threatened community. Figure 36 shows that the levee protects the community from a hurricane, decreasing the flooding to 0.45 m rather than 0.732 m, but there is still flooding happening because the rainwater is not draining properly due to a poor drainage system and the levee is blocking the flow.

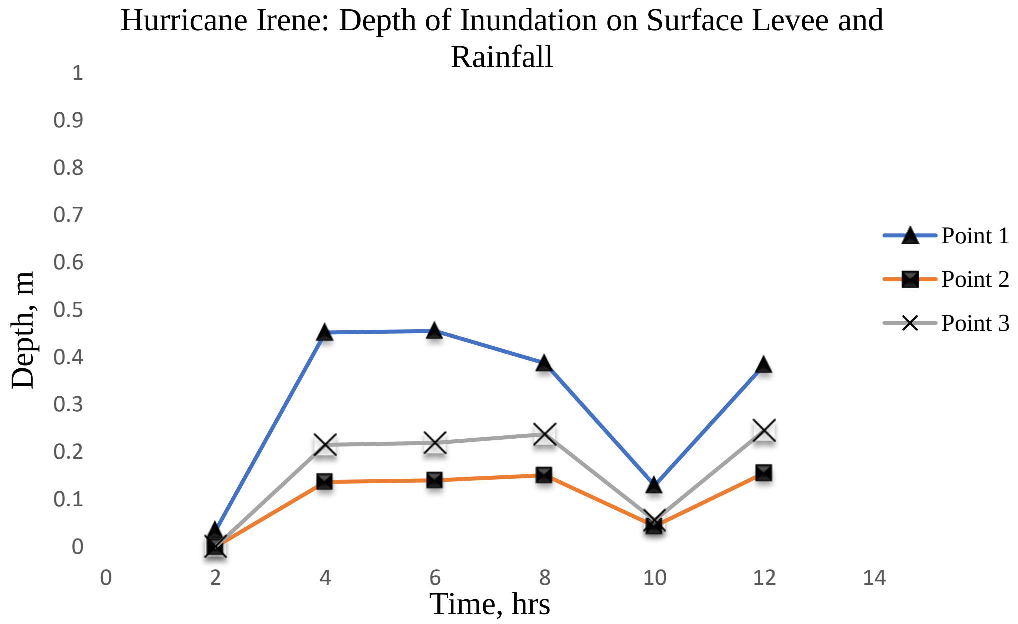


Figure 36. Flood Depth of Hurricane Irene with Levee and Rainfall.

4.1.2.4 Fourth Analysis. To reiterate the importance of such sophisticated modeling, Study Area 2 was analyzed for Hurricane Irene as well. This area is highly vulnerable due to its low resilient characteristics of little to no infrastructure protection.

The graph in Figure 37 shows the flooding pattern of three points within the area of interest. These points were in proximity of about 5 m apart, to show a different range. Even in a different area, these three points still have different flood depths when using the fine-scale hydraulic model.

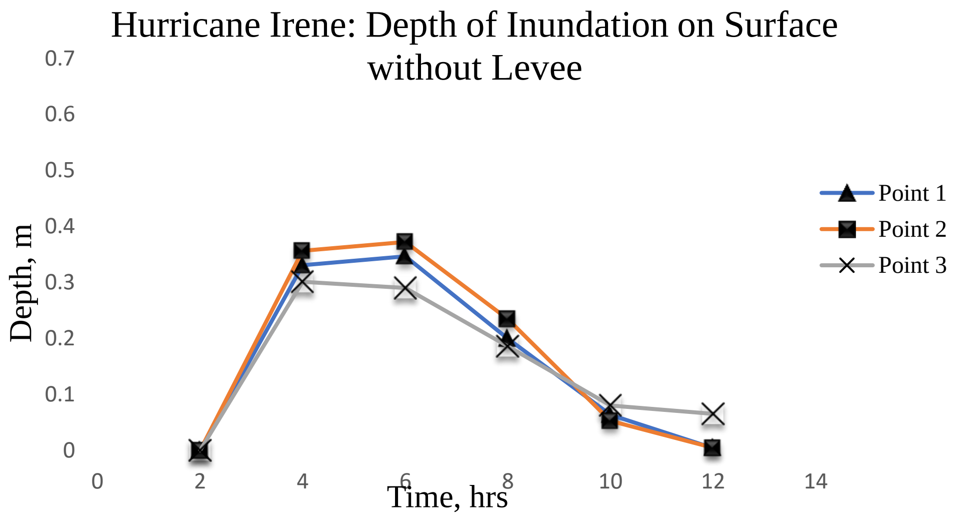


Figure 37. Flood Depth of Hurricane Irene, Second Study Area.

Figure 37 shows the flood pattern of three points in Study Area 2. This area has a smaller depth of inundation, at a maximum of 0.372 meters. This is due to the higher elevation of these points compared to the previous study area points. The complete analysis was done, comparing models of just the storm, the storm with a levee but no rainfall, and the storm with a levee and rainfall. Figure 38 illustrates this area with a levee but no rainfall.

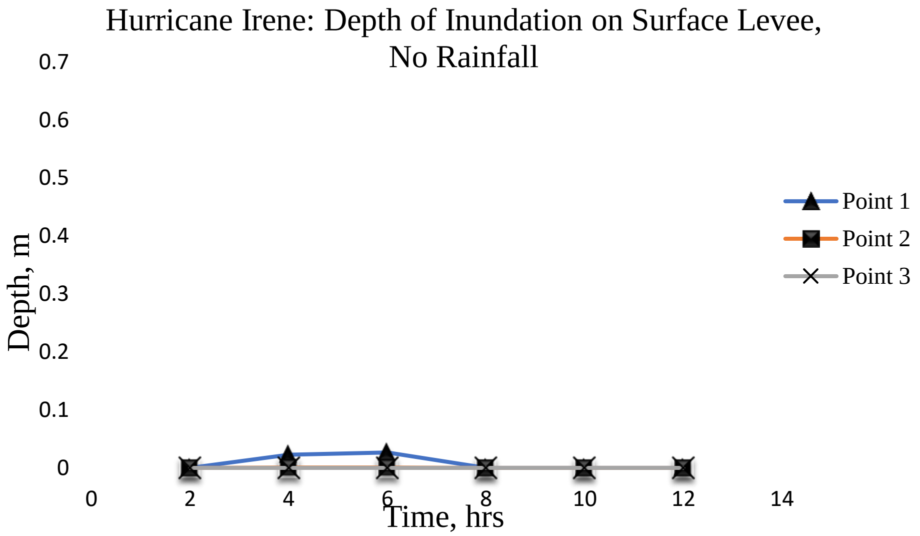


Figure 38. Flood Depth of Hurricane Irene with Levee, No Rainfall.

As expected, the levee does a tremendous job decreasing the flood depth from the storm surge. The maximum inundation level with the 2m levee put in place is 0.026 meters, which almost a half a meter decrease of water. Figure 39 shows the simulation done with a levee put in place and rainfall inputted into the system.

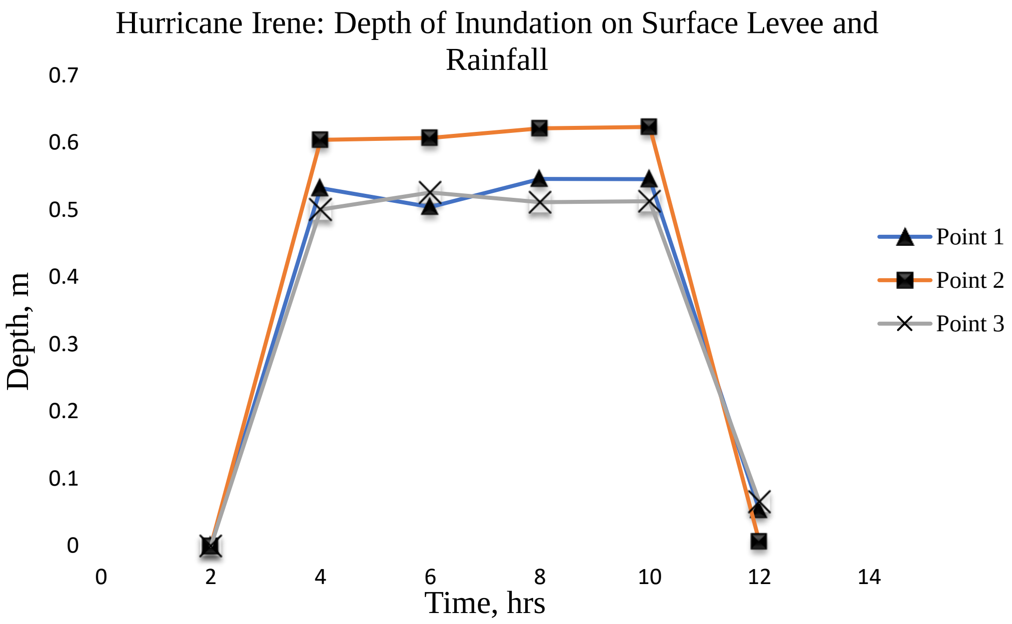


Figure 39. Flood Depth of Hurricane Irene with Levee and Rainfall.

Figure 39 shows a large increase in inundation at all three points in the second study area, due to the poor drainage of the area. The levee forces the rainwater to accumulate, without letting it drain out. With a proper drainage system, putting a levee in place for storm surge protection would be a suggestion in this area, but only if a new drainage system could be built or a pump to pump out the excess rainwater, since Figure 38 shows tremendous success for the levee against the ocean tide.

4.1.2.5 Fifth Analysis. Due to time constraints and limitations within the capacity of the computer, a full analysis using a 1m by 1m grid or less was unachievable. But, a simple analysis to show the refinement of using such a small grid was able to be developed. The simulation ran for one week due to the 0.025 time step for the 1 m by 1 m grid because otherwise, the simulation would go unstable with a larger time step. Since the grid is so small, the time step needed to be extremely small as well to be able to capture the flow through such small cells. So due to the longevity of the simulation, the time input was only 4 hours of flow rather than the full 14 hours in the previous studies.

In addition to the 1 m by 1 m grid simulation, a comparison of the four grids used in this study was done. Figure 40 shows the different grid sizes used comparing a 10 m grid to the 1 m grid and to the national model grids.

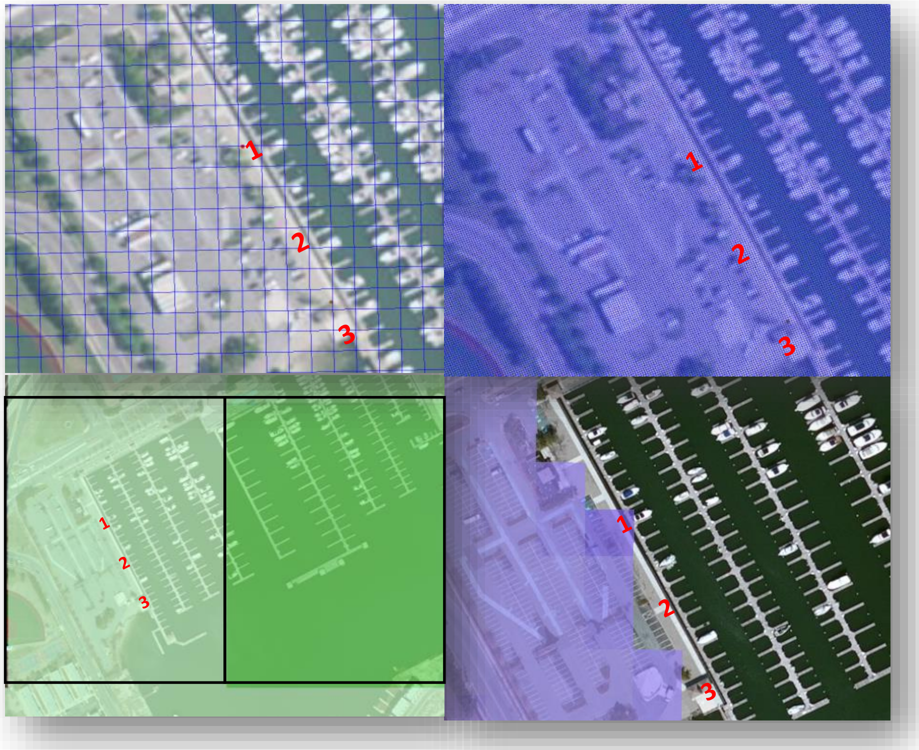


Figure 40. Left Top: 10 m by 10 m Grid; Right Top: 1 m by 1 m Grid; Left Bottom: SLOSH Grid; Right Bottom: HAZUS Grid.

Although a 10m by 10 m grid is very fine, the capabilities of this innovative software are very particular. You can see the difference between a 10 m grid and a 1 m grid. This shows how fine the scale can become and how accurate flood predictions are, using fine-scale modeling. Figures 41 and 42 show the Hurricane Irene simulation in Study Area 3, shown in Figure 3, using a 1 m grid versus using a 10 m grid. The reason for a slight difference in numbers is due to the higher resolution of grid being used.

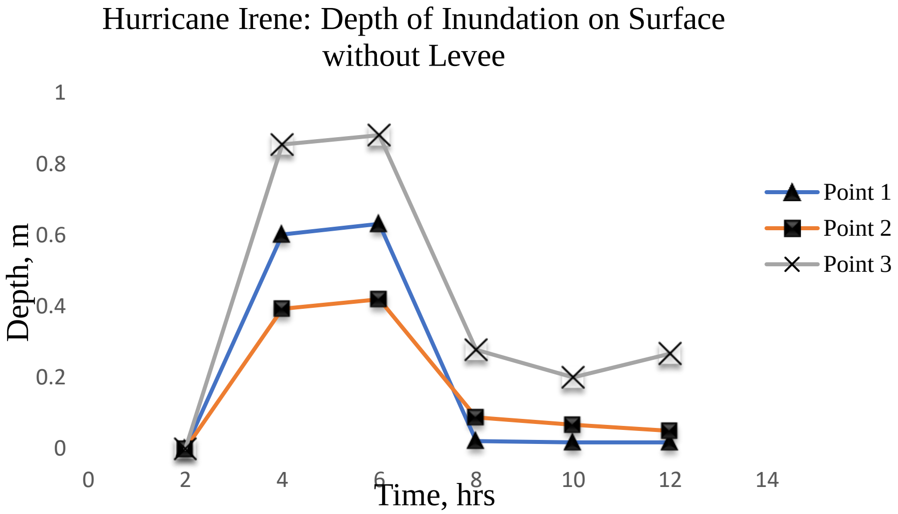


Figure 41. Depth of Inundation using a 1 m by 1 m grid for Study Area 3.

This shows that the data can get very precise with a finer grid. There is a maximum flood depth of 0.88 in Figure 41 and a maximum of 0.76 m in Figure 42. The difference in numbers show the quality of fine-scale modeling software and the significance of such a tool.

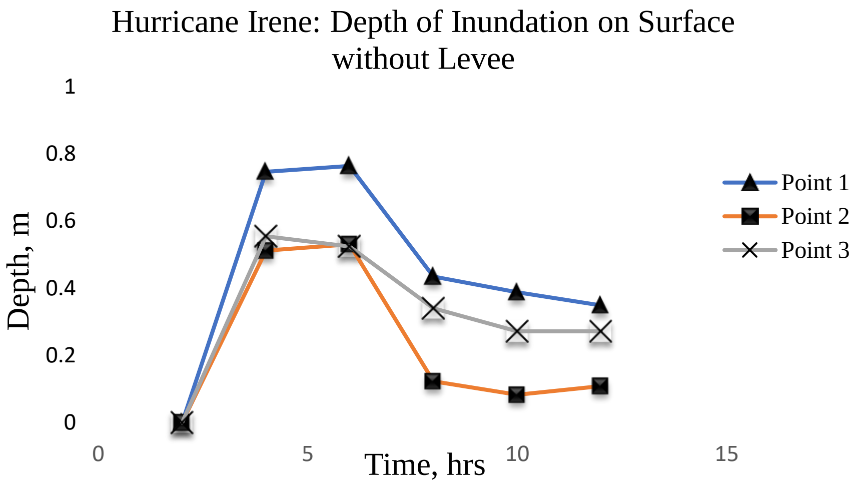


Figure 42. Depth of Inundation using a 10 m by 10 m grid for Study Area 3.

4.2 Camden, New Jersey

4.2.1 TUFLOW. TUFLOW is a dynamic tool that allows for the depiction of flooding at a finer scale as well as compared to the other models that cannot withstand the high resolution capabilities of such software. Figure 43 shows the hourly TUFLOW simulation of flooding in Camden, New Jersey. The blue coloring represents the lowest water depth and the red represents the highest, where the colors are a range in between.

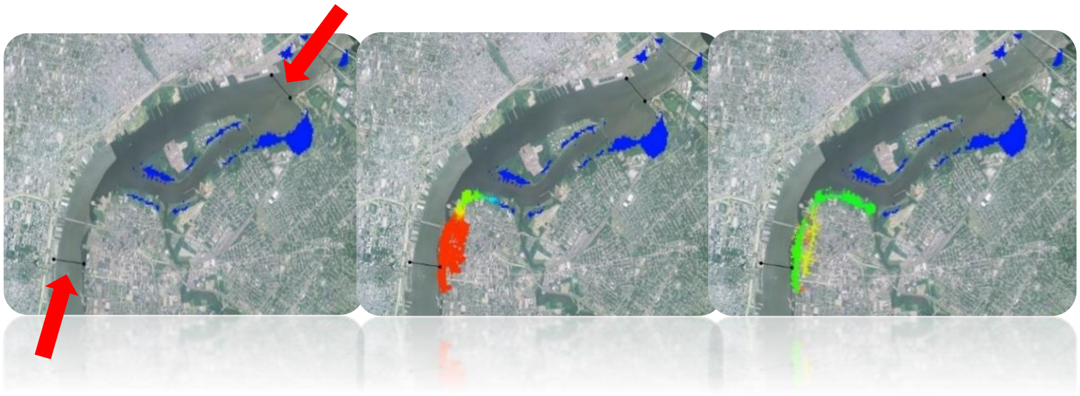


Figure 43. Hourly TUFLOW Simulation of Flooding in Camden, New Jersey; Blue represents the lowest water depth where Red represents the highest flood depth; the red arrows indicate the locations of the boundary conditions.

Figure 43 shows the flooding pattern of Hurricane Irene on August 28, 2011. The boundary conditions pointed out in red were set in the Delaware River near the Port of Philadelphia-Tioga as well as downstream near the Adventure Aquarium in Camden, using the tide gauge data provided by NOAA.

Figure 44 shows that same area, more localized and at a finer scale to show the details of the simulation. It also shows the area before the storm event occurred and then during the storm event, showing flooding in places that depicted no water before. There is a 1, 2 and 3 placed on certain points of the grid to identify specific points analyzed in this study.

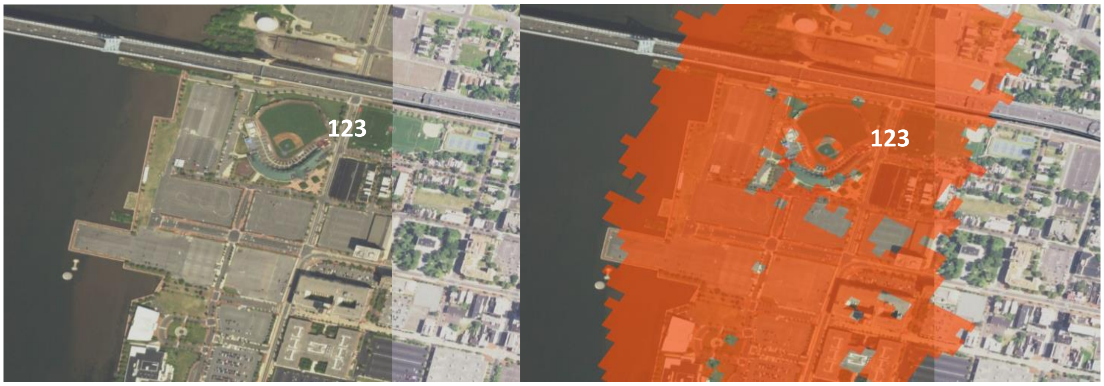


Figure 44. Pre- and Post- Flood Area.

Three points were chosen to be analyzed rather than one due to the vast possibilities of flood patterns that can happen within an area of a few meters when using different modeling programs. The more information we have about a vast area being flooded, the more of an understanding we will have to pose a solution. Figure 45 shows the same points on an image with a combined inundation map of HAZUS-MH and SLOSH data.

Figure 45. Depiction of Analyzed Points on an Inundation Map of HAZUS and SLOSH.

Points 1 2 and 3 in Figure 45 were analyzed in SMS, to understand the flooding pattern at a finer scale. This technique was also used to compare TUFLOW resolution to HAZUS and SLOSH, which use greater resolution for their data and information. The three points analyzed are very close together to show the difference between different scaled models. The green shading represents SLOSH data for a Category 1 storm and the purple shading represents HAZUS data that correlates to a Category 1 storm, using data for a 100-year return period. Figure 46 is the graph that compares all three programs, TUFLOW, HAZUS and SLOSH.

HAZUS and SLOSH only generate flood models at a larger scale. Fine- scale models allows for the flood to simulate a pattern at each point, where national models only allow for a large area at the same flood depth to be calculated. The information provided to HAZUS and SLOSH, as well as their internal capabilities don’t give the programs a fine enough grid to work with.

Figure 46 supports the statement of how fine scale models are needed to represent climatic disasters due to the difference in flood depths shown in the figure. The graph shows that TUFLOW and HAZUS are much more comparable than TUFLOW and SLOSH, which is sensible because SLOSH resolution is much greater than both HAZUS and TUFLOW. The concentration on these findings show that TUFLOW goes further into precision than HAZUS does using a smaller grid, where each point has a different flood depth rather than each certain square meter.

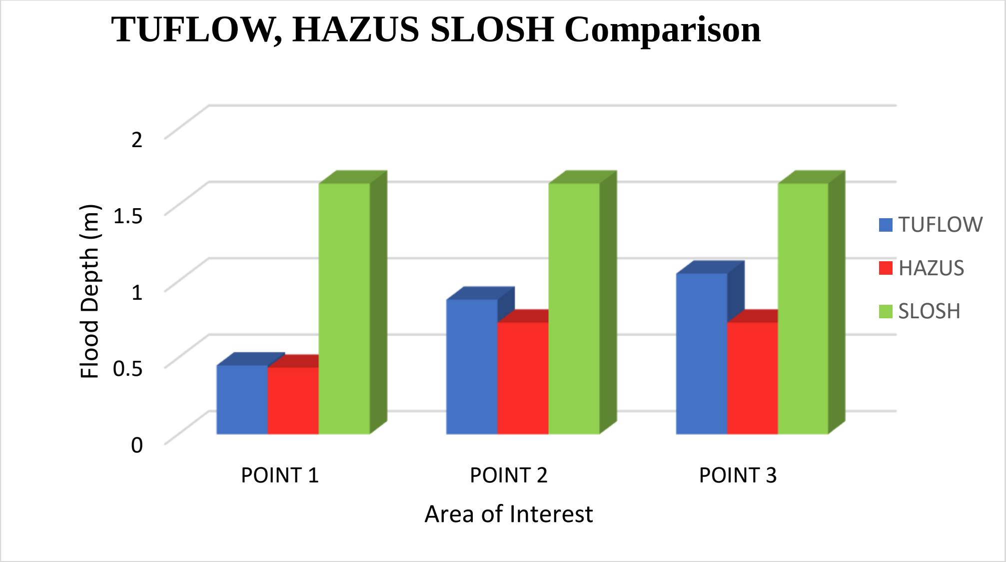


Figure 46. TUFLOW, HAZUS and SLOSH Comparison at Three Different Locations.

4.2.2 Storm Water Management Model 5.1. Storm Water Management Model (SWMM) is used worldwide for planning, analyzing and designing the pattern of water through a stormwater system.

The focus for this part of the research was to ensure green infrastructure capabilities. The first approach and emphasis was on the building scale, to see effects of a green roof on a building before and after its implementation. A subcatchment with a 100% impervious area of 0.05 ha (500 m^2) was chosen. The simulation was run with no LID controls first. The results showed a peak runoff rate for the specified subcatchment to be 0.05 CMS. Then, a green roof LID control was set in place for that same subcatchment. The green roof occupied the entire subcatchment and after implementation of a green roof, the peak runoff decreased to 0.01 CMS. This shows an 80% reduction of peak runoff, which is illustrated in Figure 47.

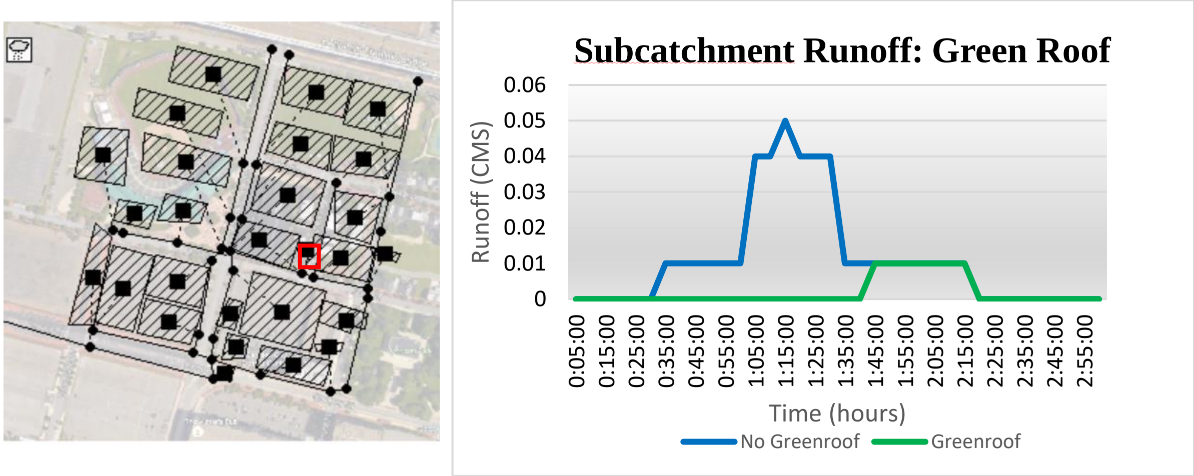


Figure 47. Subcatchment Location and Graph of No Green roof versus Green roof.

The simulation was continued with implementation of a bio-swale. Before the bio-swale was implemented, the peak runoff rate was 0.05 CMS for a different area of the same measurement of 0.05 ha (500 m^2). After the bio-swale was implemented, the peak runoff rate was 0.00 CMS, producing a 100% reduction in peak runoff for that specific area. Figure 48 shows the graph of the reduction in peak runoff.

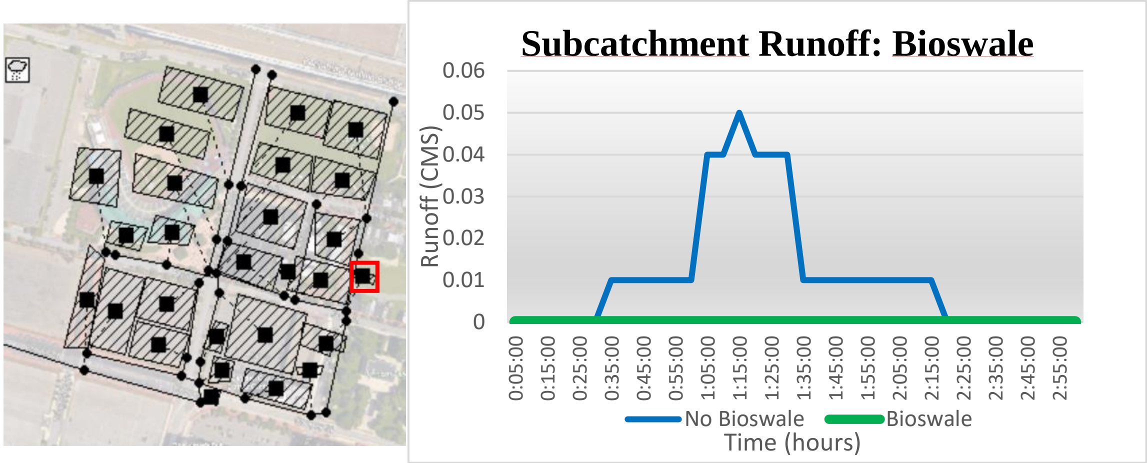


Figure 48. Subcatchment Location and Graph of No Bio-swale versus Bio-swale.

This area drains into an outlet, sometimes causing flooding problems if there is overflow. The total inflow to the outlet was analyzed as well to assure that there would be a decrease. Before implementation of the bio-swale, the total flow into the outlet was 1.37 CMS. After implementation of the bio-swale, the total flow into the outlet decreased to 1.35 CMS, a 1.46% reduction of inflow to the subcatchment outlet. The percentage decrease is not large but still illustrates how green infrastructure can impact many types of mechanisms within a system.

The entire system was then analyzed, to get an overall essence of how green infrastructure works at a greater scale. Figure 49 shows the comparison between the runoff of the whole system before green infrastructure and the runoff from the system using two types of green infrastructure, one 1000m^2 bio-swale and one 500m^2 green roof. Green infrastructure implementation resulted in a 3.21% reduction in peak runoff for the system.

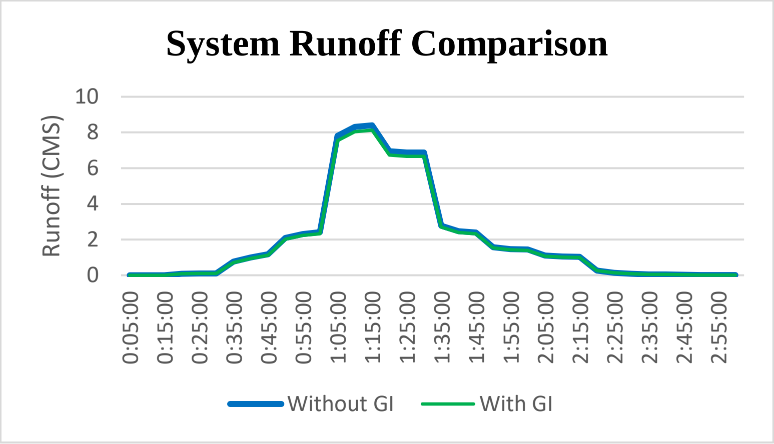


Figure 49. System Runoff Comparison between No Green Infrastructure and with Green Infrastructure.

Another scenario was modeled for the system, where a 2500m^2 bio-swale and a 500m^2 green roof were implemented into the system. This resulted in a 5.95% decrease of peak system runoff, concluding that the more GI within the system, the less runoff there will be, decreasing the amount of flooding in the streets of Camden. This result is shown in Figure 50.

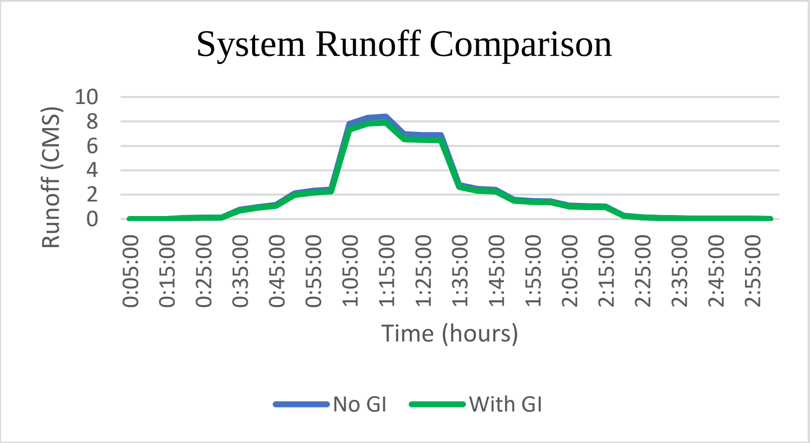


Figure 50. System Runoff Comparison between No Green Infrastructure and with Larger Green Infrastructure.

Chapter 5

Summary, Conclusion and Recommendations

5.1 Summary

The information in this study illustrates how the increase in storm events, sea level rise and storm surges are of high concern in the subjected areas and more than just current models are needed for prevention and planning.

When comparing and combining TUFLOW, HAZUS, and SLOSH models, we can get a large scale representation of hurricane and flooding impacts, as well as a finer scale representation of what is happening. TUFLOW allows the implementation of real time data into boundaries and depicts what happens when the tide levels increase. HAZUS and SLOSH are able to predict damages and losses related to a type of storm but just using national models with a coarse resolution will not help a community become resilient to climatic hazards. It is important to use high-resolution modeling and data for climatic predictions and resilience. It is crucial to create fine-scale models before implementation of any stormwater management system in a community for cost and safety reasons. When damage is under-predicted, the impacts of the storm event are devastating as well as if the damage is over-predicted; the community wastes an immense amount of money on unnecessary materials. The differences between TUFLOW, HAZUS and SLOSH are the resolution and estimation of the flood level. As shown in Figure 24, due to the low resolution of HAZUS and SLOSH, there are designated large areas with the same values of water level, which is not accurate. These coarser models tend to overestimate the storm and do not allow communities to completely understand the forecast of the storm happening in their area. TUFLOW allows high-resolution data to designate fine areas with a certain value, giving a more accurate representation of the storm predicted in coastal communities. The need for high-resolution analysis is crucial when considering flood impact on threatened communities.

The results show how SLOSH and HAZUS are based on such large grid sizes that there are inconsistencies with these model outputs. The large grid of these national models allows for gaps as well as a broad estimation for different points on the surface to receive the same amount of inundation, which is very inaccurate. These results can also be discussed in reference to a study performed by Katehis (2015), who analyzed flood levels from Superstorm Sandy using three different methods; HAZUS Coastal Surge Model (CSM), SLOSH and the FEMA MOTF (real data) model in the five boroughs of New York City.. When comparing the map of HAZUS and SLOSH as well as HAZUS and HSIA, the map clearly showed the places missed on the Eastern shoreline by HAZUS, where other models show that there was flooding in that area. In this case HAZUS predictions were faulty for not showing inundation in areas that were flooded from the storm, while flooding was indicated for the other models. Katehis (2015) attributed these varied results to miscalculations of flood surface geometry, resulting in “gaps” in the flood data. Other differences such as how HAZUS uses 2000 TIGER data (FEMA 2012a) for its counties while HSIA used default ArcGIS basemaps and grid cell measurements are also factors.

It is likely that a similar explanation can be made for gaps in Atlantic City and Camden from HAZUS and SLOSH data for Hurricane Irene inundation predictions. The presence of these data gaps show that it is important to have high resolution elevation data and observed data for use with simulations, i.e. tide gauge data and historical precipitation data to create a more accurate prediction of storm flooding. Even with such a large grid to predict storm values, depending on topographic data and the default settings within the program, important information still may not be conveyed.

Green infrastructure is the second part of this research. Green infrastructure nourishes cities environmentally and increases its resiliency to climatic disasters as well. It is used all over the globe because it is very important to maintain effectiveness and efficiency within such an urban city. In highly developed urban regions such as Camden, NJ, low lying areas within the city fill up due to an abundance of impervious materials used for city structure, when those spots normally would be able to drain naturally. Due to this fill up, any stormwater and runoff gets directed into storm and sewer systems, overflowing and mixing raw sewage with clean water. This contaminated water lies all over the parking lots, sidewalks and driveways, eventually making its way to streams and oceans. Implementing rain gardens and bio-swales is a simpler and cheaper solution to help mitigate flooding. It’s a technique that the city has already implemented within their Camden Smart Program which can expand to applying green roofs and bio-swales into their projects as well.

5.2 Conclusion

Community members need accurate and reliable models for a foundation of their understanding or the community will not be readily prepared for a climatic hazard. The need for fine-scale modeling before coastal resiliency tactics are implemented in threatened coastal communities like Atlantic City is apparent as national and regional coarse scale models can lead to inaccurate information for design and lack of consistency. With climate change, the frequency of storms is increasing, and resiliency methods against such threatening climatic events are crucial for coastal communities. Results indicate that, using fine scale modeling, the catastrophic flood risk will be known more accurately, and potential solutions will be able to be presented quicker and more correctly, than with a coarse-scale estimation using the current national models. More accurate predictions allow the community to prepare more cost effective solutions. Awareness is crucial part in resiliency planning and without explicit advanced modeling and research, no community will be responsive to the dangers ahead.

The study provided illustrates how storm events are of high concern in the subjected area presented, and the great flooding potential within Atlantic City and Camden City. This research promotes the need for dual resiliency tactics such as fine-scale modeling and green infrastructure to be implemented in threatened communities. With fine-scale modeling, flooding is able to be tracked at a much finer scale and the modeling capability allows for greater resiliency for the community.

Green infrastructure implementation is cost effective, environmentally friendly and fairly easy to implement. The usefulness of green infrastructure is endless, from filtering out contaminants to storing water and infiltrating it through the ground. They mimic natural drainage systems by using such materials as roots of the plants and layers of gravel, soil and mulch to filter the water seeping into the ground. Figures in 47-50 show the benefits of implementing green infrastructure into urban regions. Figure 47 shows an 80% decrease in runoff by implementing a green roof, and even better results by using a bio-swale for a 100% decrease in runoff. System runoff is a much smaller decrease, but at such a large scale there are many more components such as impervious area that affect the outcome. The evidence is supportive to the fact that green infrastructure will help urban cities with the climatic threats of climate change and sea level rise and the use of fine scale modeling combined will create a great mitigation technique to reduce flooding and its negative impacts.

5.3 Limitations and Recommendations

Due to the RAM capacity of the computer that was being used for the first year and a half of this study, certain amount of data were unable to be imported into the model interface. Bathymetry data that was used to help calculate flow data were input at a minimum because the capacity of the computer could not handle the large amount of bathymetry data. Another problem due to the capability of the computer used was that the program kept crashing and shutting down, so time was a constraint in this study. A third issue with the computer's minimal capacity created a problem when generating the grid for the model. The capability of the model that was run is high functioning and very fine. The computer's capacity was unable to handle the advanced modeling proficiencies, until further investigation was performed later and due to timing constraints, multiple data that were encouraged were not able to be obtained. Even with such constraints, this paper still exemplifies the objectives and goals of the study performed properly and sufficiently.

There are a few recommendations that can be made for this research project, as well as future work considerations. A high functioning, super computer needs to be used for modeling purposes and this type of research since the program kept crashing and time started to become an issue. Another recommendation for this research is to solely run the model using a 1m by 1m grid as well as even a finer grid, to get the most precise results possible.

Future work involves developing a framework for resiliency planning in the face of extreme storm events. This includes building an interactive map online for users to be able to understand the problem of flooding and sea level rise, and then be able to choose the best mitigation technique on a legend for the area they are located in. The goal is to have this interactive map completed for the whole coast, as well as inland areas and eventually the whole country, for areas that are threatened by flooding. Using fine-scale models and interactive maps will help the communication barrier between community members and professionals about this climatic problem and increase coastal community resiliency in the near future.

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