Using an Urban Growth Model Framework to Project the Impacts of Future Flooding on Coastal Populations

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Urbanization in coastal areas of the United States is increasing as simultaneously the East and Gulf coasts of the United States face increasing threats from climate change from hurricanes and storm surge inundation. This study will evaluate urban growth using a cellular automata model to analyze the trends in urbanization between 1996 and 2019 and predict how it will continue until 2050. The study uses historical trends in land use and urbanization, as well as spatial and environmental data, to evaluate the likelihood of urban growth in two modeled scenarios: one that accounts for flood risk and one that does not. The study evaluates trends over the entire coastal buffer area, including the 150-kilometers adjacent to the East and Gulf coasts as well as targeted areas of New Orleans, Louisiana and Houston, Texas to determine growth at the scale of a metropolitan area. Both the scenarios have an overall prediction accuracy of 93% in determining the projected land use of a cell on the gridded map; however, the two models have different strengths. The scenario excluding storm surge impacts better predicts urban growth across the entire study area categorically, while the scenario accounting for the suitability of growth in areas at risk of storm surge inundation is more reliable in showing the specific areas urban growth occurred. The comparison of the strengths and weaknesses of the models will help determine if urbanization and population shifts are impacted by threats of storm surge and hurricanes in the study area. The outcome of the model analysis can be used to influence how communities burdened by climate change can strategically grow to limit the impacts of flooding on their residents and infrastructure.
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GENERAL AUDIENCE ABSTRACT

The flood impacts of hurricanes regularly impact the coastline of the United States, however populations in the same coastal areas are continuing to grow. This study models how cities are growing along East and Gulf coasts and the factors influencing that growth. The concern with increasing urban areas in coastal areas is that these areas are also being affected by climate change, which can cause flooding and other dangerous conditions. These flood events are a risk to human lives and the built environment of the communities. This study uses a computer model to analyze how these cities are growing using historic data from 1996 to 2019 and how they will continue to grow through 2050. The model considers factors like the risk of flooding, as well as information about the land and environment in these areas. This study used this information to identify how cities are growing and determine if there is a need to better account for flooding risks and other problems caused by climate change as growth continues. The work looked at two different scenarios, one that accounts for flood risk and one that allows growth without concern for flood risk, to see which one more closely models historic growth. This study will help communities along the coast make smart decisions about how to grow and adapt to the challenges of climate change.
Dedication

I would like to dedicate this work to Cameron K. Gallagher, a fierce friend and fighter whose legacy brings hope and strength to those struggling with their mental health.
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1. Introduction

Urban growth in the coastal zones of the East and Gulf coasts of the United States has become a significant area of concern due to the threats of storm surge and flooding from hurricanes and the impacts these threats have on the natural environment, infrastructure, and human communities. These threats are environmental phenomena that are being exacerbated by climate change. As coastal areas continue to expand, developments need to be strategically planned to avoid placement in high-risk areas. To address this issue, this study has been conducted to predict future urbanization trends in the coastal regions along the East and Gulf coasts. This study employs an urban growth model based on historical trends in land use from 1996 to 2019 as well as spatial and temporal indicators such as elevation, slope, proximity to roads, and existing urban areas to predict the likelihood of future urban growth from 2020 to 2050.

The entire study area is evaluated for urban growth along with detailed analysis of the metropolitan areas of New Orleans, Louisiana and Houston, Texas. These two cities have experienced impacts from large hurricane events and have differing urbanization and population trends as a result. The area of New Orleans experienced considerable damage to the infrastructure during Hurricane Katrina in 2005, and as a result, a portion of the population moved out of the Louisiana coastal area. Conversely, the Houston area has experienced significant growth in urban areas and in population between 1996 and 2019, and it became home to many residents who evacuated from the New Orleans area during Hurricane Katrina.

In order to understand if the risks imposed by environmental threats are impacting the way coastal cities are growing, the model has been further developed to include flood hazard data to determine if storm surge and hurricane risks influence urbanization and population shifts. This second scenario for growth considered one smaller and one larger storm surge event from modeled hurricanes to compare predicted growth to each other and to the scenario that does not account for environmental factors. This comparison indicated if coastal areas are expanding into increasingly hazardous areas, or if responsible growth is occurring to avoid development in flood risk areas.
The study also utilizes population statistics and climate change metrics to compare the projected urban growth with vulnerable communities and their environmental burdens. The results of this study provided valuable insights into the potential risks and opportunities associated with urban growth in these coastal regions. The results may help inform policymakers, planners, and stakeholders to make informed decisions to achieve resilient urban expansion in coastal cities as populations continue to shift towards urban areas.

This study presented a background literature review of methods for urban growth modeling and the factors influencing expansion. The methods of data processing and model construction are then presented with initial findings. Finally, the modeled scenarios for growth with and without environmental considerations have been validated, and the results are presented. The conclusions and summary of this work summarize the findings of the results and future work that can be completed to determine additional environmental, socioeconomic, and temporal factors that can be considered to further evaluate urban growth in coastal areas.
2. Review of Literature

The literature review conducted for this work has targeted three (3) primary focuses:

- Land cover/land use models and statistical analysis for projecting land use,
- Driving factors impacting land use and coastal population dynamics, and
- Population correlations with land use and environmental factors.

The previous literature analyzed as part of this work provides context for the modeling methods applied in this work, identifies trends in climate change that impact coastal populations, and quantifies interdisciplinary factors driving population shifts. This literature review establishes prior work relating environmental hazards with human coastal populations. The research as part of this study analyzed historical data for land use and environmental change to show historic shifts in coastal areas that drive population changes. Furthermore, the work modeled future shifts in land use related to development and environmental factors and correlate these modeled changes with projected population models to determine which factors drive population shifts in the short- and mid-term.

2.1. Cellular Automata (CA) Models for Land Use Projections

In order to evaluate spatial patterns, spatially explicit models (SEMs) can be employed to simulate changes in geographic patterns in natural and built environments (Liu et al., 2017). The most widely used SEMs for analyzing land use changes are Cellular Automata (CA) models (Tong and Feng, 2020). CA models analyze geographic spaces in a grid format that allows each cell to change its state as it relates to the neighboring cells over time, which allows the model to determine overarching patterns for local spatial transitions (Wolfram, 2002). This approach is particularly useful in analyzing changes in land use data and predicting future changes in time that are based on overall historic growth trends and local growth in neighborhoods of grid cells.

Transition rules are used in CA models to determine the probability that a transition will occur in each cell in a binary way, which is 0 indicating no change occurring in the cell or 1 indicating change occurred in the cell (Crols et al., 2017). This transition can then be projected over time based on the patterns of development identified in the historical data (Crols et al., 2017). For this study, this methodology has been applied to historical data to identify areas that shifted from
non-urban to urban and the factors that impacted that transition. By understanding the transitions occurring in the historical data, the same transitions can be modeled to project urban growth.

While a CA model is utilized for this study, there are other methods to model urban growth. In a critical review study of urban growth modeling methods, Hassan and Elhassan (2020) reviewed different modeling methods including CA models, genetic algorithms, regression models, survival analysis, Markov chains, and other models to determine the strengths, techniques, and results of urban growth models (Hassan and Elhassan, 2020). These methods include models that rely on spatial factors, like CA models, to determine where urban growth developed or regression-based models that use machine learning to determine likely development areas (Hassan and Elhassan, 2020). The review identifies the strength of CA models as identifying growth using a neighborhood approach to cell transitions (Hassan and Elhassan, 2020).

2.2. Random Forest Algorithms for Projecting Land Use

Random Forest (RF) algorithms have been used in conjunction with CA models to predict land use change as shown in the Lui et al. (2021) paper figure below detailing the workflow integration used to determine the transition rules for a land use model (Lui et al., 2021).

Figure 1: Flowchart of CA-RF model (From Lui et al., 2021)
The above workflow details the inputs of land use and driving factors to train a random forest model in the same structure that has been applied to this study to understand the transition probability in the CA model for this study. The driving factors contribute to each cell’s properties and then the data is run through the random forest algorithm to determine the transition probability. The driving factors and land use data can vary based on the goals for the research and the available data for area of study.

2.3. CA Model Accuracy

Tong and Feng (2020) report in their review study of CA models that one of the areas that is lacking in the field is an appropriate way to quantify or evaluate error propagation in the modes that have used processes such as scaling, sampling, or transition rules (Tong & Feng, 2020). The methods proposed in this study have been well documented to identify any potential errors based on these processes that have been necessary to evaluate the large geographic area and project into the future. It is recommended to complete a procedure assessment to determine the quality of the simulation results (Tong & Feng, 2020).

In order to ensure the accuracy of the CA model, there are several ways to assess the performance of the models, two of which has been employed for this study. The first method is a visual inspection of expected results, which can be one of the most effective ways of identifying modeling errors or unexpected results (Straatman et al. 2004). This method can be used to inspect the change in urbanization and can be used to validate the CA model by using a portion of the data to train the model and the remaining to validate the projections.

A more detailed inspection of model accuracy also has been completed and used the technique of completing a map overlay, which spatially compared maps of actual land use data from the beginning and end of the historical datasets to the map of the predicted land use generated by the model for the end of the historical dataset year (Tong and Feng, 2020). This allowed for a direct comparison of the actual versus predicted land use and confirm the accuracy of the model’s predicted land use prior to being applied to future projections. The overlaid maps have been compared using a confusion matrix to calculate the Kappa Coefficient, Producer’s accuracy, and User’s accuracy to determine the overall accuracy and reliability of the modeled projections (Tong and Feng, 2020).
2.4. Driving Factors Influencing Land Use and Coastal Populations

Urban growth models are used to simulate and predict the growth and expansion of urban areas. In these models, transition rules are used to determine whether a cell or location will transition from a non-urban to an urban state. These transition rules typically consider a range of factors that influence urbanization, including Slope Land use Exclusion Urban Transportation Hillshade, or SLEUTH, factors as the primary drivers of urban growth (Votsis, 2017, Clarke and Gaydos, 1998). The spatial and temporal driving factors of SLEUTH models are incorporated in this work as baseline factors driving urban growth and defined by the data sets used for this study in the Chapter 3 and 4 Methods sections.

For this work, the study area is divided into a grid of cells, 1-kilometer by 1-kilometer, and each cell is assigned an initial state based on its land use, such as agricultural, wetlands, or urban. The transition rules in this CA model are based on the characteristics of neighboring cells and the current state of the cell being analyzed. For example, a cell may transition to an urban state if a certain percentage of its neighboring cells are already urban and if the slope of the area is under a certain threshold.

To target growth-driving factors that are unique to coastal areas, additional consideration is given to hurricane and sea level rise impacts. These factors are evaluated to determine if coastal urban growth is impacted by environmental causes and if climate change is impacting the rate of coastal urbanization or trends in population shifts.

2.5. Hurricane Storm Surge Impacts on Coastal Populations

For this study, the data utilized are the National Storm Surge Risk Maps from the National Hurricane Center (NHC) and National Oceanic and Atmospheric Administration (NOAA), which simulate the impacts of storm surges caused by tropical cyclones along the entirety of the U.S. coast. The NHC model for determining projected storm surge is a Sea, Lake and Overland Surges from Hurricanes (SLOSH) model that generates simulated results from inputs of hurricane track, size, and intensity (Zachry et al., 2015). The composites from 100,000 simulated storms with “varying forward speed, radius of maximum wind, intensity (Categories 1-5), landfall location, tide level, and storm direction” are combined to generate Maximum Envelopes
Various factors can influence the magnitude of a hurricane's storm surge, including wind speed, central pressure, forward speed, size, angle of approach, slope of the continental shelf leading up to the coast, and other local features. Some of these factors are not considered in the Saffir-Simpson hurricane scale, which categorizes hurricanes as Category 1 to Category 5 based on their intensity, and the storm surge resulting from a hurricane of a certain intensity can vary by up to 30% within the same category (Irish et al., 2008). The maximum of the MEOWs generated from the model simulations are recorded in the raster datasets used for this work, which report the inundation depth in each cell of the storm surge impacted area. While the data is reported based on the Saffir-Simpson hurricane scale, it is important to note that variables for each storm will change and generate different storm surge inundation zones, and these projections are only used for modeling purposes.
2.6. Correlating Urban Growth with Land Use and Environmental Factors using Suitability Factors

While the risk of storm surge threatens much of the Gulf and East coasts, there has been significant urban development in these areas due to the importance of ports and the appeal of coastal property. As storms continue to increase in frequency and magnitude due to climate change, it is important to understand the risks of further urban development in flood-prone areas. In order to account for the risk of developing in a flood-prone area, the projected storm surge depth can be used to create a weighted likelihood of development that impedes urban growth in higher flood risk areas (Hansen, 2010). Similar to the Hansen et al. study where “the 0 and 1 constraint values in the baseline scenario are replaced by fuzzy like values of 0.25 and 0.75”, the 0 to 1 urban change scale has been weighted by depth of storm surge with 0.75 representing the first 5 feet of depth, 0.5 to represent 5 to 10 feet of depth, and 0.25 representing more than 10 feet of depth (Hansen, 2010). The weighting ensures the maximum likelihood of transitioning to urban is restricted by the flood risk associated with living in an area susceptible to storm surge flooding.

2.7. Urban Growth and Population Projections

Urban growth and population growth trends have been linked together as urban areas need to expand in order to provide more housing and services for increasing populations. Egidi et al. (2020) found that “settlement expansion was progressively decoupled from population growth – with the former advancing more rapidly than the latter” (Egidi et al., 2020). Given the nature of urban expansion surpassing population growth in some areas, it is important to first look at urban growth as an indicator for future population growth and as an indicator for the community’s willingness to accept or avoid expansion into areas with higher flood risk. Urban planning can be a valuable non-structural measure to reduce the risk of storm surge damage to a coastal community and can protect infrastructure to make urban growth, and subsequent population growth, more sustainable (Correia et al., 1999).
2.8. Urban Growth and Environmental Factors Driving Population Trends

The final component of this work seeks to look at how urban growth, socio-economic factors and environmental factors including flood risk and climate change are driving population shifts in coastal areas. Hemmati et al. analyzed a set of studies focusing on the “effect of urban growth on exposure and risk assessment” and determined increased exposure of people and infrastructure to flooding particularly in areas with increasing population growth and economic development (Hemmati et al., 2020). The Climate Economic Justice Screening Tool (CEJST) developed by the Council on Environmental Quality (CEQ) utilizes key factors related to climate change, both environmental and socio-economic, to identify burdened communities in the U.S. (CEQ, 2023). These burdened communities are increasingly at risk of facing a flooding event. When faced with a devasting hurricane or flooding event, this increased exposure to populations living in areas that are at risk of flooding can cause mass evacuations or migrations of communities. In the year following Hurricane Katrina in 2005, over 200,000 residents of New Orleans left the city permanently (Hori et al., 2009).

2.9. Summary

The methodology for this study aims to analyze historical data for land use and environmental change in coastal areas to predict future shifts in land use related to development and environmental factors. The study employed Cellular Automata (CA) models to simulate changes in geographic patterns in natural and built environments and use transition rules and a Random Forest (RF) algorithm to predict land use change. The study also identified driving factors impacting land use and coastal population dynamics, including SLEUTH factors, and assessed the accuracy of the CA model through visual inspection and spatial overlay methods. Finally, this model has been used to understand how populations will shift around the coastal area and determine how the continued growth may burden communities that are threatened by climate change.
3. Using an Urban Growth Model Framework to Project the Impacts of Climate Change on Coastal Populations


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3.1. Abstract

Coastal populations are facing increasing environmental stress from coastal hazards including sea level rise, increasing tidal ranges, and storm surges from hurricanes. The East and Gulf Coasts of the United States (U.S.) are projected to face high rates of sea level rise and include many of the U.S.’s largest urban populations. This study proposes modelling land-use change and coastal change between 1996-2019 to project the impacts of intensifying coastal hazards on the U.S. Gulf and East Coast populations and to estimate how coastal populations are growing or retreating from high-risk areas. The primary objective is to develop a multifaceted spatial-temporal (MuST) framework to model coastal change through land-use projections and thorough analysis of the indicators of coastal urban growth or retreat. While urban growth models exist, one that presents an interdisciplinary evaluation of potential growth and retreat due to geographic factors and coastal hazards has not been released.

This study proposes modelling urban growth using geospatial metrics including topographic slope, topographic elevation, distance to existing urban areas, distance to existing roads, and distance to the coast. The model will also use historic hurricane data, including storm track and footprint for named storms between 1996-2019 and the associated flood claims data from Federal Emergency Management Agency (FEMA), to account for existing impacts from coastal storms. Additionally, climate change data including sea level rise projections and future tidal
ranges will be incorporated to project the impacts of future coastal hazards on urban expansion over the next 30 years (2020-2050). The basis of the urban growth model compares land-use change between 1996-2019 to complete a geospatial analysis of both the areas shifting from rural (agricultural, forest, wetlands) to urban, indicating change in population data from 2000-2020, to evaluate coastal retreat or abandonment over the next 30 years. It is expected that slow or no growth may indicate retreat from coastal areas, while urbanization and increasing population will indicate a shift towards coastal areas and growth.

3.2. Introduction

Coastal populations are facing increasing environmental threats from sea level rise and hurricane impacts. Hurricane Katrina inflicted devasting damage to New Orleans, Louisiana in 2005, while storms as recent as Hurricane Ian, making landfall in southwest Florida in 2022 have caused billions of dollars of damage to coastal urban areas and displaced large populations. It is important to understand how populations are reacting to storm impacts to project how coastal communities will change. This work uses an urban growth model to help predict how coastal areas are developing, in order to project population change. The population projections are further refined to include the impacts of climate change on coastal communities by overlaying hurricane paths and factoring in sea level change to model how increasing storm impacts may affect coastal development.

This paper presents the proposed framework and preliminary results from analyzing the observed population data and urban growth of the East and Gulf coastal areas. The results and analysis presented here are generated from a partial implementation of the framework for developing the coastal population predictive model; however, the complete analysis is still a work in progress.
3.3. Methods

In order to evaluate how coastal populations are changing, the population data used for this work is prepared by the Integrated Public Use Microdata Series (IPUMS) National Historical Geographic Information System (NHGIS), which provides United States (U.S.) census data on population statistics suitable for use in GIS (Manson et al. 2022). The population data considered as part of this work spans the decades of 2000, 2010, and 2020 focusing on the U.S. East and Gulf coast states including Texas, Louisiana, Mississippi, Alabama, Florida, Georgia, South Carolina, North Carolina, Virginia, Maryland, Delaware, Pennsylvania, New Jersey, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine. The NHGIS data provided by IPUMS is geographically standardized to the 2010 Census units, providing consistent geographic blocks to evaluate population change over time. The data includes statistical bounds capturing the potential population related to the 2010 boundaries in instances where the 2000 and 2020 census blocks changed shape. The time series data table provided by IPUMS has been linked to the NHGIS shapefile of U.S. Counties using the GISJOIN attribute, and the census blocks were aggregated up to the County level. This population data will be used to calibrate the urban growth model to the existing population change experienced in coastal areas over the 20-year period.

The population change shown between 2000 – 2020 will be evaluated against land-change and climate change indicators in order to predict how coastal populations will change between 2020 – 2050. The urban growth indicators include land-use, topographic slope, topographic elevation, distance to existing urban areas, distance to existing roads, and distance to the coast. The land-use change included in urban growth model compares the change between 1996-2019 using 1996 Coastal Change Analysis Program (C-CAP) Regional Land Cover and Change Data from National Oceanic and Atmospheric Administration (NOAA) as the initial land use dataset and the National Land Cover Database (NLCD) 2019 land cover data from the Multi-Resolution Land Characteristics Consortium at the United States Geological Survey (USGS) as the present-day dataset (Dewitz et al. 2021). These datasets were selected because both were readily available and provided complete land cover data for the contiguous U.S. The combination of these two datasets provides an extended study time-period that can be used for future projections. Both datasets are processed in RStudio to reclassify the land-use
codes to five general categories for comparison to determine areas that have urbanized over the period between 1996-2019 (R Core Team, 2021). These categories are urban, agricultural, forest, wetlands, and other.

In the 1996 dataset, NOAA tracks land-cover using Landsat Thematic Mapper imagery to categorize land-use into 26 categories ranging from 0 - 25 (Office of Coastal Management, 2022). For the purpose of this work, categories 0 (Background) and 1 (Unclassified (Cloud, Shadow, etc.)) have been excluded from consideration. Categories 2 – 5 have been reclassified to urban (1), categories 6 – 8 have been reclassified to agricultural (2), categories 9 – 12 have been reclassified to forest(3), categories 13 – 18 have been reclassified to wetlands(4), and categories 19 – 25 have been reclassified to other(5).

The 2019 dataset from the USGS also uses Landsat imagery to categorize land-use, consistent with the NOAA methods, into classes ranging from 11 – 95 (Dewitz and U.S. Geological Survey, 2021). Categories 22 – 24 have been reclassified to urban (1), categories 71 – 82 have been reclassified to agricultural (2), categories 41 – 52 have been reclassified to forest (3), categories 90 – 95 have been reclassified to wetlands (4), and categories 11, 21, and 31 have been reclassified to other (5). The comparison of these two land-use data sets will show urban development in the coastal region between 1996 – 2019.

In RStudio, the 1996 and 2019 datasets were compared using the classification codes described above to determine areas that experienced no change (codes were the same from 1996 to 2019) and areas that shifted to urban. The areas that shifted to urban were identified as areas coded as agricultural (2), forest (3), or wetlands (4) to urban (1) between the two datasets. The areas that shifted between other classifications were not evaluated as part of this work, because the focus of the model is on urban growth only. Areas that shifted from other (5) to urban (1) were not included as part of this work as they were unlikely to be developed and were assumed to be errors or irregularities in the data as they would indicate a shift from open water to urban or similar changes that are unlikely. Figures 3 and 4 on the following page show the urban change along the U.S. East and Gulf coast in the 150-kilometers (km) adjacent to the coastline, and the growth at a sample location of Houston, Texas to show the extent of growth captured at a larger scale.
Figure 3: U.S. East and Gulf Coast Urban Growth (150 km buffer)
The next urban growth factor evaluated as part of this work will be a digital elevation model (DEM) which accounts for the elevation along the coastal buffer. The DEM used for this work is the 1-meter DEM collected as part of the 3D Elevation Program (3DEP) from the USGS; this data holds the elevation layer of the Nation Map for the United States (U.S. Geological Survey, 2020). The elevation collected throughout the coastal region will be analyzed in relationship to urban growth and it will also be used when analyzing the impacts and projections for sea level rise and vulnerability to hurricane flooding. The DEM data will additionally be processed to calculate the slopes throughout the coastal buffer. The slopes calculated from the DEM data will further assist in modeling urban growth potential based on the land with would be developable based on the existing slopes.

The final urban growth factor evaluated as part of this work is the distance to existing roads from non-urban areas. It is expected that areas closest to other urban areas or existing roads will be the most likely areas to develop due to the ease of development and existing access to infrastructure. The existing roads data used for this work is the USGS Transportation data that is part of the Nation Map (U.S. Geological Survey, 2020). The roads data is analyzed in
ArcGIS using geoprocessing to determine the Euclidean distance to existing roads.

All of the urban growth indicators will be used to train a generalized linear model built in R to perform a statistical analysis of the impact of indicators on urbanization and help predict urban growth between 2020 – 2050. The results of this model will be used to correlate population growth with development. This will serve as the basis for the population projections.

In order to accurately account for climate change in the modeled population predictions, sea level rise and hurricane impacts will be used to force the population model. Sea level rise is quantified in this work by applying the sea level rise scenarios by applying the NOAA global and regional sea level rise scenarios for the U.S. (Sweet et al., 2017), where the Intermediate scenario will first be considered. The relative sea level change calculated as part of the 2017 NOAA et al. analyzes multiple projection scenarios, and for this work the Intermediate scenario will be included in the model to project sea level. The projected sea level change for 2030, 2040, and 2050 is added to each NOAA water level station along the coast to best model the local change along the entire coastline.

The final environmental factor included in this work is the hurricane track data to help determine if hurricane paths and the resulting impact from the storms is impacting coastal population change. The Hurricane Database (HURDAT2) storm data from the National Hurricane Center (NHC) provides post-storm data measuring the hurricane location and magnitude throughout the progression of each storm (Landsea et al., 2013). This data will be used to create a buffered area along each hurricane’s track to analyze population change in the buffered area. Additionally, the areas where there has not been a direct hurricane impact over the period of 2000 – 2020 will be analyzed to determine how the populations in those areas have been growing without the impact of a storm.
3.4. Preliminary Results

The initial result of the population analysis shows that when comparing the 2000 census data for population to the 2020 census data for population, the coastal counties see growth in many areas of the coast. The urban growth model shows coastal communities, specifically urban areas and cities, as continuing to develop and grow as well. However, there is a significant decline in population in the New Orleans, Louisiana area that is estimated to be a result of the 2005 storm, Hurricane Katrina. Figure 5 shows the population change in coastal counties along the U.S. East and Gulf coast in the 100 kilometers (km) adjacent to the coastline. Figure 6 shows this same date in more detail in the New Orleans, Louisiana area, showing the lasting impact on population resulting from Hurricane Katrina. This storm showed the extent of how devastating a storm can be to a coastal community and the lasting impacts on population and development that can result from a powerful storm.

Figure 5: U.S. Observed Population Change between 2000 – 2020 (150 km buffer)
This storm alerted many coastal communities to the risk of high intensity hurricanes and the need for coastal resilience and emergency preparedness plans. The State of Louisiana created the Coastal Protection and Restoration Authority (CPRA) following Hurricane Katrina and Hurricane Rita in 2005; the work completed by this Authority is focused on preserving the coastal area of Louisiana and serves as an example of the importance of coastal planning for ensuring future viability of coastal areas (CPRA, 2017).

3.5. Expected Results and Future Work

It is expected the majority of the Gulf and East Coast areas will show significant growth over the period from 2000 – 2020, particularly in existing urban areas. This growth will be further analyzed along the paths of hurricanes, where in some cases population in the area declined. The primary example of this population shift away from the coast is presented in New Orleans following the 2005 storm Hurricane Katrina.

In order to further isolate the direct impact of hurricanes on coastal populations, the population data will be further refined to include the 2010 census population data as another point to help
project population shift over a shorter period of time. If possible, the population data collected at more frequent intervals will be included to investigate storm impacts on population for each storm or hurricane season.

This work currently uses the 2017 NOAA Intermediate scenario projections for sea level change, but additional work will include the Low and High scenarios for sea level change to evaluate uncertainty in population change as it relates to uncertainty in sea level projections. Additional ocean impacts could include modeling the impacts of tidal ranges on storm intensity and flood risk to a coastal area and determining whether these factors increase the potential for hurricane to displace, temporarily or permanently, part of the population.

Future work will include the additional analysis of the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP) claims to identify damages resulting from storms and flooding and to identify areas that have not redeveloped as a result of storm damage. The intent of this work is to produce a coastal population model that will project the growth or retreat of coastal populations and the impact of climate change and hurricanes on those populations. This work can be used as a planning tool to protect coastal communities, and to inform local governments of the importance of risk management and master planning for resilience.

**Acknowledgments:** This material is based upon work supported by the National Science Foundation under Grant Nos 1735139 and 1920478 and by Virginia Tech’s Center for Coastal Studies.
4. Results of Using an Urban Growth Model Framework to Project the Impacts of Future Flooding on Coastal Populations


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4.1. Abstract

Coastal areas of the United States (U.S.) are facing increasing risk from the threats of tropical cyclones and storm surge while coastal metropolitan areas are continuing to urbanize. The demand for increased urban growth in coastal cities and encroaching sea levels has led to coastal populations living in areas at risk of damage from hurricanes. This work presents an urban growth model to predict urbanization in the coastal zone of the East and Gulf coasts of the U.S. The model is built using historic trends in land use and spatial and temporal characteristics such as elevation, slope, proximity to primary and secondary roads, and proximity to existing urban areas. Additionally, the model includes flood hazard data to determine if urbanization and population shifts are impacted by threats of storm surge in the study area. The results show that urban growth has occurred primarily in major metropolitan areas in coastal regions, and that hurricanes have impacted growth in historic data and should be considered when modeling future urban growth. The work also compares the model results with climate change metrics to identify burdened communities that may be impacted by urbanization. Overall, the model provides insights into future urban growth trends and their impact on environmentally vulnerable communities.
4.2. Introduction

The United States (U.S.) is experiencing a rise in urban populations across the country fueling urban growth in cities. Many of the largest cities on the East and Gulf coasts of the U.S. are situated on or near the coastline and are susceptible to coastal hazards including seal level rise, storm surge, and hurricanes. The vulnerability of coastal populations to storms encompasses topographic features and flooding from hurricane storm surge. By looking at historical trends in land use and urbanization, a cellular automata (CA) model has been built to analyze the trends in urbanization related to flood hazards and seeks to predict how urbanization will continue through 2050. The study area for this work is the 150-kilometers (km) adjacent to the coastline on the East and Gulf coasts of the U.S.

4.3. Methods

An urban growth model based on historical trends in land use has been built for this work to predict urbanization in the coastal zone of the East and Gulf coasts of the U.S (Naurath et al., 2023). The model references GeoTiff files of raster data for land use, topographic features, spatial features, and environmental risk data processed in ArcGIS Pro to simulate urban growth. All layers were clipped to a 150-km buffer from the coastline and resampled to a 1-km resolution using the majority of the area in each resampled area to form the cells of the resampled data. All maps presented as figures in this study show the data at 1-km resolution. Table 1 below provides an overview of the data included in this work. Further detail on the layers used for this study is provided in this section and in Appendix A.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Source</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Use/Land Cover</td>
<td>NOAA</td>
<td>1996</td>
</tr>
<tr>
<td>Land Use/Land Cover</td>
<td>USGS</td>
<td>2019</td>
</tr>
<tr>
<td>Elevation</td>
<td>USGS</td>
<td>2020</td>
</tr>
<tr>
<td>Slope</td>
<td>USGS</td>
<td>2020</td>
</tr>
<tr>
<td>Roads</td>
<td>U.S. Census Bureau</td>
<td>2019</td>
</tr>
<tr>
<td>Storm Surge</td>
<td>NOAA</td>
<td>2022</td>
</tr>
<tr>
<td>Population</td>
<td>IMPUS</td>
<td>2000, 2020</td>
</tr>
<tr>
<td>Climate Burden</td>
<td>CEQ</td>
<td>2023</td>
</tr>
</tbody>
</table>

Table 1: Summary of Layers
The urban growth model compares the change in land use between 1996 to 2019 using 1996 Coastal Change Analysis Program (C-CAP) Regional Land Cover and Change Data from National Oceanic and Atmospheric Administration (NOAA) and 2019 National Land Cover Database (NLCD) land cover data from the Multi-Resolution Land Characteristics Consortium at the United States Geological Survey (USGS) (Dewitz et al. 2021). The land uses identified in these datasets were generalized into categories of urban, agricultural, forest, wetlands, and other. The datasets were resampled to a 1-km grid to evaluate trends over the entire study area.

The model is further built out using spatial and temporal characteristics to predict likelihood of urban growth. These indicators include elevation, slope, proximity to primary and secondary roads, and proximity to existing urban areas. The elevation data used for this work has been sourced from the United States Geological Survey (USGS) in the Elevation Derivatives for National Application (EDNA) database derived from the National Elevation Dataset (NED). The raster dataset is at a 30-meter resolution across the entire study area. From this Digital Elevation Model (DEM), the slopes across the study area are extracted through the spatial analyst tool in ArcGIS Pro. In order to evaluate proximity to transportation, primary and secondary roads data was analyzed from the U.S. Census Bureau's Master Address File / Topologically Integrated Geographic Encoding and Referencing (MAF/TIGER) Database (MTDB). The Euclidean distance from all major roads was determined using spatial analyst tools in ArcGIS Pro. Similarly, the proximity to existing urban areas was also evaluated based on the Euclidean distance, and the urban areas were identified in the 1996 land use dataset from NOAA described above.

In addition to the geographic indicators for growth, a second alternative for the urban growth model is built to include flood hazard data to determine if urbanization and population shifts are impacted by threats of storm surge in the study area. The data selected for this work is NOAA and the National Hurricane Center’s (NHC) National Storm Surge Risk Maps, which simulate storm surge impacts along the entire U.S. coast for tropical cyclones (Zachry et al., 2015). It is important to note that there are a number of factors influencing the magnitude of storm surge from a hurricane including wind speed, central pressure, forward speed, size, angle of approach, slope of continental shelf running up to the coast, and other local features (Zachry et al., 2015). Some of these factors are not accounted for in the Saffir-Simpson hurricane scale that designates
the intensity of a hurricane in the range of a Category 1 to Category 5 intensity, and storm surge resulting from a given intensity storm can vary up to 30% within the category (Irish et al., 2008).

The raster data provided by NOAA shows the depth of inundation during the different storm intensity events at local high tide using input parameters of storm intensity, track, and size to determine the wind field associated with the storm, which is then used to project the storm surge (Zachry et al., 2015). For this study, the scenarios of a storm surge event predicted from the limited inputs accounted for in NHC’s storm surge model for Category 1 and a Category 5 hurricane are analyzed for impact on urban growth to determine if coastal populations are developing with consideration given to potential storm surge. For the purpose of this study, the output of NHC’s storm surge model will serve as a representative Category 1 and Category 5 hurricane, but it should be noted that there is significant variation in storm surge that can result from these intensity storms (Irish et al., 2008).

Using the NHC storm surge data, the areas estimated to be inundated by storm surge can be identified and evaluated for their suitability for development. The risk associated with developing urban areas in a flood-prone area should impact the way development occurs in coastal area; however, that is not always the case. In order to restrict the growth to account for flood risks, a suitability factor is applied based on the depth of inundation projected during a hurricane along the coastal area. Within the model, these suitability factors will lower the likelihood of growth in the high-risk areas and allow the model to shift projected development away from the flood-prone areas. The output of the initial urban growth model that does not account for flood risks can be compared with the output of the flood conscious model to determine if urban growth is occurring with consideration for flood risks.

Integrated Public Use Microdata Series (IPUMS) National Historical Geographic Information System (NHGIS) produces U.S. census data on population statistics that are standardized by geographic blocks (Manson et al. 2022). The census block group data provides information on local population changes that are analyzed decade over decade. For this work, the decades of 2000 – 2020 are compared to identify areas of population decline and areas of population growth. The population is evaluated at the level of census block groups.
Finally, the urban growth projected by the model has been compared to climate change metrics prepared by the Climate Economic Justice Screening Tool (CEJST). In the data provided generated by the United States Council on Environmental Quality (CEQ), “a community is highlighted as disadvantaged on the CEJST map if it is in a census tract that is (1) at or above the threshold for one or more environmental, climate, or other burdens, and (2) at or above the threshold for an associated socioeconomic burden.” (United States Council on Environmental Quality, 2023). The climate change burdened communities are identified by this tool and marked as disadvantaged if they meet low-income criteria and at least one of the following criteria: “expected agriculture loss rate, or expected building loss rate, or expected population loss rate, or projected flood risk, or projected wildfire risk.” (United States Council on Environmental Quality, 2023)

4.4. Results

The results for this work are reported in the following sections: initial data analysis, model validation, results from Scenario 1 (not including flood hazard metrics), and results from Scenario 2 (including flood metrics). Following the comparison of results between the two scenarios, an analysis on the correlation with U.S. population change and vulnerable communities will be presented.

4.4.1. Initial Data Analysis

The preliminary analysis required to evaluate and predict urban change starts with processing the historical data for land use collected between 1996 and 2019. Using the collected land use data from the 1996 NOAA dataset, the urban areas were identified and compared to the urban areas of the 2019 USGS dataset. The calculated difference between the urban areas in 1996 and 2019 is presented in Figure 7 showing the entire study area and the vicinities for the Houston, Texas and New Orleans, Louisiana metropolitan areas in Figure 8. A full-size map of the study area is provided in Appendix A.
Figure 7: Observed Coastal Urban Growth from 1996 to 2019

Figure 8: Observed Coastal Urban Growth from 1996 to 2019 in the Houston, Texas and New Orleans, Louisiana Metropolitan Areas
Much of the growth shown is clustered around major metropolitan areas such as Houston, TX and Washington, D.C. The coastal areas of Florida and Massachusetts also experienced significant growth in urban areas, while the Louisiana coastal areas show very little growth. This is likely due to the devastation of Hurricane Katrina, which made landfall in Louisiana in 2005 during this study period.

4.4.2. Model Validation

The urban growth model produced for this work can be trained using the above identified change in urban areas from 1996 to 2019 to predict the likelihood of future urban growth from 2020 to 2050 using a generalized linear model and a random forest algorithm. In order to confirm the validity of the model using this data, the 1996 existing urban areas were input into the model and the urban growth was predicted for 2019. The results of the predicted 2019 urban areas based on the actual urban areas in 1996 are presented in Figure 9. A regional map of the Gulf coast growth from Texas to Louisiana is presented in Figure 10 to show more defined growth at a larger scale. A full-size map of the study area is provided in Appendix A.
In order to evaluate the accuracy of the predictive model, the output data frame showing the likelihood of each cell to transition to urban is compared to the actual change in urban cells using a kappa coefficient confusion matrix evaluating the agreement between predicted and observed values (Tong and Feng, 2020). This method of evaluating model effectiveness is widely used for urban growth models and allows the evaluation of error types and comparison of each cell status (Tong and Feng, 2020). The confusion matrix measures the cells that were predicted to be non-urban and urban by the model and compares that to the actual measured cells that are observed to be non-urban and urban in 2019, with results presented in a summary table. The actual urban growth and predicted urban growth of each cell is listed in a matrix showing correct predictions highlighted in green and incorrect predictions without a background color. In addition to the overall accuracy of the predictions, two other measures of accuracy are also calculated in the confusion matrix: the Producer’s accuracy and the User’s accuracy. The User’s accuracy identifies Type 1 errors, or false positives, and describes the accuracy of the location of the cells predicted in the map. This represents the accuracy of the locations of the urban and non-urban cells throughout the study area. The Producer’s accuracy identifies Type 2 errors, or false
negatives, and describes the overall percent of correctly predicted cells in the map. This represents the overall accuracy of the classification scheme and how well the model performs over the entire study area.

The summary table detailing the agreement between the modeled and observed urban growth for the entire study area is provided in Table 2. The cells marked in green indicate the cells that the model correctly predicted for the non-urban (716,237) and urban areas (34,704). The remaining cells show the errors in the model prediction.

<table>
<thead>
<tr>
<th>Predicted Urban Growth</th>
<th>Actual Urban Growth</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Use</td>
<td>Not Urban (0)</td>
<td>Urban (1)</td>
<td>Sum</td>
<td>User’s Accuracy</td>
</tr>
<tr>
<td>Not Urban (0)</td>
<td>716,237</td>
<td>16,616</td>
<td>732,853</td>
<td>98%</td>
</tr>
<tr>
<td>Urban (1)</td>
<td>33,520</td>
<td>34,704</td>
<td>68,224</td>
<td>51%</td>
</tr>
<tr>
<td>Sum</td>
<td>749,757</td>
<td>51,320</td>
<td>801,077</td>
<td></td>
</tr>
<tr>
<td>Producer’s Accuracy</td>
<td>96%</td>
<td>68%</td>
<td></td>
<td>93%</td>
</tr>
</tbody>
</table>

Table 2: Model Correlation and Predicted Urban Growth from 1996 to 2019 Using a Kappa Coefficient Confusion Matrix

The accuracy for predicting non-urban areas is very high, likely due to the significantly higher number of non-urban areas in the coastal study area; this results in an overall accuracy of 93%. The Producer’s accuracy indicates the percentage of correctly predicted cells in the map (Tong and Feng, 2020). The model correctly predicted urban growth from a producer’s perspective for 68% of the urban cells. The values for overall accuracy, Producer’s accuracy, and User’s accuracy are consistent with other values for published urban growth models (Ke et al., 2015, and Oguz et al., 2007). A map showing the correctly and incorrectly predicted cells is provided in Figures 11 and 12.
One of the areas where the model varied from the actual growth is in the New Orleans area in Louisiana (Figure 12), where the model overpredicted urban growth. This overprediction is likely due to the model not accounting for the devastation of Hurricane Katrina in 2005 and the lingering effects of resettlement and rebuilding after the storm. Similarly, the predicted growth in the Houston, Texas area is overpredicted as it did not account for the number of displaced people who would move to the area after Hurricane Katrina. The estimated population loss reported in Hori et al. for Louisiana between 2005 and 2006 is over 200,000 residents, with many of the displaced residents reporting a move to Houston (Hori et al., 2009). While the model did more accurately predict urban growth around Houston, it could not account for the influx of new residents following a disaster. These predictions underscore the importance of understanding how tropical cyclones can impact urbanization and population shifts in coastal areas. Tables 3 and 4 detail the kappa coefficient confusion matrices for New Orleans and Houston, respectively.
### Table 3: Model Correlation and Predicted Urban Growth for New Orleans, Louisiana from 1996 to 2019 Using a Kappa Coefficient Confusion Matrix

<table>
<thead>
<tr>
<th>Actual Urban Growth</th>
<th>Land Use</th>
<th>Not Urban (0)</th>
<th>Urban (1)</th>
<th>Sum</th>
<th>User’s Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Urban Growth</td>
<td>Not Urban (0)</td>
<td>41,652</td>
<td>659</td>
<td>42,311</td>
<td>98%</td>
</tr>
<tr>
<td></td>
<td>Urban (1)</td>
<td>1,095</td>
<td>1,645</td>
<td>2,740</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>42,747</td>
<td>2,304</td>
<td>45,051</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Producer’s Accuracy</td>
<td>97%</td>
<td>71%</td>
<td></td>
<td>96%</td>
</tr>
</tbody>
</table>

### Table 4: Model Correlation and Predicted Urban Growth for Houston, Texas from 1996 to 2019 Using a Kappa Coefficient Confusion Matrix

<table>
<thead>
<tr>
<th>Actual Urban Growth</th>
<th>Land Use</th>
<th>Not Urban (0)</th>
<th>Urban (1)</th>
<th>Sum</th>
<th>User’s Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Urban Growth</td>
<td>Not Urban (0)</td>
<td>36,464</td>
<td>1,522</td>
<td>37,986</td>
<td>96%</td>
</tr>
<tr>
<td></td>
<td>Urban (1)</td>
<td>1,577</td>
<td>2,962</td>
<td>4,539</td>
<td>65%</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>38,041</td>
<td>4,484</td>
<td>42,525</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Producer’s Accuracy</td>
<td>96%</td>
<td>66%</td>
<td></td>
<td>93%</td>
</tr>
</tbody>
</table>

The smaller, primarily metropolitan areas included more urban density than the overall study area, and the confusion matrices for New Orleans and Houston return equal or higher overall accuracy than for the larger area. However, these areas have room for improvement that may be accounted for due to the impacts of storm surge and hurricanes on urban growth.
Figure 12: Correctly and Incorrectly Predicted Cells in the Gulf Region from 1996 to 2019 using the Urban Growth Model

4.4.3. Scenario 1

The historical change in urban areas was input into the model to predict the likelihood of urbanization in the study area under normal growth conditions, not accounting for environmental risk. Figure 13 shows the existing urban areas in 2019 and the likelihood of the remaining coastal study area to develop into urban areas by 2050, and Figure 14 presents a larger scale map of the Gulf coast modeled results. A full-size map of the study area is provided in Appendix A.
Figure 13: Projected Urban Growth from 2020 to 2050 using Urban Growth Model

Figure 14: Projected Urban Growth in the Gulf Region from 2020 to 2050 using Urban Growth Model
The predicted growth for the New Orleans area shows a low likelihood of growth in the coastal Louisiana area as a reaction to the low growth experienced from 1996 to 2019. The predicted growth is primarily clustered around the transportation corridor and farther inland from the Louisiana coast and around the Houston area. The model also predicts a high likelihood of growth throughout the coast of Florida, both on the East and Gulf coasts, clustered around the existing urban areas and spreading farther inland.

4.4.4. Scenario 2

For Scenario 2, the model is rerun to account for the risk of storm surge flooding to assess the impact of the risk on urban growth. The inundation thresholds were applied to the East and Gulf coasts to develop a mask over the areas projected to be inundated by storm surge during a Category 1 or Category 5 hurricane in the NHC model. The masked area applies a suitability factor based on the inundation depth during an event. Table 5 below shows the applied suitability factors corresponding to the inundation depth predicted.

<table>
<thead>
<tr>
<th>Inundation Depth</th>
<th>Suitability Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 5 feet</td>
<td>0.75</td>
</tr>
<tr>
<td>Between 5 and 10 feet</td>
<td>0.50</td>
</tr>
<tr>
<td>More than 10 feet</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 5: Applied Suitability Factors by Inundation Depth

The validation process was repeated for this Scenario, now comparing the predicted urban growth between 1996 and 2019 accounting for flood risks for storm surge events representative of a Category 1 or Category 5 hurricane with the actual growth between the same years. While the Category 1 storm surge did not cause much change in the results shown in the kappa coefficient confusion matrix due to the smaller storm surge inundation area and depth, the Category 5 storm did impact both the Producer’s and User’s accuracies. The overall accuracy is reported to be 93%, which is the same to the Scenario 1 results; however, the User’s accuracy for correctly predicting a change to urban increased to 80% while the Producer’s accuracy dropped to only 49%; this indicates that the map is more reliable on where the urban change occurs, but it omits more urban growth. The summary table detailing the results of the confusion matrix for the entire study area is shown in Table 6.
Table 6: Model Correlation and Predicted Urban Growth Accounting for Flood Risk from Storm Surge Representative of a Category 5 Hurricane Between 1996 to 2019 Using a Kappa Coefficient Confusion Matrix

<table>
<thead>
<tr>
<th>Predicted Urban Growth</th>
<th>Actual Urban Growth</th>
<th>User’s Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Land Use</td>
<td>Not Urban (0)</td>
</tr>
<tr>
<td></td>
<td>Not Urban (0)</td>
<td>706,703</td>
</tr>
<tr>
<td></td>
<td>Urban (1)</td>
<td>10,382</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>717,085</td>
</tr>
<tr>
<td></td>
<td>Producer’s Accuracy</td>
<td>99%</td>
</tr>
</tbody>
</table>

The Producer’s accuracy for this scenario is only 49% for predicting urban areas, which does not perform as well as the Scenario 1 model. This shortcoming may need to be further evaluated to improve this accuracy by either including actual storm surge data from historic storms from 1996 – 2019 to evaluate growth, or to revisit the suitability factor and inundation depth ranges. Figures 15 and 16 show maps of correctly and incorrectly predicted cells for Scenario 2 including the storm surge representative of a Category 5 Hurricane.
The model showed a small amount of improvement in the New Orleans and Houston areas (Figure 16), both in reliability. However, they did not show significant overall improvement, which indicates that urban growth is still occurring in areas that are inundated during a storm. The model used predicted storm surge data rather than actual storm surge data from historic storms. The model may be improved by including actual data that captures the frequency and magnitude of historic storm surge events to train the urban growth model. Tables 7 and 8 summarize the kappa coefficient confusion matrices for New Orleans and Houston, respectively.
### Table 7: Model Correlation and Predicted Urban Growth Accounting for Flood Risk from Storm Surge Representative of a Category 5 Hurricane in New Orleans Between 1996 to 2019 Using a Kappa Coefficient Confusion Matrix

<table>
<thead>
<tr>
<th>Predicted Urban Growth</th>
<th>Land Use</th>
<th>Actual Urban Growth</th>
<th>User’s Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not Urban (0)</td>
<td>Urban (1)</td>
<td>Sum</td>
</tr>
<tr>
<td>Not Urban (0)</td>
<td>41,200</td>
<td>1,547</td>
<td>42,747</td>
</tr>
<tr>
<td>Urban (1)</td>
<td>334</td>
<td>1,970</td>
<td>2,304</td>
</tr>
<tr>
<td>Sum</td>
<td>41,534</td>
<td>3,517</td>
<td>45,051</td>
</tr>
<tr>
<td>Producer’s Accuracy</td>
<td>99%</td>
<td>56%</td>
<td>96%</td>
</tr>
</tbody>
</table>

Table 8: Model Correlation and Predicted Urban Growth Accounting for Flood Risk from Storm Surge Representative of a Category 5 Hurricane in Houston Between 1996 to 2019 Using a Kappa Coefficient Confusion Matrix

<table>
<thead>
<tr>
<th>Predicted Urban Growth</th>
<th>Land Use</th>
<th>Actual Urban Growth</th>
<th>User’s Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not Urban (0)</td>
<td>Urban (1)</td>
<td>Sum</td>
</tr>
<tr>
<td>Not Urban (0)</td>
<td>36,018</td>
<td>2,023</td>
<td>38,041</td>
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<tr>
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<td>3,335</td>
<td>4,484</td>
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<tr>
<td>Sum</td>
<td>37,167</td>
<td>5,358</td>
<td>42,525</td>
</tr>
<tr>
<td>Producer’s Accuracy</td>
<td>97%</td>
<td>62%</td>
<td>93%</td>
</tr>
</tbody>
</table>

The Producer’s accuracy for these individual metropolitan areas is higher than for the entire study area, indicating that this scenario may be better suited for modeling at the city scale. As seen in Figure 16, in the New Orleans area, there are less incorrectly predicted cells in the coastal delta area surrounding New Orleans compared to the Scenario 1 validation map presented in Figure 12.
Figure 16: Correctly and Incorrectly Predicted Cells in the Gulf Region from 1996 to 2019 using the Urban Growth Model Accounting for Suitability from Category 5 Hurricane Flood Hazard Potential

After evaluating the confusion matrices for the flood risk scenarios, the projections can be applied to model the future. With these suitability factors added to the flood impacted areas, the model is rerun to determine areas that are most likely to transition to urban between 2020 and 2050. The results of the modeled suitability impacted likelihood of urban growth have been overlaid for both the Category 1 Hurricane flood hazard in Figure 17 and the Category 5 Hurricane flood hazard in Figure 18. Both figures show the Houston to New Orleans area to compare how the model changes recommendations based on the flood hazard and to evaluate if the consideration of flood potential impacted the model to fix a weakness determined in Scenario 1. Much of the urban development that was projected for the coastal areas that are in the storm surge inundation zone has been pushed farther inland. The full-size maps showing the entire study area can be found in Appendix A.
Figure 17: Projected Urban Growth in the Gulf Region Accounting for Suitability from Category 1 Hurricane Flood Hazard Potential from 2020 to 2050 using Urban Growth Model

Figure 18: Projected Urban Growth in the Gulf Region Accounting for Suitability from Category 5 Hurricane Flood Hazard Potential from 2020 to 2050 using Urban Growth Model
By accounting for the impact of risk of storm surge from a Category 1 or Category 5 storm, the urban growth likelihood significantly drops in the low-lying coastal area of Louisiana. Some of the growth previously shown around the New Orleans area and north towards the transportation corridor in Louisiana has shifted to more suitable areas around Houston, seen in Figure 16 in the darker green. This shift echoes the transition of the New Orleans population to the Houston area following Hurricane Katrina in 2005. Given the results of the evaluation of the confusion matrices used to validate this work, the results show a shift away from the higher risk areas and push it towards higher elevation urban areas.

4.4.5. Population Shifts Driven by Urban Growth and Storm Impacts

These shifts of urbanization are echoed in population statistics showing population change between the 2000 and 2020 census. Figure 19 below shows the change in population throughout the coastal areas relating to urban growth. Figure 20 shows the population growth in Houston and decline in New Orleans compared to the projected urban growth. The full-size maps showing the entire study area can be found in Appendix A.
4.4.6. Populations Burdened by Climate Change

The Houston area shows high rates of population growth in the city and surrounding county that correlates with the projected urban growth for the area. In contrast, the New Orleans population has declined since 2000, and the area shows significantly less likelihood for urban growth. Throughout the coastal region, the projected urban growth is primarily clustered around existing cities, which follows population trends that show increases in urban populations and decreases in rural populations. The decrease in population rate is one of the metrics measured by CEQ and factored into the CEJST screening for the burden of climate change. The tool also identifies flood hazard as a contributing factor to climate change vulnerability, which is shown by this study to impact urban growth and populations. Figure 21 shows a map for the census block groups identified as burdened by climate change.
Figure 21: CEJST Identified Communities Burdened by Climate Change

The coastal region of Louisiana that has been thoroughly studied in this work is identified as burdened under the flood hazard and population loss (CEQ, 2023). Conversely, much of the area surrounding Houston does not qualify under CEQ metrics. Much of the northern East coast also does not qualify, but the majority of the coast of North Carolina and South Carolina does qualify. The results of this modeling study can help to identify areas for future growth and caution against growth in unsuitable areas to account for burdens of climate change.

4.5. Summary and Conclusions

The rise in urban populations across the United States has led to urban growth in many of the largest cities on the East and Gulf coasts, making them susceptible to coastal hazards such as storm surge, and hurricanes. To model this issue, a cellular automata (CA) model has been developed using historical trends in land use to analyze and predict urban growth in the 150-kilometer adjacent to the coastline on the East and Gulf coasts of the U.S. The model takes into account spatial and temporal indicators, such as elevation, slope, proximity to transportation and existing urban areas, and flood hazard data. The results of this study show that integrating flood hazard metrics in urban growth modeling can have significant impacts on accurately projecting
coastal growth, and identify areas that area suitable for growth, which is especially for vulnerable communities. The confusion matrix results for both scenarios are shown to have overall accuracies that are consistent with other published models, and the user’s accuracy for Scenario 2 showed that the inclusion of storm surge suitability factors can improve the reliability of the model; however, the producer’s accuracy needs to be improved over the entire study area (Ke et al., 2015, and Oguz et al., 2007). Such studies are crucial in informing policy and decision-making for sustainable urban planning in the face of climate change.

**Acknowledgments:** This material is based upon work supported by the National Science Foundation under Grant Nos 1735139 and 1920478 and by Virginia Tech’s Center for Coastal Studies.
5. Summary and Conclusions

The urban growth models used for this work projected growth under scenarios accounting for spatial and temporal features, and it evaluates the impact of the increasing environmental threats faced by coastal populations due to storm surge and hurricanes. This work used a framework for an urban growth model to predict how coastal areas will develop and how population changes will occur. The basis of the study used historic land use data from 1996 to 2019 along with population data spanning the years 2000 to 2020. The land use data is used to calibrate the urban growth model and to evaluate land change and climate change indicators, including topographic slope, elevation, distance to existing urban areas, roads, and the coast. The environmental threat of coastal storms is modeled using storm surge inundation projections and suitability factors. The suitability factors are used to generate a mask that is applied to the inundated area to restrict growth in the areas with high flood risk. Finally, this study analyzes the observed population data and urban growth of the East and Gulf coastal areas and compares it with environmentally burdened populations.

The results from the validation for the models indicate that both urban growth models, with and without consideration for environmental hazards, are able to predict the likelihood of urban growth effectively. The two models do have different strengths in predicting growth as shown by the kappa coefficient confusion matrices. The Scenario 1 model better predicts urban growth throughout the study area, while the Scenario 2 model is more reliable in showing the locations where urban growth is most likely to occur. These conclusions indicate that the addition of environmental risk aids in the reliability of the model, and it is more likely to predict change in the correct locations. However, the growth is more accurately captured by the Scenario 1 model excluding environmental factors. The Scenario 2 model is more likely to miss actual changes in urban growth, which may lead to the conclusion that urban growth is still occurring in areas that are at risk for flood inundation during a storm. In order to raise the producer’s accuracy for Scenario 2, the suitability factor values and corresponding inundation depth ranges could be revisited to determine the sensitivity of the model to changes in those factors to better capture the overall transitions to urban throughout the study area.

The population data evaluated as part of this work more closely agrees with the Scenario 2 model when looking specifically at the areas of New Orleans, which experienced catastrophic flooding.
from Hurricane Katrina in 2005, which was within the time period for both land use change and population change for this study. The area showed some of the largest population decline over the study period of 2000 to 2020, and much of the New Orleans metropolitan area has been identified as burdened by climate change. The consideration for inundation risk is important to evaluate to understand and better predict with higher reliability the areas that will urbanize. This information is important to local governments protecting their communities and evaluating the areas at risk of storm surge as hurricanes impact their coastal areas. It can further be used as a tool for understanding the risks of approving further development in areas that have higher flood risks.

The results of this study indicate that urban growth is occurring around coastal metropolitan areas, and this growth can be modeled using a CA model with spatial and temporal factors determining the transition rules of cells across the study area. The results of the validations for both the Scenario 1 and Scenario 2 models show that the inclusion of storm surge inundation data in the model can make the projections more reliable in determining the precise locations where growth will occur; however, it does not make model overall more accurate. This conclusion signifies that urban growth is most easily predicted in areas that are outside of the storm surge inundation zone, and that growth may still occur within the areas designated as less suitable by their risk for storm surge inundation.

The models for this work analyzed the entire study area, including the 150-km buffer area of the East and Gulf coasts. While the data was also presented for the metropolitan areas of Houston and New Orleans, the model was not rerun based only on the data for these areas. The spatial scale of the input data likely influences the accuracy of the overall model since it is predicting growth over such a larger area. While this model is able to predict growth throughout the large study area with acceptable accuracy, the accuracy of the model could be improved by looking at smaller study areas, like individual metropolitan areas, with unique regional or local factors accounted for in the input data.

The factors that best predicted growth in the study area for both scenarios are the distance to existing urban areas and distance to existing roads. The elevation and slope factors did not contribute as much to the accuracy of these models, likely due to the nature of the coastal area
having relatively low elevation throughout and flatter slopes throughout the coastal zone. This study would benefit from the inclusion of more environmental and socio-economic factors that may be able to improve the accuracy of the models. The recommended future work for this study is to increase the factors integrated into this urban growth model and incorporate sea level rise projections for the time period of 2020 to 2050, and the distance to urban areas that have filed flood claims through the National Flood Insurance Program. This data will provide insight into how coastal communities are preparing for future climate change and if past disasters are a deterrent for future growth in the neighboring areas. The sea level rise data provided by NOAA in 2017 can be used to determine the location of the future shoreline, and the storm surge inundation can be more accurately predicted based on that location through 2050.

This work could also benefit from more detail population trend analysis including dasymetric mapping of U.S. Census population data to determine trends at a finer scale. By looking at population changes at a larger scale and the relationship to land use, the model may be able to better identify areas that are designated as urban but may have experienced damage from storms leading to the area no longer being inhabited. The identification of areas where populations have been forced out due to inhabitable conditions will likely still be shown in the land cover data as urban, so it is important to identify those areas to understand the population dynamics of the area and to discourage growth from occurring in places that are prone to frequent storm damage.
References


CPRA. (2017). Louisiana’s Comprehensive Master Plan for a Sustainable Coast; Coastal Protection and Restoration Authority: Baton Rouge, LA, USA.


U. S. Council on Environmental Quality, “Climate and Economic Justice Screening Tool (Beta).”


Appendix A

Additional Mapping
Projected Urban Growth from 2020 to 2050 using Urban Growth Model

Figure A-3
Projected Urban Growth Accounting for Suitability from Category 1 Hurricane Flood Hazard Potential from 2020 to 2050 using Urban Growth Model

Figure A-4
Projected Urban Growth Accounting for Suitability from Category 5 Hurricane
Flood Hazard Potential from 2020 to 2050 using Urban Growth Model

Figure A-5
U.S. Population Change between 2000 and 2020 Compared to Existing Urban Areas and Projected Growth between 2020 and 2050

Figure A-6