An examination of land use impacts of sea level rise induced flooding

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Abstract. Coastal regions become unprecedentedly vulnerable to coastal hazards that are associated with sea level rise. The purpose of this paper is therefore to simulate prospective urban exposure to changing sea levels. This article first applied the cellular automaton-based SLEUTH model (Project Gigalopolis, 2016) to calibrate historical urban dynamics in Bay County, Florida (US~~A~~)–a region that is greatly threatened by rising sea level~~s variations~~. This paper estimated five urban-growth parameters by multiple-calibration procedures that used different Monte Carlo iterations to account for modelling uncertainties.~~increasingly accurate levels of calibration. A four-stage calibration was done by running four, seven, nine, and one hundred Monte Carlo iterations in each step so as to account for modelling uncertainties.~~ It~~The paper~~ then employed the calibrated model to predict three scenarios of urban growth up to 2080–historical trend, ~~compact development, and~~ urban sprawl, and compact development. We also assessed land-use impacts of four~~various~~ policies: no regulations; flood~~ing-risk~~ mitigation~~s~~ plans based on the whole study region and on those areas that are~~the Areas~~ prone~~More Likely~~ to e~~E~~xperience g~~G~~rowth; and the protection of conservational lands. ~~conservation land protection.~~T~~ Eventually, t~~his study lastly overlaid projected urban areas in 2030 and 2080 with 500-year flooding maps that were developed under~~under~~ zero, 0.2-m, and 0.9~~-~~m sea level rise~~ with forecasted urban areas~~. The calibration results ~~show spillover effect is the most significant urban-growth force, indicating~~ that a substantial amount of~~substantial~~ built-up regions extend from established coastal settlements. The predictions suggest that ~~As demonstrated by the predictions, if the urbanisation progresses with few policy interventions,~~ total flooded area of new urbanised~~built-up~~ regions in 2080 would be more than 25 times that under the flood~~ing-risk~~ mitigation policy, if the urbanisation progresses with few policy interventions. The joint model generates new knowledge in the domain~~coupled field~~ between land use modelling~~urban growth~~ and sea level rise. ~~As a decision support tool, I~~It ~~also offers actionable information on~~contributes to coastal spatial planning by helping develop hazard mitigation schemes~~planning~~ and can be employed in other international communities that face combined pressure of urban growth~~isation~~ and climate change.

1 Introduction

Coastal areas are the most intensively exploited places where urban expansion largely alters natural landscape. As land-sea interfaces, however, these~~coastal~~ regions are featured by various conflicts between anthropogenic pressures and natural sustainability. Moreover, such conflicts have become~~ been~~ exacerbated in recent years. While coastal zones increasingly attract population and investments, their communities are~~become~~ more aware of the intensified frequency of natural incidents and possible associations with climate change. It is evident that c~~C~~limate change partly ~~is likely to~~ contribute to intensified hurricanes and floods (Hsu, 2014), rising sea level (IPCC, 2013), and other coastal hazards. Moreover~~ specifically~~, S~~s~~ea L~~l~~evel R~~r~~ise (SLR) may worsen~~worsen~~ coastal flooding, land submergence, and saltwater intrusion~~ (SLR)~~ (Nicholls and Cazenave, 2010). According to the fifth~~ assessment~~ report published by the Intergovernmental Panel on Climate Change (IPCC) in 2013, ~~by 2100~~ approximate 70% coastlines will experience rising sea levels by 2100. Nonetheless~~However~~, ~~different stakeholders—residents, tourists, and~~ developers, business owners, and other stakeholders will ~~—~~still continue to compete for limited coastal resources, and the competition has been even more intense. Developers expedite new real estate projects; local governments offer appealing incentives to attract new infrastructure investments; and Coastal areas attract more residential projects and infrastructure investments; companies extensively extract oil and natural gas in offshore regions (Felsenstein and Lichter, 2014). Since coastal zones are both battlegrounds of conflicting interests and vulnerable low-lying places and the battleground of conflicting interests, coordinating land uses, hazard mitigation, and different interests has become everlastingly important. SuchThe coordination, therefore, calls for effective tools to inform assist in the formulation of coastal management plans. Moreover, spatial planning plays a pivotal role in a pivotal part of these schemes is spatial planning, which can be guided by Land Use/Land Cover Changes (LULCC).

Various techniques can helphave been applied to detect LULCC patterns. The class of Cellular- Automaton (CA) models receive wide attention around the world due to their simplicity and effectiveness in capturing complex urban dynamics (Akın et al., 2014). The operationalization of CA in modelling urban phenomena was first introduced by Clarke et al. (1997) who designed the prototype of SLEUTH–a CA-based urban simulation program. In their model, each cell had a state which updated at consecutive every time pointsstep according to predefined a predefined set of transitional rules. These rules took into accountintegrated the current condition of a cell, and its neighbours, and as well as environmental constraints. Numerous A wide range of models and software packages have developed since the introduction of CA. Santé et al. (2010) evaluated thirty-three CA models and concluded that the two widely applied models were SLEUTH gained more popularity than the other alternatives. The Sand another package developed by White and Engelen (2000). SLEUTH has been adopted by urban researchers all over the world since 2000 (Project Gigalopolis, 2016). Its popularity is partly due to free availability, user-friendliness, simple data inputs, and well-developed– (Sekovski et al., 2015)(Sekovski et al., 2015)(Sekovski et al., 2015)(Sekovski et al., 2015)(Sekovski et al., 2015)(Sekovski et almanuals, and a support forum. An elegant feature of the SLUETH is the application of excluded layers. These layers denote different scenarios in a calibration procedure so as to exemplify how policies influence the expansion of built-up regions (Akın et al., 2014). Recently, SLEUTHSLEUTH was improved by the incorporation of external information induring the excluded layers calibration. Rienow and Goetzke (2015) used the support vector machine to enhance the predictive power of SLEUTH's predictive power by developing probability-based excluded excluded layerslayers for future scenarios. Likewise, Sakieh et al. (2015) applied a multi-criterion evaluation method to develop generate suitability-based surfaces as policyexcluded layers.

Based on historical urban expansion patterns, Sscenario-based SLEUTH and other CA and other CA models can also forecastsimulate future land use, based on historical urban expansion information. By applying a constrained CA model, Hansen (2010) simulated future land conditions under different emission scenarios developed by the IPCC (2013). The author and concluded that significant areas in Aalborg would would be increasingly exposed to futuredeal with potential flooding hazards. Although the author incorporated adaptation strategies in his model, Hansen (2010) further suggested that more aggressive strategies, such as population relocation and managed retreat, may be evaluated in future simulations. SimilarlySimilarlyLikewise, Sekovski et al. (2015) assessed the impacts of coastal flooding upon urban growth using the SLEUTHSLEUTH model. Inouye et al. (2015) applied a comparative modelling approach to validate the importance of zoning in land useurban growth simulations. By applying a CA package (the Dynamic EGO) software, they statedstated that the developments in ecological-economic zones might heightened future urban exposurethe vulnerability to to land sliding, intensified precipitation, SLR, and other coastal hazards. Their results provide actionable information to decision makersgreatly benefit the formulation of to develop relocation, planned retreat, and other adaptation strategiespolicies. More specificallyIn addition, some researchers also highlighted the importance of zoning information in SLEUTH applications. Akin et al. (2014) used future current zoning maps as excludedexcluded layers and evaluated the accuracy of hindcasting-based calibration. Onsted and Chowdhury (2014) employed a historical zoning map in their SLEUTH model and suggested that land use planning~~zoning~~ strongly influenced urban growth in Florida.

While the majority of SLEUTH applications focused on different urban forms (e.g., urban sprawl)~~urban sprawl, other urban forms and,~~ their exposure to flooding received less attention. To the best of our knowledge, only two studies (Garcia and Loáiciga, 2014; Sekovski et al., 2015) attempted to couple land use predictions with marine flooding maps using ~~SLEUTH~~SLEUTH. The combination of SLEUTH simulations and flooding hazard maps, however, should be prioritised ~~in coastal land use modelling~~ to enhance~~inform~~ spatial management (Onsted and Chowdhury, 2014). Therefore, this study aims to evaluate the extent to which SLR-induced flooding will threaten different urban growth patterns using SLEUTH urban growth model ~~may be exposed to SLR-induced flooding~~. Specifically, two research questions of this study are:

1. How does~~may~~ different urban growth patterns affect~~increase~~ coastal~~regional~~ vulnerability to SLR-induced flooding?
2. Will ~~Would land use~~ zoning and flood~~ing~~ mitigation plans help ~~to~~ steer prospective developments away from low-lying~~flood-prone~~ regions?

This paper is organised as follows. Section 2 describes our~~the~~ study area and why this region was selected as a case study ~~and data collection~~. Following this, section 3 illustrates an~~the~~ overall ~~modelling~~ framework, describes data inputs, and outlines major steps for the calibration and prediction of urban growth in the study area~~calibration, prediction~~ as well as ~~, and the~~ the development of SLR-induced flooding maps~~floodplain generation~~. In section 4 we present the calibration coefficients and discuss forecasting outcomes that were overlaid with flooding maps. Finally, section 5 offers a brief conclusion and provides the outlook for future research.

2 Study area ~~and data description~~

2.1 Background

This work selected Bay County in Northwest Florida (~~,~~ US~~A~~) ~~,~~ as a primary case study region. Bay County and its adjacent areas (Washington and Walton Counties) were used to prove~~test~~ our hypotheses based on two considerations: high exposure to coastal hazards and SLR that are experienced in the majority of worldwide coastal zones ~~globally~~; and data availability for modelling. Bay County has a long shoreline along the Gulf Coast (Figure 1). It is representative in the context of climate change, since it faces unprecedented and accelerated threats from storm surges, hurricanes, and projected sea level variations. Similar exposure~~vulnerabilities~~ ha~~s~~ve been demonstrated in the European coastline (Vousdoukas et al., 2016), West U.S. Coast (Ludy and Kondolf, 2012), South Vietnam (Apel et al., 2016), and many other coastal megacities around the world.

Figure 1 about here

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Specifically, Bay County's exposure to marine disasters~~SLR~~ is pronounced. ~~Historically, T~~th~~is~~e coastal county~~zone~~ has been hit by seventeen hurricanes since 1877 (Hurricanecity, 2015). Among these incidences, Hurricane Eloise in 1975 led to enormous ~~$23.1 million~~ damages in structures, seawalls, and patios ~~–~~equivalent up to $23.1 million (Shows, 1978). Moreover, land development patterns render this region extremely susceptible to ~~storm surges and~~ hurricanes and SLR. A considerable amount of~~Considerable~~ ~~residential and commercial buildings~~ structures encroached upon seafront areas in Panama City due to the absence of land use regulations in the past~~; as a result, urban growth largely occurs in flood-risk zones~~ (Bay County Online, 2016). Primary industrial sectors in Bay Country, as in other coastal communities, are largely susceptible to coastal hazards as well. Bay County relies on tourism related industries which are deemed vulnerable to ~~in the face of~~ rising sea levels (Ebert et al., 2016). ~~In Bay County, the total spending on tourism as of June 2015, which was $121 million, had doubled since 2008 (Bureau of Economic and Business Research, 2015).~~ Bay County has 10,222 firms, of which approximate 90% are small businesses. Unfortunately, s~~S~~mall companies have insufficient resources to cope with storm surge, flooding, and other environmental disasters (Runyan, 2006; Song et al.~~, Peng, Zhao, & Hsu~~, 2016).

The second rationale for choosing Bay Country is the data variability for modelling. This work used an integrative framework, requiring high-quality data sets regarding land cover and hydrological factors. Land use data can be obtained from different sources ~~(such as local GIS department and satellite-image vendors)~~. However, ~~Generating~~ generating SLR-induced flooding maps requires sufficient observations at local and global levels, hurricane records, and many other ~~high-quality~~ marine and meteorological variables~~—~~—these are available for the study area. ~~These reasons, as mentioned above, justify the selection of Bay Country, Florida (USA).~~ Based on these considerations, we chose Bay County to explore the research questions.

~~**FIGURE 1 ABOUT HERE:** The study area.~~

~~**FIGURE 2 ABOUT HERE**: Historical urban changes (left) and current land uses and zones (right) for the study area.~~

2.2 Urban change and zoning

Figure 2 ~~displays historical urban growth and current land use zoning for the study area. It~~ displays~~indicates~~ that urban extent expanded primarily in the southern part of Bay County and~~. As shown in Figure 2, urban developments~~ largely conformed to historical trends. A multitude of ~~Substantial~~ ~~commercial and~~ residential developments~~developments~~ occur in Panama City and shoreline regions~~two major cities: Panama City Beach and Panama City~~. ~~In~~ A~~a~~dditionally, ~~a large piece of land~~many areas in the north ~~region~~ are~~is~~ zoned for residential uses. This information suggests that local governments and planning agencies have taken measures to encourage spatially diverse~~inland~~ developments. There exists, however, an apparent discrepancy between zoning and urban growth: a substantial amount of~~. Substantial~~ urban~~built-up~~ areas have appeared in ~~the Towns of~~ Fountain and Youngstown. Nonetheless, the zoning unclearly reflects this pattern, and ~~such a patter n is not seen on the zoning map where~~ only some areas are designated for the residential land use ~~use~~ in the two towns. This inconsistency implies~~suggests~~ that planners need a comprehensive understanding of past land use changes ~~is required~~ to better design~~inform~~ zoning schemes~~prospective land use zoning better~~.

Figure 2 about here

~~**2.3 Data description**~~

~~**TABLE 1 ABOUT HERE**~~

~~Land use and SLR data were prepared for this study. The land use data included five remotely sensed images on 1974, 1995, 2004, 2007, and 2013; these data were obtained from the Florida Geographic Data Library. These data sets were categorised into nine level-one land cover classes, among which the built-up land was coded as one, according to the Florida land use, cover and~~

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forms classification system published by the Florida Department of Transportation (1999). Flooding hazards and zoning information were also collected. Two Flood Insurance Rate Maps (FIRM), developed by the U.S. Federal Emergency Management Agency, were downloaded from the Florida Geographic Data Library. Current zoning map and the comprehensive plan for the study area were obtained from the online GIS websites of Bay County and Washington County. The zoning map specified exactly the degree to which different land uses were allowed for urban developments. According to the Bay County Comprehensive Plan (2009 to 2020), the zoning regulations are shown as follows:

-Developments were not allowed in the zone of conservation (for the preservation purpose), and impervious areas must be no more than 5%;

-In the area of conservation (for the habitation purpose), impervious surface must be no more than 50%;

-In the zone of conservation (for the recreation purpose), impervious coverage must be no more than 10%; and

-In the zones of agriculture (for the timberland purpose) and agriculture, impervious areas must be no more than 10% and 25% respectively.

Finally, the data of projected SLR and sea surface temperatures were collected from the fourth assessment report published by the IPCC (2007). Table 1 displays detailed information regarding all data sets.

3 Methodological approach

FIGURE 3 ABOUT HERE: Overall study framework. HUG is historical urban growth; USG is urban sprawl growth; and CUG is compact urban growth.

Figure 3 displays the overall research framework. Specifically, the technical Theroadmap workflow for this research was organized into four phases: 1) data collection and pre-processingthe preparation of input layers, 2) the calibration in the SLEUTH environment, 3) the simulationspredictions of urban growth up to 2080 under the combined scenarios of different urban-growthdevelopmental patterns and various excluded layers, and 4) the comparisonoverlaying of urban growthfuture urban areasestimates and 500-year flooding maps that were induced by SLR. Figure 3 displays the overall research framework. The frameworkoutline has two major tasks: the SLEUTH urban growth model and SLR-induced flooding maps, as will be discussed in the following sections.

Figure 3 about here

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3.1 Rationale for model selection

We applied SLEUTH as a generaln overall modelling architecture based on the following reasons. SLEUTH is a CA-based program which only relies on five inputs: urban, transportation, slope, hillshade, and exclusion, and thus it is moderately data driven. First, The family of CA models has gained more popularity than other modelling techniques. CA models are advantageous over other counterparts due to their spatial explicitness, flexible transitional rules, compatibilitypowerful performance with large data sets (Wagner, 1997), and easy integration with ArcGIS®Geographical Information System (Santé et al., 2010). Second,

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SLEUTH only relies on five inputs: urban, transportation, slope, hillshade, and exclusion.~~Furthermore, the SLEUTH model was selected for this research because of the following considerations.~~ Third~~First~~, ~~-~~SLEUTH employs excluded layers ~~as probability maps which specify developmental potentials over a study region (~~where a~~the~~ cell value of zero represents an attracting point for development, and 100 or higher reflects that urbanization~~development~~ is strictly prohibited~~)~~. Such a functionality makes SLEUTH an excellent platform for scenario-based studies (Leão~~, Bishop, & Evans~~ et al., 2004~~; Jeffrey A. Onsted & Chowdhury, 2014~~). ~~Second, SLEUTH uses five parameters—dispersion, breed, spread, road gravity, and slope—to establish transition rules which determine whether or not a cell is urbanised (Project Gigalopolis, 2016).~~ Finally, its~~the~~ calibration process applies a "brute force" approach and is scientifically sound for regional studies ~~-~~(~~Jeffrey A~~ Onsted and~~&~~ Clarke, 2011).

3.2 An introduction to SLEUTH

3.2.1 Background

SLEUTH is a packed C language-based source code that was developed by Dr Keith C. Clarke at the Department of Geography, University of California Santa Barbara. The source code is freely available through its official website called "Project Gigalopolis" (http://www.ncgia.ucsb.edu/projects/gig/index.html).

SLEUTH has two modules: the ~~the~~ Urban Growth Model and the ~~the~~ Land Cover Deltatron Model. The Urban Growth Model mainly focuses on ~~the~~ urban/non-urban dynamics and thus~~. Modellers adopted it more frequently than the Land Cover Deltatron Model which investigates changes among different land cover classes. The Urban Growth Model is, therefore~~ ~~,~~ a primary focus of this work.

3.1.2 SLEUTH workflow

SLEUTH is a scale-independent CA model that updates the binary state of each cell per growth cycle. A growth cycle is one year and determined by four rules ~~consists of four steps~~: spontaneous growth, new spreading centres, edge (organic) growth, road-influenced growth (Clarke et al., 1997). These transitional rules are controlled by one or more ~~parameters that were mentioned previously~~of the five parameters: dispersion, breed, spread, road gravity, and slope (Project Gigalopolis, 2016). Each parameter, with ~~which has~~ a value range of 1 to ~~–~~100, is dimensionless and can be compared regarding their contributions to overall growth. Specifically, the dispersion factor determines the probability by which a cell will be randomly selected for urbanisation (Silva and~~&~~ Clarke, 2002). The breed factor determines the likelihood by which a ~~newly formed~~new urban cluster will start its growth cycles (Berberoğlu et al.~~, Akın, & Clarke~~, 2016). The spread factor controls how likely outward growth will develop near an existing settlement. The road gravity factor demonstrates the influence of road systems upon land use~~urban growth~~ by attracting new developments~~settlements~~ that are within a certain distance of a road (Silva and~~&~~ Clarke, 2002)~~ (Rafiee, Mahiny, Khorasani, Darvishsefat, & Danekar, 2009)~~. Finally, the slope factor calculates~~determines~~ how likely a cell with a steeper slope will be urbanised (Rafiee et al.~~, Mahiny, Khorasani, Darvishsefat, & Danekar~~, 2009). Table 1~~2~~ summarises the relationships between transitional rules and five parameters.

Table 1 about here

The main workflow of a SLEUTH application includes input compilations, a calibration process based on actual urban growth, and predictions. The Urban Growth Model requires at least four maps of different dates which show obvious urban changes. Two road networks of different periods and one percentage-slope map are additional date sets. An optional hillshade map is used to improve visualisation performance. The goal of the calibration is to select a combination of the parameters that best replicate historical urban changes. This process, however, is enormously time-consuming if modellers assess all combinations–up to 10

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billion. Therefore, SLUETH applies a four-stage calibration process (coarse, fine, final, and derive) to reduce computational time. Finally~~Eventually~~, the predictions with 100 Monte Carlo (MC) runs are conducted using the best-fit parameters.

~~**FIGURE 3 ABOUT HERE:** Overall study framework. HUG is historical urban growth; USG is urban sprawl growth; and CUG is compact urban growth.~~

~~**The workflow for this research was organized into four phases: 1) the preparation of input layers, 2) the calibration in the SLEUTH environment, 3) the predictions of urban growth up to 2080 under the combined scenarios of different developmental patterns and excluded layers, and 4) the overlaying of urban growth estimates and 500-year flooding maps that were induced by SLR. Figure 3 displays the overall research framework. The outline has two major tasks: the SLEUTH urban growth model and SLR-induced flooding maps.**~~**3.3 Data description for the Urban Growth Model**

Table 2 displays detailed information regarding all data sets required by the Urban Growth Model. The land use data were obtained from the Florida Geographic Data Library (FGDL) and included five remotely sensed images in 1974, 1995, 2004, 2007, and 2013. These data sets were categorised into nine level-one land cover classes, among which the built-up land was coded as one, according to the Florida land use, cover and forms classification system published by the Florida Department of Transportation (1999). Flooding hazard and zoning information were also collected to create excluded layers. Two Flood Insurance Rate Maps (FIRM), developed by the U.S. Federal Emergency Management Agency, were downloaded from the FGDL. Current zoning map and the comprehensive plan for the study area were obtained from the online GIS websites of Bay and Washington Counties. The zoning map specified the degree to which different land uses were allowed for urban developments. According to the Bay County Comprehensive Plan (2009 to 2020), the zoning regulations are shown as follows:

-Developments were not allowed in the zone of conservation (for the preservation purpose), and impervious areas must be no more than 5%;

-In the area of conservation (for the habitation purpose), impervious surface must be no more than 50%;

-In the zone of conservation (for the recreation purpose), impervious coverage must be no more than 10%; and

-In the zones of agriculture (for the timberland purpose) and agriculture, impervious areas must be no more than 10% and 25% respectively.

Table 2 about here

3.4~~2~~ Urban Growth Model

3.4~~2~~.1 Land use/cover related layers

All input data were processed in ArcGIS® 10.3. Five land use maps in the vector format were converted into raster files using the nearest neighbourhood method. Figure 4 shows urban changes in Bay County from 1974 to 2013. Only two most recent road-network maps were used due to data limitations. Because local roads may have a very limited influence upon urban growth, only main arteries were extracted from original line files according to the MAF/TIGER Feature Class Code. These polylines were then converted into raster files using the nearest neighbour resampling method. The s~~S~~lope and hillshade maps, collected from the National Elevation Dataset, were finally generated ~~from the National Elevation Dataset~~ using the spatial analyst tool~~ in ArcGIS~~.

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3.4~~2~~.2 The creation of E1 excluded layer

An excluded layer reflects the urbanisation probabilities of cells. Its cell values range from 0 (unaffected) to 100 (entirely excluded) (Akın et al., 2014). ~~Many publications have investigated how to use excluded layers to enhance calibration accuracy (Rienow & Goetzke, 2015; Sakieh et al., 2015) and evaluate policy scenarios (A. S. Mahiny & Clarke, 2012).~~ Onsted and Clarke (2012) ~~and Akin et al. (2014)~~ recommended that the calibration and prediction stages utilise different excluded layers. The excluded layer for the calibration is suggested to be at minimal restrictions to obtain more precise results of~~for~~ urban growth, according to Akin et al. (2014). Hence, this ~~excluded~~ layer (E0) only covers water bodies where urban developments are unrealistic (Figure 4). For the prediction phase~~s~~, however, three ~~excluded~~ layers were applied to represent flood ~~ing-risk~~ mitigation based the whole region (E1), conservational/agricultural land protection (E2), and flood~~ing-risk~~ mitigation based on the Areas More Likely to Experience Growth (AMLEG) (E3).

Figure 4 about here

~~**FIGURE 4 ABOUT HERE:** Urban layers, transportation, topographic and historical excluded layer (E1) for model inputs. For the excluded layer, the higher value represents higher resistance to urban growth. The value ranges from 0 to 100.~~

The E1 attempted to assess how likely urban growth appeared in the Special Flood Hazard Area (SFHA) which may be inundated by 100-year floods. Landowners must purchase mandatory flood insurance in these areas. Increasing construction costs in high-risk regions may partly inhibit vulnerable urban growth. Therefore, the E1 could represent a scenario which ~~guides urban development towards fewer flood-prone areas~~prohibits land developments in floodplains.

Weights in the E1 layer were determined according to the approach which Onsted et al. (2014) used to reduce the errors~~bias~~ of randomly assigned values. To avoid arbitrarily assigning values to excluded layers, ~~Onsted et al. (2014)~~the authors elegantly used historical zoning maps to calculate the weights. Their method bases on~~relies on~~ annual ~~the~~ growth rates whereby new urban developments appear ~~occurs~~ in different~~each~~ zones. This method has a great potential to become a general rule in future SLEUTH applications. However, it assumes the annual rate remains unchanged over time~~a linear relationship between urban growth rates and time series~~. Therefore, concerns may arise if a study area experiences non-linear growing ~~growth~~ rates over a period, which should be addressed in future studies. ~~It is therefore suggested that modellers modify the Methodological assumptions when applying the method to these study regions.~~

To retrieve past growth information, we selected the1996 FIRM~~lood Insurance Rate Map (FIRM)~~ as a reference layer and calculated the area of SFHA and non-SFHA zones as well as the amount of new urban areas from 1995 to 2013 in these zones respectively.

Next, the annual rate of urban growth in each zone was determined by Eq. (1):

$$g_n = 1-((1-(\frac{G_n}{Z_n}))^{(1/T)}) \quad (1)$$

where G_n is the total actual urban growth in zone n (1 is the SFHA and 2 is the non-SFHA zone) from 1995 to 2013,

Z_n is total area of zone n according to the 1996 FIRM, and

T is the number of years, i.e., 18~~ years~~.

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~~Finally, ~~T~~t~~he growth rates were used to generate the excluded value in the SFHA zone by Eq. (2):

$$E_{SFHA} = 100(1-(\frac{g_1}{g_2})) \tag{2}$$

where g_1 and g_2 denote the growth rates in the SFHA and non-SFHA zones respectively. Table 3 indicates that the growth rate in low-risk areas was approximately three times that in the SFHA zone, suggesting that mandatory flood~~ing~~ insurance constrained urban expansion in flood-prone~~vulnerable~~ regions. Finally, the E1 layer was created based on the 2015 FIRM and represented a growth management that aims at mitigating flood risks (Figure 5).

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~~Finally, E1 layer was created based on the 2015 FIRM and represented a managed growth plan that accounted for moderate protection from flooding risks (Figure 5).~~

3.4~~2~~.3 The creation of E2 excluded layer

The 2020 Bay County Comprehensive Plan was published in 2009 and represented the most recent managed growth option for the study area. Hence, excluded values in the E2 layer were weighted according to this plan and modified based on the work of Akin et al. (2014). Specifically, a cell value of 100 was assigned to water bodies, 95 to the conservation/preservation zones, 50 to the conservation/recreation and agriculture/timberland areas, 25 to the other agricultural areas and conservation/habitation zones, and 0 to all other areas (Figure 6).

Figures 5 and 6 about here

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~~**FIGURE 5 ABOUT HERE:** Special Flood Hazard Area in 2015 (left) and the E1 excluded layer (right) (based on the whole study area). For the excluded layer, the higher value represents higher resistance to urban growth. The value ranges from 0 to 100.~~

~~**FIGURE 6 ABOUT HERE:** The E2 excluded layer (based on current zoning plans). For the excluded layer, the higher value represents higher resistance to urban growth. The value ranges from 0 to 100.~~

3.4~~2~~.4 The creation of E3 excluded layer

Most SLEUTH modellers apply the above-mentioned methods to develop excluded layers. However, such approaches may~~methods~~ be~~are~~ deficient since these ~~usually~~ treat the whole study area homogeneously. Realistically~~Conversely~~, urban growth involves~~is more likely to involve~~ heterogeneous changes~~changes~~ across the study area. For instance, ~~in coastal regions,~~ new residential developments largely extend from existing settlements that may only cover a small ~~portion of the whole study region~~area within a city boundary. Thus, Onsted and Chowdhury (2014) developed a procedure that corrects the growth rates in the AMLEG. The authors concluded that the AMLEG technique produced more accurate results than the other ~~two~~ methods: arbitrary guessing and the calculation based on the whole study area. Therefore, the AMLEG approach was applied ~~applied~~ based on the E1 scenario

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(flood ~~ing~~ mitigation). Specifically, ~~The SLEUTH~~SLEUTH was first run in a~~the~~ prediction mode with ~~for~~ 100 MC~~Monte Carlo~~ times for the period of 1995 to 2013. All five growth coefficients were set as 100, and the cells with an urbanisation probability of 50% or more were considered in the AMELG ~~(, as shown in~~ Figure 7). Second, excluded values in the E3 excluded layer were re-calculated using the equations (1) and (2), based on the AMLEG effects (Table 4). Finally, ~~Accordingly,~~ the E3 ~~excluded~~ layer was created based on the 2015 FIRM (Figure 8).

Figure 7 about here

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~~**Figure 7 ABOUT HERE:** The areas more likely to experience growth (AMLEG) in the coastal region from 1995 to 2013. The cells with 50% or more urbanisation probability were considered as AMELG.~~

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~~Figure 7 shows the coastal areas of high urbanisation potentials. The rudimentary simulation of urban growth from 1995 to 2013 justifies the heterogeneous evolution of urban landscape within the whole study region. Thus, the excluded values were re-calculated using the equations (1) and (2), based on the effects of AMLEG (Table 4).~~

~~**TABLE 4 ABOUT HERE**~~

Figure 7 shows the coastal areas with high-urbanisation potentials. The rudimentary simulation of urban growth from 1995 to 2013 justifies the heterogeneous evolution of urban landscape within the whole study region. The excluded value (27) of the SFHA zone is considerably less than that (68) in the E1 excluded layer. Such a decrease was also discovered by Onsted and Chowdhury (2014) ~~also discovered such a decrease in the excluded value~~. Also, this finding indicates that substantial urban growth occurs in flooding-prone areas if we considered the AMLEG effects. This phenomenon is intuitively reasonable since existing coastal regions are both low-lying places and developmental attractors.

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~~Accordingly, the E3 excluded layer was created based on the 2015 FIRM (Figure 8).~~

~~**FIGURE 8 ABOUT HERE.** E3 excluded layer (based on the AMLEG technique). The excluded value ranges from 0 to 100. A higher value represents larger resistance to urban growth.~~

All pre-processed ~~these~~ raster files, including land use maps and four excluded layers, were eventually resampled at a spatial resolution of 30 m * 30 m, which is adequately high since the resolutions of most SLEUTH applications are in the range of 10-100m (Akın et al., 2014). These raster data ~~files~~ with 1972 rows * 2383 columns were then exported as grayscale GIF images and imported into the ~~the SLEUTH~~SLEUTH program.

3.42.5 Model calibration

As mentioned, urban-growth parameters were calibrated based on the "brute force" technique where analysts follow four calibration stages—coarse, fine, final, and derive. Increasingly higher image resolutions were typically used from the ccoarse to finalderive calibrations for computational efficiency (Akın et al., 2014; Chakraborty et al., Wilson, & Kashem, 2015; Rafiee et al., 2009). However, different resolutions may be problematic and lead to a biased estimation of growth patterns (Dietzel and& Clarke, 2007; Sekovski et al., 2015). Thus, the consistent resolution of 30 * 30 m was employed during the entire calibration process.

In each calibration phase, several Monte Carlo (MC) iterations were simulatedrun to account for the uncertainty associated with parameter estimations (Project Gigalopolis, 2016). A general strategy of identifying the "best-fit" parameters is to shrink the range of parameters during each phase. While increasing the number of MC iterations can slightly enhance accuracy, the rise in calculation time is extremely pronounced. To balance model fit and efficiency, SLEUTH developers and users experimented in different study areas and developed experiential numbers of MC runs during different steps: 4-5 (coarse); 7-8 (fine); 8-10 (final); and 100 or greater (derive) (Project Gigalopolis, 2016). Hence, this work utilised 4, 7, 9, and 100 MC iterations for each of the four steps respectively. This set is consistent with Sekovski et al. (2015) who examined coastal vulnerability to flooding at a similar geographical scale.

Four MC runs were conducted in the coarse calibration, and the widest range of the parameters, 0 to 100, were evaluated with an increment of 25 at a time. The goodness of fit in models was assessed by thirteen metrics, the majority of which were least-square regression scores between simulated urban components (e.g., increased urban pixels and clusters) and real counterparts. SLEUTH scholars, however, largely debated the selection of the optimal metric which could determine model performance. Most disputes centred on whether a combination of several indicators outperform a single metric. Dietzel and Clarke (2007) developed a composite metric, known as the Optimal SLEUTH Metric (OSM). The OSM is the product of the compare, population, edges, clusters, slope, X-mean, and Y-mean metrics. The authors evaluated different combinations of the thirteen metrics and found that the OSM contributes to more accurate and superior predictions than single-metric approaches. Recent studies have furthermore suggested OSM'sthe robustness (Jantz et al., Goetz, Donato, & Claggett, 2010; Sakieh et al., 2015; Sekovski et al., 2015) of O. Hence, it was applied in this work to narrow parameter ranges after each stage. Specifically, seven MC iterations with narrower parameter ranges were employed in the fine stage. Further refined parameter ranges of the parameters with nine MC iterations were next tested during the final calibration. This whole process took around one-month processCPU time and was conducted using the standard 3.0 SLEUTH model executed in the Cygwin UNIX Windows compiler. This three-stage processcalibration generated five candidate parameters; however, this set may be biased due to the self-modification nature of SLEUTH. Therefore, a "dderivinge" calibration with the candidate set was performed with 100 MC iterations.

3.42.6 Model prediction

Three approaches have been widely applied in model predictionin the literature. The first is to adjust one or more of the fivegrowth parameters (Leao et al., Bishop, & Evans, 2004; Rafiee et al., 2009) which affect the way urban growth evolves (i.e., infilling or outward dispersion) (Leao et al., 2004; Rafiee et al., 2009; Sekovski et al., 2015). The second is to modifyadjust the growth-resistance levels in excluded layers (Jantz et al., 2010; Sekovski et al., 2015) or apply distinctly excluded layerss as different policies (Akın et al., 2014). The last one, less frequently used than the first two methods, is to alter self-modification parameters which control overall growth rates (Yang and & Lo, 2003). This research used a combination of the first two approaches, and the results were overlaid with SLR-induced flooding maps. The urban growth was predicted up to 2080, and the exposure to flooding under different growth patterns and policies were analysed in 2030 and 2080.

As in widespread use in similar studies, this work first simulated three growth patterns: Historical Growth (HUG), Urban Sprawl (USG), and Compact Development~~Urban Growth~~ (CUG). The HUG assumed that prospective urban extent expanded at an existing growth ~~-~~rate~~s~~, and ~~. f~~Five parameters remained unchanged over the forecasting period. The USG resulted in more scattered urban communities~~ which appeared in the suburbs and along transportation corridors~~. In the model, the dispersion, breed, and road gravity factors controlled sprawling growth (Table 2), so increasing these parameters produced more dispersed developments~~growth~~. On the contrary, the CUG ~~greatly~~ is characterised by~~relied on~~ the ~~expansion~~enlargement of current settlements. Compact development is ~~is~~ apparent in Bay Country ~~the study area~~ and many other populated coastal regions. In SLEUTH, compact development was positively associated with the ~~parameter,~~ spread parameter (Table 2). In addition, decreasing road gravity inhibited new growth along corridors and thus contributed to compact urban forms (Table 2).

These growth patterns were next simulated under three policy scenarios: flood ~~ing-risk~~ mitigation (E1, based on the whole region), conservational/agricultural land protection (E2), and modified flood~~ing-risk~~ mitigation (E3, based on the AMLEG). E1 restrained growth in low-lying areas and served as an adaptation strategy to SLR. Alternatively, E2 reflected how future city expansion may be impacted by ~~land use~~ zoning that~~which~~ represent~~s~~~~ed~~ a strong predictor of urban growth in Florida (~~Jeffrey A.~~ Onsted and~~&~~ Chowdhury, 2014). E3 is a modified scenario of the flood~~ing-risk~~ mitigation due to heterogeneous ~~based on the fact that~~ urban growth~~ is heterogeneous~~. Finally, these ~~urban growth~~ predictions were coupled with SLR-induced flooding. ~~, whose methodology was briefly introduced in the next section.~~

3.5~~3~~ SLR-induced f~~F~~looding maps

The detailed methodology for generating SLR-induced flooding was developed by Hsu (2014). In his hurricane model, the effects of ~~the~~ rise in sea level and s~~S~~ea s~~S~~urface t~~T~~emperature (SST) were considered in two stages. First, the increase in SST decreased central hurricane pressure over the sea surface (Knutson and~~&~~ Tuleya, 2004). Changed central pressure and other parameters were next used to calculate projected surge heights using the s~~S~~urge r~~R~~esponse f~~F~~unction (SRF) developed by Irish et al. (2009)~~-~~. Based on this information, a hypothetical hurricane was projected to make landfall at a place where it caused the most damages to coastal areas and resulted in a 500-year flood. Second, the projected surge height ~~for the study region~~ was adjusted by local SLR (Udoh, 2012). Two extreme SLR scenarios were considered, as shown in Table 5. A1F1 corresponded to the highest level of global greenhouse gas emissions (IPCC, 2007). ~~Global data were finally adjusted according to local marine conditions in Panama City.~~ Next, different ~~the~~ surge heights were calculated in numerous SRF stations which were defined along the coastline of Bay County~~the study area~~. SRF zones associated with each station were delineated, and each zone had a height value. Finally~~Eventually~~, flooding areas were identified by comparing surge heights and local elevation data. All the required data sets regarding projected SLR and SST were collected from the fourth assessment report published by the IPCC (2007) (Table 5).

Table 5 about here

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4 Results and discussions

4.1 Model calibration

The multi-stage calibration process generated the following parameters: 71 (dispersion), 92 (breed), 70 (spread), 3 (slope), and 35 (road gravity). High values of the first three parameters suggest that the past several decades have witnessed apparent urban sprawl and growth surrounding established settlements. As indicated in Figure 2, the previous urbanisation in the past several decades primarily occurred in the vacant areas immediate to central Panama City and southwest shorelines. Such an The considerably outward expansion of cities is demonstrated by the breed parameter — the most influential factor affecting urban growth. Additionally, two newly urbanised clusters in the north have appeared and been expanding since 1995 (Figure 2). Such a spatial structure is largely captured by the dispersion and breed factors: theirwhose values are the second (71) and third (70) highest respectively. By contrastOn the contrary, the low value of the slope parameter value is understandable since Bay Countrythe case study region barely has few mountainous areas, and therefore elevation the slope is not a limiting factor. This finding suggests that the weight of elevation can be further reduced in plain regions, pointing out a direction for customising the data structure of SLEUTH. The road gravity's coefficient is much lower than those of the dispersion, breed, and spread parameters, indicating a limited impact of road systems upon land use allocation. This effect is intuitively reasonable in that transportation networks in the study area have remained stable since the 1980s.

4.2 Model prediction

It isSimilar studies have suggested that a sensitivity analysis should be conducted before predictions to identify the most significant parameter (Sekovski et al., 2015). Thise assessment was carried out by subsequently setting each parameter as 80 and keeping the others as the lowest value of one1 and running predictions up to 2030. The results indicate that the "spread" parametercoefficient has the greatest impact on future urban expansion, leading to a 13.99% increase in urban areas up to 2030.

Different sets of parameters can characterise urban sprawl and compact development. Specifically, urban sprawl is referred to as scatteredly formed settlements and developments along major transportation networks. Conversely, compact developments are in proximity to existing urban areas. Therefore, this work applied the following criteria to develop two alternative scenarios of future urban growth scenarios , urban -sprawl (USG) and compact development (CUG), were developed according to the following criteria.

1. The dispersion, breed, and road gravity's coefficients coefficients were increased and decreased by 25 in USG and CUG respectively.
2. The "spread's" coefficient was risen and lowered by 10 in USG and CUG respectively. Since this parameter was much more influential in urban growth than the otherss regarding urban growth, ten was selected as an adjusting value in two scenarios.
3. As its impact was quite marginal, the slope parameter remained unchanged across all scenarios. Table 6 summarises different sets of parameters for three scenarios.

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We applied different parameter combinations into the ~~the SLEUTH~~SLEUTH model and generated various maps which showed the probability of each cell being urbanised. These maps were~~could be~~ then converted to urban/nonurban results by a cut-off probability value. Here, a~~A~~ justified approach to identify the reasonable cut-off value is to assess the histogram frequency of probabilities (Dezhkam~~, Amiri, Darvishsefat, & Sakieh~~ et al., 2013; Rafiee et al., 2009; Wu et al., 2008). After evaluating the projected~~forecasting~~ maps in 2080, we found that there was a steep increase of urbanised cells around the probability of 90%. The cut-off value of 85~~, accordingly,~~ was selected to determine whether a cell was converted into urban accordingly.

Figure 9 summarises the growth statistics with different policies under three urban development scenarios. It ~~The results~~ show that, without ~~under~~ ~~no~~ land use regulations, city areas grow~~increase~~ substantially under all scenarios (Figure 9 a). For instance, urban region expands up to 826 km^2 in 2080 under the historical growth. Similar patterns can be seen in alternative growth scenarios as well, as shown in Figure 9 a. Under stricter land use restrictions, the simulations with the E1 excluded layer generate the smallest increase in urban extent from 2013 to 2080 (Figure 9 b). In addition, their~~the~~ growth curves that gradually level off from 2013 indicate a steadily falling ~~decreasing~~ growth rate. Under compact growth, which shows the highest ~~most~~ rise in urban areas among three scenarios, the city region expands by 15% within seven decades (Figure 9 b). This is intuitively reasonable because the flooding map exerts a heavy constraint on undeveloped lands, and therefore new developments largely appear near existing cities and towns~~settlements~~. Nonetheless, the predictions with the E3 excluded layer produce approximately the same amount of new growth as those with the E1 layer (Figure 9 d). Similarly, urban growth with the E2 layer (~~under the~~ conservational/agricultural land protection) ~~(E2)~~ has a similar pattern as the simulations with no regulations. Figure 9 c shows that the growth rate in compact development reaches the peak (19%) at 2044 and then gradually levels off. However, land use zoning does have an impact on the amount of new urban areas. The simulated urban area in 2080 with the historical growth pattern is 709 km^2 (Figure 9 c), only 85% of that under no restrictions (Figure 9 a). ~~Overall, the results are consistent with similar findings (Sekovski et al., 2015). First,~~In sum, spreading development from existing coastal areas is the~~the~~ leading force behind land use changes. Second~~Second~~, the changes are also driven by the dispersion, breed, and road parameters~~network~~ but less associated with the slope factor.

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~~**FIGURE 9 ABOUT HERE:** The Simulations of urban changes to the year 2080 of three urban growth patterns under four excluded layers. a) E0: water bodies, b) E1: flooding-risk mitigation (based on the whole region), c) E2: conservational/agricultural land protection, and d) E3: flooding-risk mitigation (based on the AMLEG).~~

Figure 10 shows predicted urban growth up to 2080 under different excluded layers. These illustrations further depict urban expansion trends indicated by the growth curves in Figure 9. In other words, historical growth and urban sprawl share similar developmental patterns where the majority of projected~~increased~~ urban cells appear under flexible~~less strict~~ land use regulations. Moreover, a considerable portion of urban expansion~~development~~ would fall into~~be steered towards~~ flooding zones if no land use policy is implemented.

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4.3 The exposure of urban growth to flooding risk

Figure 11 shows 500-year flooding maps that would be exacerbated by SLR in 2030 and 2080. ~~A~~ Large ~~vast~~ areas~~region~~ immediate to the West, North, and East Bays would be flooded, and the regions~~areas~~ adjacent ~~immediate~~ to the West and North Bays would be even more susceptible in 2080. As shown in Table 7, the total inundated area in 2080 would be more than ten times that in 2030. Additionally, the total amount of landsarea with a flooding depth over 3 m would rise considerablyincrease exponentially from 2030 to 2080.

FIGURE 10 ABOUT HERE: The comparison of modelled urban extent in 2080 with different excluded layers. E0: water bodies, E1: flooding-risk mitigation (based on the whole region), E2: conservational/agricultural land protection, and E3: flooding-risk mitigation (based on the AMLEG).

Figure 11 about hereIGURE 11 ABOUT HERE: 500-year flood-risk zones of 0.2-m sea level rise (SLR) (a) and 0.9-m SLR (b).

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Future urban growthFuture urban simulations were overlaid with flooding maps to show how different developmental patterns guided by distinct policies are vulnerable to SLR-induced flooding (Tables 8-–9). The results unveil that, if urban growth progresses compactly, total inundated area in 2030 would be the largest among three growth scenarios (Table 8). This finding is echoed by a previous study (Sekovski et al., 2015). In other words, compact development normally appears surrounding existing urban areas, the majority of which are low-lying and prone to flooding. For land use policies, urban growth under regulations leads to less flood-prone developments. By contrastSpecifically, if no regulations are implemented, the total inundated area of projected urbanised cells in 2080 is 111.243 km^2 on average, more than 25 times the area in the flood ding-risk mitigation strategy based on the whole region (Table 9). Therefore, bBoth growth patterns and land use policies, accordingly, affect the have substantial impact on the susceptibility of coastal cities to flooding hazards substantially.

Figure 12 shows how three urban growth scenarios are exposed differentially to SLR-induced flooding at a larger geographical scale. . It suggests that First, urban growth is extremely limited if we implement the excluded layer that representss the flooding-risk mitigation strategy based on the whole region. Conversely, if water bodies are used as an excluded layer, urban areas expand considerably in coastlines and hinterlands. Noticeably, urban expansion with the E3 excluded layer also generates a vulnerable landscape to flooding. This phenomenon reflects the heterogeneous developments over the study region. Coastal areas would probably continue to be urbanised even if they are threatenedjeopardised by flooding and storm surge. Such aThis growth pattern may be partly because the high value -of properties along shorelines diminishes SLR impacts. Protective structures along coastlines and flooding- insurance programs even attract new developments in flood-prone areas.

Second, a vast majority of urbanised areas that would be within flooding polygons are situated in the proximity of the West and North Bay and the shoreline areas of Panama City.

TablesABLES 8 and AND 9 about hereABOUT HERE

FIGURE 12 ABOUT HERE: Flooded urban extent in 2080. E0: water bodies, E1: flooding-risk mitigation (based on the whole region), E2: conservational/agricultural land protection, E3: flooding-risk mitigation (based on the AMLEG), HSU: historical growth, USG: urban sprawl, and CUG: compact development**Figure 12 about here**

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4.4 Discussion

4.4.1 Modelling and uncertainties

According to Box and Draper (1987), “Essentially, all models are wrong, but some are useful” (p. 424). ~~In other words,~~ S~~s~~imulations are different levels of the approximations of real-world phenomena. This norm also applies to this work. The primary contribution of this paper is to seek methodological incorporation between urban growth models and SLR-induced flooding, although it attempts to tie land use predictions with coastal planning practice. However, this research suffers from a few limitations associated with the case study region~~s~~, assumptions, ~~-~~and uncertainties.

Frist, Bay Count~~r~~y is a typical land-sea interface confronted with heightened pressure from SLR, and the results are analogous to those in other similar coastal zones. However, we inadequately evaluate the effect of elevation on urban exposure to flooding~~ as Florida is a plain with few mountains~~. Thus, our findings may have limited comparability with hilly areas.

Second, the SLEUTH model in its current form excludes several ~~other~~ critical variables contributing to urban dynamics. It may insufficiently~~adequately~~ capture various~~the whole range of~~ factors affecting urbanisation (Herold et al.~~, Goldstein, & Clarke~~, 2003). The demand for urban growth comes from population and economic increase. The Bureau of Economic and Business Research at the University of Florida (2016) forecasts that the total population of Bay County will increase by almost 40% by 2030. Such a~~n apparent~~ rise~~, probably~~ demands ~~significant urbanisation~~additional urbanisation capacities. Therefore, future applications should consider socioeconomic factors behind urbanisation~~ should be considered in applications~~. Population growth~~increase~~, however, is linked with migration, overall economic conditions, and other factors, which is complicated and hard to predict. Additionally, urbanisation in coastal regions is driven by economic activities, the majority of which are related to tourism and real estate. Nevertheless, barely do CA models integrate ~~are~~ these factors~~ taken into account in CA models~~.

Third, this paper bases on couples of assumptions to forecast urban landscape evolution. It determines the excluded values of the E2 scenario according to future land use plans and suggestions from other studies (e.g., Akin et al., 2014). Although the lack of ~~historical~~ zoning information forced us to make this assumption, the predictions under the E2~~ scenario~~ may become problematic. Besides~~Additionally~~, the extrapolation of future urban growth beyond the calibration range can be questionable and generate uncertain results (Goldstein et al.~~n, Candau, & Clarke~~, 2004). Modellers ought to make a trade-off between land use~~urban~~ predictions and the projections~~forecasts~~ of climate change related hazards. Climate change is slow going, but urbanisation may be rapid in populated coastal regions. For instance, SLR may become significant only after an adequate period~~time frame~~ that probably exceeds that~~the period~~ of historical urban data. Such coupled analyses should aim at identifying the general impacts of climate change on future urbanisation~~prospective urbanisation~~, rather than replicating the past urban patterns~~ of urban development~~. The last assumption relates to adaptation strategies. ~~In~~ SLEUTH~~, urban growth predictions~~ fails to incorporate seawall, population relocation, and other adaptation strategies to SLR. This limitation can be seen in the given examples of future flooding risks (Figure 12). Many~~Considerable~~ existing urban areas would fall into flooding polygons in 2030 and 2080. Essentially, the model assumes a “do-nothing” option regarding adaptation strategies; such a limitation~~, which~~ is addressed in a following paper~~ may be improved in future research~~.

Eventually, uncertainties come from two aspects. The “best-fit” parameters are non-deterministic and estimated by distinct numbers of MC iterations in different calibration stages. Thus, when comparing this work’s numerical results with those of similar research, readers should be aware of the stochastic nature of the model. Second, additional concerns arise when it comes to SLR projections and their impacts on hurricanes. Researchers have not yet reached an agreement as to SLR estimates~~predictions~~; ~~. s~~Sea level may increase more rapidly than people initially thought. Nicholls and Cazenave (2010) reviewed numerous ~~prediction~~ sources ~~-~~and concluded that globally mean sea level would rise between 0.19 m and 1.7 m by 2100. Given these uncertainties, therefore, the simulation results should be interpreted with caution~~extreme carefulness and objectivity~~.

4.4.2 Urban growth and coastal hazards

The calibration results indicate that main driving force for the study area is spread, followed by dispersion and breed. Such findings are in line with~~consistent with~~ similar coastal studies (Sakieh et al., 2015; Sekovski et al., 2015). In other words, urban growth is likely to take place around current settlements in a compact fashion. Existing settlements are featured by excellent accessibility to infrastructure, activity centres, and coastal amenities. Additionally, a multitude of new urban areas clusters around coastlines, which is evident either in the business-as-usual or urban sprawl scenarios. Increased human activities and the competition for limited resources, therefore, intensify environmental pressures at land-sea interfaces. Furthermore, the interface faces unprecedented threats from SLR and other intensified coastal hazards. SLEUTH could provide useful information about future urban growth and thus benefit coastal city managers and land use planners.

4.4.3 Policy implications

Compact urban forms are advocated because of their environmental friendliness and benefits for energy conservation (Dezhkam et al., 2013; Mahiny and~~&~~ Gholamalifard, 2007). However, this might not be true in flat coastal areas from the perspective of hazard mitigation. As indicated in Tables 8 and 9, the compact growth scenario~~model~~ generates more extension of current flood-prone areas than the scenarios of historical growth and urban sprawl. For instance, if the flood ~~ing-risk~~ mitigation policy is implemented, new built-up regions that would be flooded in 2030 under the compact growth pattern are over 2.5 ~~,500,000~~ km^2, almost double the area under historical growth scenario. However, such conclusions are made only based on our case study area where slopes~~the elevation is low and~~ change insignificantly. Thus, t~~T~~he effects of compact urban forms on ~~regional exposure to flooding~~flooding exposure require further investigation in other coastal regions with different topographical features. ~~Therefore, it is recommended that spontaneous urban growth should be regulated to prevent farmland loss, and urban development should also be oriented towards hinterland that already has significant urban areas.~~

Population and economic growth largely drive urban expansion~~urban growth~~. Nevertheless, policies behind such growth should also be investigated since these policies (e.g., land use plans and economic strategies) ~~-~~represent developmental blueprints. Thus, it is beneficial to reflect upon ~~different policies~~how policies contribute~~ing~~ to distinct urban growth patterns: urban sprawl and compact growth. Urban sprawl is characterised by unplanned and scattered developments in suburban areas. Uncoordinated growth in the city edge has been suggested to relate to ~~be associated with~~ multidimensional factors regarding economic incentives, housing development plans, and transportation policies (De Vos and~~&~~ Witlox, 2013; Lopez and~~&~~ Hynes, 2003; Yue et al.~~e, Zhang, & Liu~~, 2016). Economic incentive packages launched by the central government have contributed to urban sprawl in the developing world. For instance, China took an economic reform in the 1970s by opening up land markets and commercialising housing units. This economic stimulus gave rise to many sprawling mega-cities such as Beijing, Shanghai, and Chengdu. In Europe and ~~and~~ North America, though, microeconomic theories may majorly explain urban sprawl. For example, h~~H~~ouseholds begin to relocate to the suburbs when the land prices in city centres become prohibitively high. Their relocation decisions are further strengthened by housing and land development policies. Developers promote low-density communities in the city periphery. Local governments help ~~to~~ build large retail centres to accommodate the increased demands. Motorization policies and low fuel costs result in automobile-oriented cities. Even public transit policies aggravate outward city growth by charging long-distance commuters less than the riders for short distances (De Vos and~~&~~ Witlox, 2013).

As urban sprawl increasingly threatens public health, social equity, and the built environments, people start to develop different urban containment policies. There are primarily two forms of containment policies that were adopted in the US. The State law in Oregon and Washington requires that local land ~~-~~use plans should clearly define an urban growth boundary. In other states such as Florida and Maryland, governments develop urban service limits, public facilities ordinances, and other policies to promote compact urban forms (Aytur et al., Rodriguez, Evenson, & Catellier, 2008). However, the effects of urban containment policies have been hotly debatedd. For example, not all urban growth boundaries significantly affect housing markets and the rates of urbanisation paces (Dempsey and& Plantinga, 2013). Thus, De Vos and Witlox (2013) suggest the integration of spatial planning policies, mobility policies, and road pricing. Spatial planning can strictly limit new developments outside urban areas. Transit-oOriented dDevelopment benefits nurturing high-density and mixed land-use neighbourhoods. LastlyAlso, road pricing increases long-distance travel costs, thereby curtailing urban sprawl.

The modelling approaches and results offered by this work could aid in the development of an integral land-use enforcement system. Building a comprehensiven integrated land use policy for the urban growth landscape is a recommended option in coastal communities, which is currently lacking in existing principal planning practices for future SLR in the US (Fu, Gomaa, Deng, & Peng et al., 20167). An integrative policy framework can coordinate the increased demand for urbanisation and the goal for hazard mitigation. In other wordsFurthermore, planners ought to incorporate the land use zoning offor existing coastal areas should be incorporated into the adaptation strategies to SLR and develop R. rRural land use e management and regulations should be oriented thatto attract new development inland. While prohibiting developmentsthe prohibition of development within flooding zones partly greatly constrains urban growth and is, therefore,may be unrealistic, only relying on land use zoning could lead to considerable inundated urban areasmassive areas subject to flooding. A compromise of these two alternatives, accordingly, could be developed to both ensure- adequate urbanisation and steer new developments away from low-lying areas. Finally, planners should also consider seawall, planned retreat, and other adaptation strategies as key components of the proposed framework should be incorporated into the framework to protect existing urban areas from being inundatedflooding risks. Furthermore, iIn the long term, policy makers should formulate adaptation plans ought to considerthat address other SLR aspects such as groundwater pollution and saltwater intrusion beneath protective structures.

5 Conclusions

Environmental and resource pressures are increasingly intensified given ongoing coastal urbanisation. Besides, the urbanisation process amplifies the exposure of coastal communities to flooding hazards. UnfortunatelyFurthermore, we are uncertain about the degree to which SLR may contribute to the increased intensity of storminess. The possibility of more exacerbated consequences, however, cannot be neglected from a precautionary perspective. Therefore, it is crucial to building an effective coastal management plan to balance land use, competing interests, and hazard mitigation.

This work contributes to the literature by integrating urban growth dynamics, land use policies, and SLR-induced flooding. We successfully calibrated the SLEUTH model for Bay County coastal areas, Florida (US), based on historical data from the year 1974 to 2013. By applying the best-fit coefficients, we developed three urban growth scenarios and assessed the exposure of future urban extent to SLR-induced flooding under different land use policies. These scenarios reflected various growth strategies that are widely applied in urban planning. Our results indicate that the parameters associated withof compact development largely drive urban growth in Bay County and similar coastal communities. The results show that substantial urban growth would be prone to coastal flooding if no land use policy is implemented.

SLEUTH is particularly useful in modelling complex spatial dynamics. Moreover, the computational capacity of SLEUTH is greatly enhanced due to the rapid advancement of computer technologies. Being able toBy outputting GIF maps and statistics for each predictiveprediction year, SLEUTH can be easily linked with a raster-based GIS environment (Rafiee et al., 2009). Therefore, modellers can readily import the results of different scenarios can be readily imported into a GIS platform for presentation purposes. Such aThe coupled model serves as a decision support tool and helps city managers, land use planners, and hazard mitigation teams evaluate the outcomes of different policies. Additionally, the visualisation results can be used to raise general awareness about the vulnerability of coastal communities to SLR.

Admittedly, ~~the~~ models are~~is~~ just the ~~a~~ simplifications of reality, and urban growth is an intricate process that involves population increase, economic activities, and many other factors. Since the level of SLR impact on flooding is quite unclear, and growth predictions could be probably biased, the model cannot generate exact results regarding~~of~~ urban growth and flooding extent. However, we believe that the "what-if" estimations are useful in helping decision makers understand how policies mould distinct~~ifferent~~ developmental patterns~~s may be oriented~~. Therefore, probabilistic models and scenario-based planning should be advocated to evaluate planning alternatives and their consequences (Xiang and~~&~~ Clarke, 2003) as well as to offer reliable estimates of flooding damages.

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