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Analysis of non-linear inundation from sea-level rise using LIDAR data: a case study for South Florida

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Abstract By analyzing a digital elevation model (DEM) derived from airborne light detection and ranging (LIDAR) data and airborne height finder measurements, this study demonstrates that a 1.5 m sea-level rise by 2100 would cause inundation of large areas of Miami-Dade County, southern Broward County, and Everglades National Park. Inundation processes are non-linear: inundation is gradual before reaching a threshold, and speeds up rapidly afterwards due to the regional topography. Accelerated sea-level rise will cause the threshold to be reached sooner by amplifying the non-linear inundation, and must be considered in policy-making. Comparison of inundated areas extracted from 30 m LIDAR and USGS DEMs indicates that the vertical accuracy of a DEM has a great effect on delineation of inundation areas. For a 1.5 m sea-level rise, the inundated area delineated by USGS DEM for Broward County is 1.65 times greater than that indicated by the LIDAR DEM.

1 Introduction

Sea-level rise has caused inundation, erosion, saltwater intrusion, and increased storm surge flooding along the world's coastal zone. The 2007 IPCC report projects a global sea-level rise of 0.18–0.59 m by 2100 due to climatic changes (Meehl et al. 2007). Recent studies on ice disintegration in Greenland and West Antarctic ice sheets (Cazenave 2006; Luthcke et al. 2006; Rignot and Kanagaratnam 2006; Sheperd and Wingham 2007) and paleoclimaic changes (Overpeck et al. 2006) suggest that the IPCC report may greatly underestimate the role of accelerated ice dynamics on sea-level rise. Alternative estimates indicate that sea level could rise by 1.4 m (Rahmstorf 2007)–5 m (Hansen 2007) by 2100. Such large rates of sea-level rise in this century

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would threaten millions of people in low-lying coastal areas such as Bangladesh in Asia and South Florida in North America.

South Florida is one of the most vulnerable areas in the US to the sea-level rise induced inundation due to its gently sloped topography with vast areas only a few meters above the current sea level. A strip of urbanized land spanning Palm Beach, Broward, and Miami-Dade Counties north to south occupies the eastern coast of South Florida, while the Everglades, the largest wetland in North America, occupies the central portion of the southern peninsula (Figs. 1, 2, 3). The total population, real property, and gross domestic product of the three counties represent more than 30% of the totals for the State of Florida (67 counties), making the three counties a center of Florida's society and economy. In addition, the federal and state governments have initiated an ambitious \$8 billion plan to recover the degraded Kissimmee-Okeechobee-Everglades ecosystem by restoring the sheet flow that has been severely disrupted by past human activities. In order to cope with the potential impacts of future sea-level rise on South Florida, the inundation extents and processes by various sea-level rise scenarios and the associated impacts on property, population, and the Everglades ecosystem must be quantified.

Potential impacts have been studied extensively for vulnerable coastal zones because of adverse consequences of sea-level rise on built and natural environments (Kana et al. 1984; Leatherman 1984, 2001; Nicholls 2004; Nicholls et al. 1995, 2007; Schneider and Chen 1980; Titus and Richman 2001). Several attempts have also been made to analyze the impact of sea-level rise on South Florida. Wanless (1989) analyzed the history of sea-level rise in South Florida for the past 15,000 years and qualitatively examined impacts of future sea-level rise. Titus and Richman (2001) delineated the inundation extents of the U.S. East and Gulf coasts, including South Florida, using a U.S. Geological Survey (USGS) one degree digital elevation model (DEM) based on sea-level rise scenarios of 1, 2, 3, and 5 m. Harrington and Walton (2007) estimated the values of impacted property in Miami-Dade County to be approximately \$57 and \$128 million if sea-level rises 0.31 and 0.65 m, respectively. Unfortunately, the accuracy of these quantifications is limited by the poor vertical resolution of DEMs.

Recently, Titus and Wang (2008), and Titus and Cacela (2008) employed the landward boundary of a tidal marsh to create a supplemental elevation contour to better delineate topographic changes in coastal areas where the contour interval from a USGS DEM is large. The landward boundary of a tidal marsh is assumed to represent the position of spring high water. This method reduces errors in estimating topographic elevation caused by a direct interpolation of two adjacent contours in coastal areas in the Mid-Atlantic Region, consequently improving the delineation of inundation zones. However, there are still considerable errors in the DEM generated using USGS and supplemental contours.

Topographic elevations are usually derived from topographic maps or DEMs provided by the USGS. The vertical resolution of USGS DEMs is about 1.5 m (5 ft.) for South Florida, which can correspond to a horizontal extent of tens of kilometers. Fortunately, the advance in airborne light detection and ranging (LIDAR) technology in the past 10 years has allowed the rapid mapping of topography over a large area with a vertical resolution of 0.15 m and horizontal resolution of 1–2 m (Whitman et al. 2003). Topographic elevations of several U.S. coastal areas have been mapped in the past several years using LIDAR and more will be mapped in the near future as

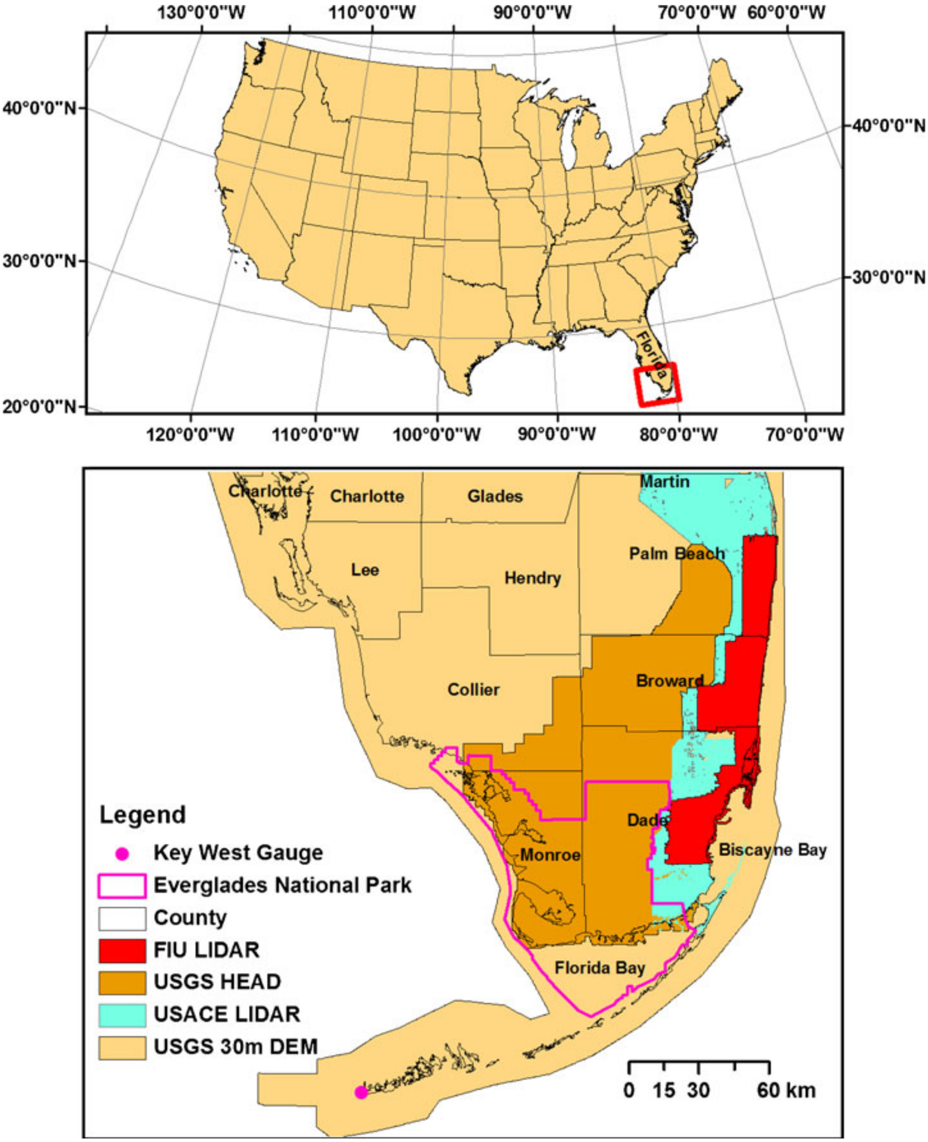


Fig. 1 The study area displaying the coverage of airborne LIDAR measurements and USGS airborne height finder data

part of the Map Modernization Program of the Federal Emergency Management Agency (FEMA) (www.fema.gov). However, the magnitude of improvement in delineating inundation zones induced by sea-level rise using LIDAR data has not yet been investigated systematically.

To design sound policies to reduce the tremendous risk to South Florida associated with future sea-level rise, the inundation extent and dynamics caused by various scenarios of sea level rise, and associated social, economic and ecological

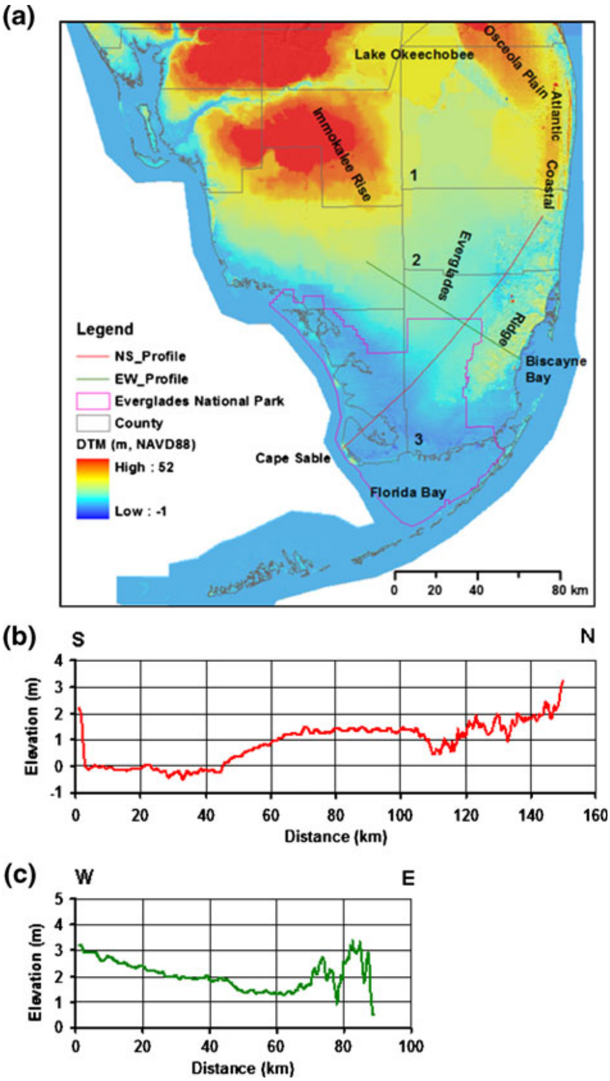


Fig. 2 The topography of south Florida (**a**), the elevation profile through the Everglades along the northeast-southwest direction (**b**), and the elevation profile across the Everglades along the northwest-southeast direction (**c**). 1 Palm Beach County, 2 Broward County, and 3 Miami Dade County in (a). The elevation values along the profiles were derived by first sampling the merged 30 m DEM every 30 m and then smoothing samples using a moving average method with a window of 11 points

impacts must be quantified. The potential value lost in inundated real properties is a critical component of both economic and social well-being. In order to estimate the value of an inundated real property, data on the location and market value of the property are needed. A real property value consists of the value of the land which is delineated by a parcel and the values of buildings over the parcel. The property value for a parcel with multi-unit buildings such as condominiums and cooperatives has to be derived through aggregation. Although parcels and estimated property values can be obtained from the county property appraisal office and the state department of revenue in Florida, they are often stored and maintained separately. Also, the aggregation of property values for multi-unit building parcels has not been performed, and the relationship between a parcel and corresponding building units

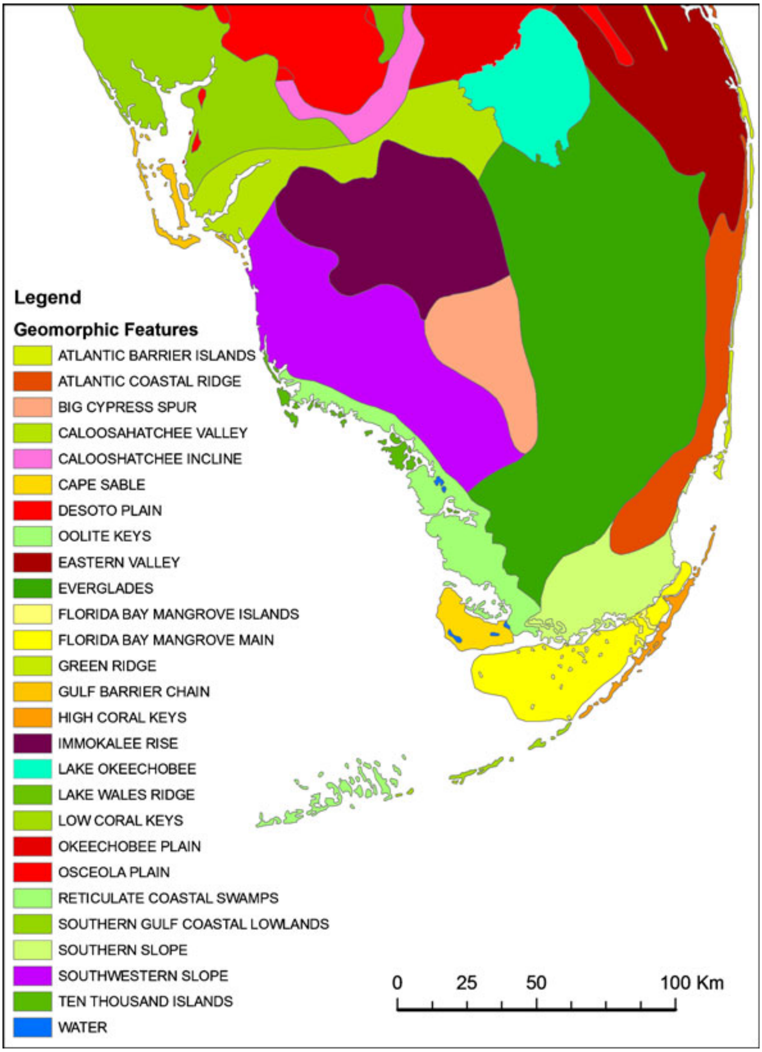


Fig. 3 Geomorphic map for South Florida. The GIS data for the map was generated by digitizing the map for physiography of Peninsular Florida (White 1970) by the Mapping and GIS Section of the Southwest Florida Water Management District

is not always consistent due to splitting and merging of parcels over time. This poses a challenge for accurately estimating the values of inundated properties over an area.

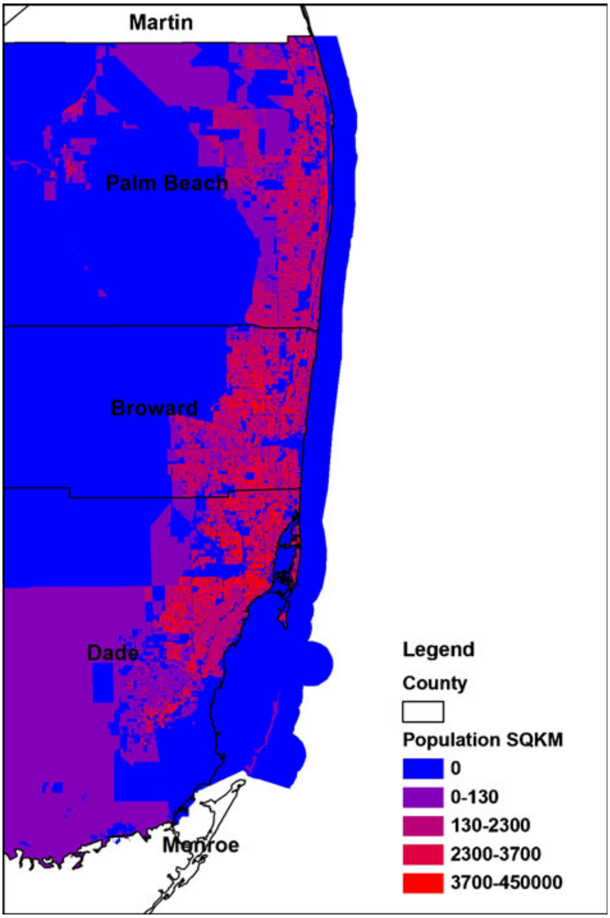
The International Hurricane Research Center at Florida International University (FIU) has mapped 2,300 km^2 of coastal urban areas in Palm Beach, Broward, and Miami-Dade Counties using airborne LIDAR since 1999 (Whitman et al. 2003). Geographic information systems (GIS) provide a powerful platform in which to manage, analyze, and visualize high-resolution DEMs from LIDAR measurements, property parcels, and population census data for the quantification of potential sea-level rise impacts. The objectives of this research was therefore (1) to develop methods in GIS to estimate land areas inundated by potential sea-level rises, (2) to examine the effect of topography and acceleration in sea-level rise on inundation, (3) to investigate the influence of the horizontal and vertical resolutions of DEMs on inundation analysis, and (4) to quantify the impact of sea-level rise induced inundation on property and population in South Florida. The remaining sections of this paper are arranged as follows: Section 2 describes the study area; Section 3 presents a polygon-based method for delineating inundation areas and a method to construct land area, population, and property hypsometric curves for elevation and time; Section 4 examines the impacts of inundation on South Florida, non-linear processes of inundation, the influence of the acceleration in future sea-level rise on inundation processes, and the effect of DEM resolution on delineating inundation areas; Section 5 discusses the effect of non-linear inundation processes on policy making; and Section 6 presents the conclusions from this study.

2 Study area

The study area includes 7 counties in the State of Florida, along with Everglades National Park (Fig. 1). From east to west, distinct topographic high, low, and high features define the geomorphic framework of the study area (Figs. 2a and 3). The high land which consists of Osceola Plain and the Atlantic Coastal Ridge occupies the east coast of South Florida (Petuch and Roberts 2007; White 1970). The Osceola Plain is a 5–9 m high and 30 km wide topographic high covering the north and east portion of Palm Beach County and the areas further north. The Atlantic Coastal Ridge with an elevation of 4–6 m and a width of 5–10 km extends from Palm Beach to Broward Counties in a near south direction. The Ridge turns to the southwest in northern Miami-Dade County and deviates away from the coast, dipping into the ground in southern Miami-Dade County. Stream and canals, following the routes of transverse glades, cut through the Atlantic Coastal Ridge in a perpendicular direction to discharge water from the Everglades into the Atlantic Ocean. The Everglades, a topographic trough with a width of 50–60 km lies west of the Atlantic Coastal Ridge and provides a pathway for sheet water flow fed by an upstream watershed including Lake Okeechobee. A profile that follows the Everglades depression in a northeast direction, shows that about half of the profile is nearly flat (Fig. 2b). The west side of the Everglades is bounded by another topographic high, the Immokalee Rise. A second profile across the Everglades indicates that the low elevation areas in the Everglades are adjacent to the Atlantic Coastal Ridge (Fig. 2c). The elevation decrease from the Atlantic Coastal Ridge to the center of the Everglades depression occurs over a shorter distance than the elevation rise from the center to the Immokalee Rise. Thus, the topographic slopes are relatively steep on the east side of the Everglades and gentle on the west side.

Only Palm Beach, Broward, and Miami-Dade Counties were selected for estimating population and property loss caused by potential sea-level rise since accurate DEMs from LIDAR measurements are limited to these areas. Historically, urban development in the three counties began on the Atlantic Coastal Ridge, then expanded toward the west, but has been limited by the eastern boundary of the Everglades. Therefore, the majority of the population and inhabitable real estate for the three counties are located on the Atlantic Coastal Ridge and adjacent areas

Fig. 4 Spatial distribution of the number of people per square kilometer for Palm Beach, Broward, and Miami-Dade counties. Population density is high on the Atlantic Coastal Ridge



(Fig. 4). The population, property, and gross domestic product of the three counties total about 5 million, $833 billion, and $169 billion (Table 1), respectively, or about 31%, 33%, and 32% of the totals for the State of Florida based on the 2000 census, 2007 property tax data, and 2003 state economic statistics (Kildow et al. 2006).

Table 1 Population, area, and gross domestic product (GDP) of Palm Beach, Broward, and Miami-Dade Counties

Geographic area	Population	Area (km^2)	GDP ($M)
Palm Beach	1,131,184	5,773	39,817
Broward	1,623,018	3,161	52,897
Miami-Dade	2,253,362	5,123	76,543
Florida	15,982,378	139,670	520,903

Population data come from 2000 census, areas were computed based on county and state boundary shapefiles provided by the ESRI data CD for ArcGIS, and GDP in million dollars ($M) comes from 2003 state economic statistics (Kildow et al. 2006)

3 Data

3.1 Population

The U.S. Census Bureau (www.census.gov) undertakes the census of population and housing for the United States every 10 years. The census data consists of Topologically Integrated Geographic Encoding Referencing (TIGER)/Line files which delineate the geographic boundaries of census units, and tables which list the aggregation of population and housing for each census unit. The TIGER/Line data have been converted by a number of vendors into a format compatible with GIS files. Census geographic units in ArcGIS (www.esri.com) shapefile format and associated tabular data can be downloaded from the Geography Network (www.geographynetwork.com). The 1990 and 2000 census block data for Palm Beach, Broward, and Miami-Dade Counties were used in this study because only 1990 and 2000 census blocks provide spatial coverage of the entire counties. The census block is the smallest geographic unit associated with aggregated population and typically has a population of 85 people (Peters and MacDonald 2004). A block within a city is typically delineated by four intersecting streets with a grid road structure, while a block in a rural area may cover many square kilometers. Detailed information about downloading, processing, and description of census data can be found in Peters and MacDonald (2004). There are about 18,000, 20,000, and 31,000 records respectively, for census blocks in Palm Beach, Broward, Miami-Dade Counties. Tabular data listing the number of people and other related information for census blocks was joined to a census block shapefile in ArcGIS using a common key to estimate the population influenced by sea-level rise.

3.2 Property

Similar to census block data, property data consist of parcels which delineate the geographic boundary of the land for a property and associated tabular tax roll data which lists the name and address of the owner, assessed value, and just value for a property. The 2007 just value of a property was used to quantify property loss due to potential sea-level rises because the just value is "the amount a purchaser, willing but not obliged to buy, would pay a seller who is willing but not obliged to sell" according to the Florida constitution, section 193.011, and represents a fair market value of a property. While parcel and tax roll data are available from either the Florida Department of Revenue (FDR) or a county appraisal office by request, different problems exist within the datasets from each source. For example, the parcel data for Palm Beach County from the FDR do not cover all properties, and parcels for some condominiums are missing, while just values of properties in the tax roll table from the Miami-Dade County appraisal office are not available. Therefore, to estimate property loss due to sea-level rise, the 2007 parcel data from county appraisal offices were combined with tax roll data from the FDR.

There are about 450,000, 490,000, and 550,000 parcel records for Palm Beach, Broward, and Miami-Dade Counties, respectively, with corresponding tax records of about 620,000, 727,000, and 848,000 entries. The total property value for a parcel has to be calculated in order to perform spatial queries related to estimating the sea-level rise impact. However, there are errors in the parcel shapefiles from county appraisal offices, including open polygons and duplicate parcel identifications (IDs). The topological errors of the parcel files were corrected by first importing the files into the geodatabase in ArcGIS and converting them into feature classes. Then, a unique parcel ID for each parcel was obtained by dissolving the parcels in the feature class based on parcel ID. In order to aggregate the property values for a parcel, a many-to-one relationship was built by creating a new ID field in the tax roll table. All properties on a parcel in the tax table were assigned the same parcel ID in this new field. In this way, a parcel polygon can be attached to the multi-property units in the tax table which are located in this parcel through the join operation in ArcGIS, and multi-property values for the parcel can be aggregated. Not all parcels were attachable to the tax roll table because updating of parcel shapefiles by county appraisal offices was not synchronized with the tax roll tables from the FDR. Therefore, the sum of aggregated property values over parcels is not the same as the sum of all property values in the tax roll table. However, the differences between these two values for three counties are relatively small, equal to or less than 0.45% of total values (Table 2), allowing us to ignore this inconsistency.

3.3 DEM

DEMs used for estimating the inundation extent caused by sea-level rise were generated from three different sources. The first source is USGS 30 m DEMs which cover the entire study area, and 10 m DEMs which covers most portions of the study area. The USGS 10 m and 30 m DEMs are mainly generated by digitizing 7.5-min topographic quadrangle maps with a scale of 1:24,000 or 1:25,000, which are typically produced using stereo analysis of overlapped aerial photographs (USGS 1992). The root mean square (RMS) error for elevations is one-half of a contour interval or better on the topographic map for low-relief areas. Since the contour interval is about 1.5 m on topographic maps for South Florida, the elevation RMS errors of USGS 10 m and 30 m DEMs should be less than 0.75 m. Both 10 m and 30 m DEMs were used in an examination of the effect of horizontal resolution of DEMs on inundation extent.

The second data source used to produce DEMs comes from airborne LIDAR surveys. The International Hurricane Research Center at FIU mapped urbanized areas in three counties vulnerable to storm surge flooding using airborne LIDAR

Table 2 The sum of just values (JV) of all properties in Palm Beach, Broward, and Miami-Dade Counties from the tax roll tables provided by the Florida Department of Revenue

County name	JV ($)	JV with aggregation ($)	Relative difference (%)	JV without aggregation ($)	Relative difference (%)
Palm Beach	227,446,708,778	226,933,772,710	0.23	184,830,579,758	18.74
Broward	256,259,327,510	255,114,512,830	0.45	204,981,793,600	20.01
Miami-Dade	348,902,758,405	348,139,868,790	0.22	268,220,069,754	23.12
Total	832,608,794,693	830,188,154,330	0.29	658,032,443,112	20.97

JV with aggregation for each county is the sum of the total property values for all parcels in a county with aggregation of the values of multi-buildings over a parcel, while JV without aggregation is the sum without aggregation. Relative difference is computed by $\frac{(\text{JV}-\text{JV With Aggregation or JV Without Aggregation})}{\text{JV}} \times 100\%$

from 1999 to 2003 (Fig. 1). Optech ALTM 1210 and 1233 systems with zigzag scanning pattern mounted on a Cessna 337 aircraft were employed to perform LIDAR surveys. The LIDAR system utilized a 10 (ALTM 1210) or 33 (ALTM 1233) kHz pulsed near infrared (1.1 μm) laser and recorded both first and last returns of an emitted laser pulse. An average flight height of 1,200 m and a scan angle of 30° produced a 650 m wide swath of laser footprints, each with a diameter of 0.3 m. The point spacing in the cross-track direction and maximum point spacing in the along-track direction is about 1.5–2.5 m (International Hurricane Research Center 2004; Whitman et al. 2003). The terrain LIDAR measurements were derived by filtering last return LIDAR points using the progressive morphological filter (Zhang et al. 2003). DEMs with a horizontal resolution of 1.5 m (5 ft.), available for download at http://lidar.ihrc.fiu.edu, were generated by interpolating terrain LIDAR measurements. The elevation RMS errors for LIDAR DEMs of less than 0.15 m were obtained by comparing DEM elevations with elevations of more than 30,000 GPS control points provided by the engineering departments of the three counties. The U.S. Army Corps of Engineers (USACE) also organized LIDAR surveys for the western portion of Palm Beach, Broward, and Miami-Dade Counties (Fig. 1). However, this data set has a positive elevation bias ranging from 0 m at nadir to a maximum of approximately 0.3 m at the edge of the swath, perpendicular to the direction of flight. Elevation RMS errors derived by comparing elevations of ground control points with filtered LIDAR points vary from 0.2 to 0.4 m.

The third type of measurements used to produce DEMs were collected by the USGS using airborne height finder (AHF) for the Everglades region (Desmond 2003). This method was employed in the Everglades because remote sensing technology such as aerial photogrammetry and LIDAR is not effective in mapping the elevations of vast areas covered by turbid water and vegetation. The AHF employs a plumb bob attached to the helicopter to measure the vertical distance from the helicopter to the land surface by penetrating through the water and vegetation. The flight positions of the helicopter are determined by differential GPS methods using records from GPS units on the helicopter and over the ground control stations. The georeferenced horizontal and vertical coordinates of a point on the land surface contacted by the plumb bob can be determined by combining the distance and helicopter trajectory data. Elevation data points for the Everglades were collected using the AHF by following a grid pattern with a cell size of 400 × 400 m. Extensive examination of the data accuracy is problematic due to the difficulty in finding reference points with higher elevation accuracy in the Everglades. A comparison of elevations of 17 AHF measurements and the elevations of first-order benchmarks of the National Geodetic Survey resulted in an RMS error of approximately 4.1 cm. The AHF elevation points were interpolated into a 30 × 30 m DEM using the Kriging method in ArcGIS.

DEMs from the USGS, LIDAR surveys, and AHF measurements were merged into 30 × 30 m DEMs for the analysis of the inundation extents from sea-level rise in the three counties and the Everglades. There is little overlap between FIU's LIDAR surveys and USGS's AHF measurements, and these two measurements have the highest data quality. Thus, the following order was used in merging the 30 × 30 m DEMs: (1) FIU's LIDAR data, (2) The AHF elevation data, (3) USACE LIDAR data, and (4) USGS 30 × 30 m DEM. In an area of overlap, the data with the highest accuracy (low order) is used. Almost the entire area of Broward and Miami-Dade

Counties, the eastern half of Palm Beach County, and the whole of the Everglades were covered by LIDAR and AHF DEMs, while the remaining area was covered by USGS DEMs (Fig. 1).

4 Method

4.1 Derivation of inundation polygons and hypsometric curves for elevation

Since it is common practice in sea-level rise impact predictions to set a time frame of 100 years (Nicholls 2004), this research focuses on the inundation impact from sea-level rises on three counties from 2000 to 2100. The sea level magnitude is set to reference the NAVD88 vertical datum to coincide with the datum of the DEMs used in this study. The differences between the NAVD88 datum and tidal datums, such as mean sea level, are often calculated using 19 years of water level records from tide gauges (Gill and Schultz 2001). In South Florida, the Key West tide gauge has a long, continuous record of water levels (Fig. 1). The mean sea level, calculated as the arithmetic mean of hourly heights observed from 1983 to 2001, is about 1.67 m above the local datum at Key West (http://tidesandcurrents.noaa.gov). The mean of the higher high water (MHHW) height of each tidal day is about 1.94 m above the same local datum. Since the difference between the mean MHHW height from 1995 to 2005 and the NAVD88 datum is about 0.01 m, the MHHW height around 2000 is very close to the NAVD88 datum. In addition, records from 14 recently established tide gauges indicate an average difference between the MHHW and the NAVD88 along the south Florida coast of about 0.1 m. Therefore, the coastal area below 0 m elevation referenced to the NAVD88 datum is inundated at least one time every day on average.

An essential step in quantifying inundation impact is to delineate inundated areas (polygons) for a given magnitude of sea-level rise, derive the properties and populations within the inundated area through spatial queries, and perform statistical analyses on these properties and populations. However, derivation of inundated areas and associated statistics for population and property for only one scenario of sea-level rise is insufficient for quantifying impact because of the large uncertainty that exists in the projection of future sea level for the next 100 years (Hansen 2007; Meehl et al. 2007). Therefore, it is necessary to calculate inundated area, population, and property based on a series of sea-level rise scenarios determined by the range of uncertainty.

Accurate delineation of inundation areas is a challenging task because the shoreline and surrounding topography are modified constantly by various coastal processes. For example, shoreline retreat on sandy coasts is exacerbated by beach erosion induced by sea-level rise (Zhang et al. 2004), while shoreline retreat on wetland coasts stops if marsh accretion processes keep pace with sea-level rise. It is difficult to include the contributions of these dynamic processes in delineating inundation areas due to a lack of reliable models for predicting site-specific erosion and accretion in response to sea-level rise. Therefore, it is assumed that the topography of the study area remains unchanged when an inundation area is delineated. This assumption is reasonable for South Florida where inundation due to a rising water level dominates erosion and accretion processes in most areas owing to the nearly flat, low-elevation topography, and a lack of significant sediment input. Shore protection measures that may be taken in the future can also alter inundation dynamics, but are difficult to include in the inundation analysis due to uncertainty in their form and extent. Analysis of inundation dynamics and the impacts caused by various scenarios of sea-level rise with current infra-structure in place is a necessary pre-cursor to consideration of future scenarios of shoreline protection.

The inundated area for a given rise in sea level h is equivalent to the coastal area below the elevation h if both sea level and elevation are referenced to the same vertical datum. Thus, hypsometric curves, which delineate the distribution of land area at different elevations in geomorphology (Ritter et al. 2001) were constructed to quantify inundated areas. Similarly, curves defining the distributions of population and property at different elevations were also created to quantify inundated population and property. Since spatial queries were involved extensively in computing inundation statistics, the delineation of inundation polygons and derivation of hypsometric curves were generated in a GIS which provides a set of powerful tools for spatial queries. ArcGIS was selected to implement our method due to the popularity of ArcGIS in research communities and government agencies. The detailed procedure is as follows:

(1) Given an elevation (or rising sea level) h and a DEM D, a new DEM was generated by setting cell value $d \le h$ $(d \in D)$ using the *Raster Calculator* function in ArcGIS. By assigning *NoData* to cell values of 0 in the new DEM using the *Reclassify* tool, we derived a DEM DI with cell values

$$di = \left\{ \begin{array}{ccc} 1 & \text{if } d \le h & d \in D \\ NoData & \text{if } d > h \text{ or } d = NoData & di \in DI \end{array} \right\} \tag{1}$$

(2) A set (feature class in ArcGIS) of inundation polygons P were derived using the *Raster to Polygon* tool with *Simplify Polygons* option. Polygons $p \in$P were classified into inside polygons $pi \in PI$ and outside polygons $po \in PO$ by adding an indicator attribute to the feature class P, where $P = PI \cup PO$. The outside polygons are adjacent to the outside boundary of DEM D which is represented by cells with *NoData* values. The outside polygon delineates the inundated coastal land area by a sea-level rise with a magnitude h (there is only one outside polygon in PO because all directly inundated areas are connected by the water). The inside polygons delineate the low-lying inland areas with elevation lower than that of the rising sea level, but not directly connected with the inundated coastal area. The inside and outside polygons are separated by barriers with elevations higher than that of the rising sea level.

(3) The total area below elevation h was computed by summarizing the areas of inside and outside polygons. Some coastal and bay water areas were included in the outside polygon because the DEM D covers these areas. These coastal water areas were removed in order to calculate the inundation caused by sea-level rise. The land areas of the outside polygons were determined by intersecting the boundary polygon of a county with the outside polygon. Only areas of intersection were used to calculate the total area of the outside polygon. In such a way, the area of the outside polygon represents the area of the land

inundated by a sea-level rise *h*, while the area of inside polygons represents the size of the inland area below *h*.

(4) The populations and properties inundated by sea level were determined through a spatial query. First, polygon feature classes for the census block and property parcel polygon were converted into point feature classes by calculating centroids of polygons using the *Feature to Point* tool. It is assumed that the population and property values at the centroid represent the values for the entire polygon. Next, populations and properties within inside and outside polygons were selected using the *Selection by Location* tool. Finally, the total populations and properties for inside and outside polygons were derived by applying the *Statistics* tool to the selected polygons.

(5) The above procedure was repeated for a series of sea-level rise scenarios. Thirty-three elevations, ranging from of 0 to 8 m with an interval of 0.25 m (most elevations in the 3 counties are less than 8 m), were used to delineate inundation areas. Inundated land area, population, and property for each elevation (sea-level rise) in each county were normalized by county totals, yielding percentages that were used to create hypsometric curves.

4.2 Projection of future sea-level rise

Together with DEMs, the projected magnitude of future sea-level rise determines the inundation extent for the study area. A global sea-level rise of 0.18–0.59 m by 2100 due to a warming climate was projected using several models in the 2007 IPCC report. However, modeled sea-level rises from 1961 to 2003 are significantly lower than observed values (Meehl et al. 2007), indicating that the IPCC report may underestimate the magnitude of future sea-level rise. By analyzing observed global sea level and temperature data from 1880 to 2001, Rahmstorf (2007) found that sea-level rise rate is proportional to the increase in the temperature. He estimated that by 2100 sea level will rise 0.5–1.4 m above the 1990 level with a temperature rise of 1.4°–5.8°C. In addition, the IPCC projection does not consider the effect of the acceleration in ice sheet disintegration due to increased ice stream flow around the edges of the Antarctic and Greenland ice sheets, which has been observed recently (Cazenave 2006; Luthcke et al. 2006; Rignot and Kanagaratnam 2006; Thomas et al. 2004). Hansen (2007) argued that the acceleration in ice sheet disintegration could increase sea-level rise up to 5 m during this century.

In order to create a sound policy to cope with the impact of sea-level rise, not only does the inundation extent need to be quantified, but the inundation process, which is influenced by the speed of sea-level rise, also must be estimated. The acceleration in sea-level rise has to happen for any sea-level rise scenarios greater than the magnitude projected using the rate of 0.18 cm/year for the twentieth century (Douglas 2001; Meehl et al. 2007). Unfortunately, even less certain than the magnitude of sea-level rise is how sea-level rise will accelerate in this century. Church and White (2006) found a quadratic acceleration in sea-level rise by analyzing reconstructed global mean sea level from 1870 to 2001. Quadratic curves also fit the sea-level rise projected by Rahmstorf (2007) in terms of his supplementary data set. Therefore, we analyzed the effect of acceleration in sea-level rise by assuming that sea-level rise would follow a quadratic form in the future. Of course, we cannot exclude the other forms of acceleration, but analysis of a quadratic sea-level rise should provide us with useful insights to the effect of acceleration in sea-level rise on inundation processes.

Changes in sea level relative to the elevation of the land mass in South Florida include two components: global sea level change and elevation change due to land subsidence or uplifting. The sea-level rise rate at Key West is 0.22 cm/year based on an annual mean sea level record from 1913 to 1997 (Douglas 2001). This rate is close to the global sea-level rise rate of 0.18 cm/year for the twentieth century, thus, it is reasonable to assume that the rate of future sea-level rise in South Florida is the same as that of global sea-level rise. Six quadratic curves for sea-level rise from 2000 to 2200 were constructed for scenarios of 0.5, 1, 1.5, 2, 2.5, and 3 m sea-level rise by 2100 (Fig. 5). The parameters for quadratic curves were estimated using these sea-level rise scenarios and the global mean sea levels estimated from satellite altimeter measurements from 1993 to 2007, downloaded from http://sealevel.colorado.edu. The reference level for future sea-level rise is the 2000 global mean sea level which is set to zero.

4.3 Derivation of hypsometric curves for inundation time

The inundation times corresponding to 33 elevations from 0 to 8 m with an interval of 0.25 m were estimated using quadratic curves for the above six sea-level rise scenarios. Hypsometric curves were constructed using inundation time as the *X* axis and the percentage of inundated area, population, and property as the *Y* axis. The influence of acceleration in sea-level rise on the inundation process was analyzed by comparing the hypsometric curves for six sea-level rise scenarios.

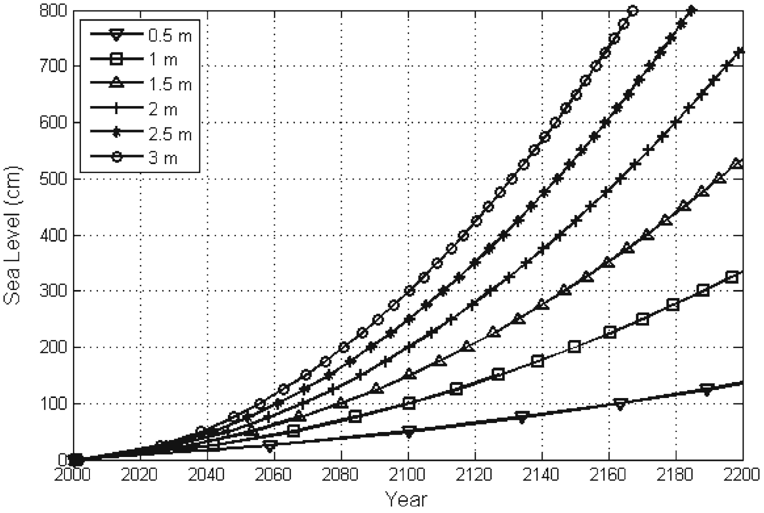


Fig. 5 Projected sea-level rise curves for scenarios of 0.5, 1, 1.5, 2, 2.5, and 3 m sea-level rise by 2100. The curves were derived by fitting quadratic equations to the annual mean global sea level measured by satellite altimeters from 1993 to 2007 and given scenarios for 2100

5 Results

5.1 Inundation caused by 0.5, 1, and 1.5 m sea-level rise scenarios

Table 3 lists the area, population, and property values of Palm Beach, Broward, and Miami-Dade Counties inundated by sea-level rises with magnitudes of 0.5, 1, and 1.5 m. In general, Miami-Dade County is most vulnerable to the inundation, followed by Broward and Palm Beach Counties, consistent with the general trend in topography (Fig. 2). Figure 6 shows inundation areas in South Florida resulting from scenarios of 0.5, 1, and 1.5 m sea-level rise by 2100. A 0.5 m rise in sea level would allow saltwater from the Gulf of Mexico to inundate large areas of Everglades National Park and marsh areas in southeastern Miami-Dade County (Fig. 6a). Several areas on barrier islands and low elevations on the mainland east of the Atlantic Coastal Ridge would be inundated by the Atlantic Ocean. Although some populated areas and expensive residential houses and condominiums at the edges of barrier islands and the mainland would be affected, sea-level rise would inundate less than 0.6% of Miami-Dade County's population and property. While there are also several topographic lows below the 0.5 m sea level west of the Atlantic Coastal Ridge in northern Miami-Dade County and in southern Broward County, since these areas are not directly connected to the ocean except for several small canals, they could be protected from inundation by preventing the saltwater flow into the canals. However, saltwater intrusion to the freshwater aquifer and disruption of infrastructure by increased surge flooding will make it difficult to maintain a modern standard of living in coastal areas.

A 1 m sea-level rise would inundate many areas on barrier islands along the Atlantic coast from the lagoon side and the low elevation areas east of the Atlantic Coastal Ridge. Large areas of low-lying lands west of the Atlantic Coastal Ridge in southern Broward County and northern Miami-Dade County would be below sea level (Fig. 6b). These inland areas are occupied by many fragmented local topographic highs, but still are separated from the directly inundated coastal area

Table 3 Impacts of three scenarios of sea-level rise, 0.5, 1, and 1.5 m on Palm Beach, Broward, and Miami-Dade counties

County	Sea level	InArea	OutArea	InPop	OutPop	InProp	OutProp
Palm Beach	0.5	11	31	2,056	911	589	526
Broward		21	12	22,915	4,634	880	645
Dade		80	1,287	36,260	6,734	3,341	1,950
Palm Beach	1.0	17	39	4,908	7,452	2,042	4,318
Broward		85	31	75,557	25,734	642	10,008
Dade		180	1,670	100,313	79,459	9,445	20,968
Palm Beach	1.5	5	77	3,517	39,950	571	19,747
Broward		169	173	169,286	148,059	15,923	41,403
Dade		168	2,955	193,064	323,492	18,260	68,235

InArea: areas (km^2) where the elevations are lower than a given magnitude of sea-level rise, but do not connect directly with ocean, *OutArea*: areas (km^2) where the elevations are lower than a given magnitude of sea-level rise and connect directly with ocean, *InPop*: total population in InArea, *OutPop*: total population in OutArea, *InProp*: total property values (million) in InArea, *OutProp*: total property values (million) in OutArea

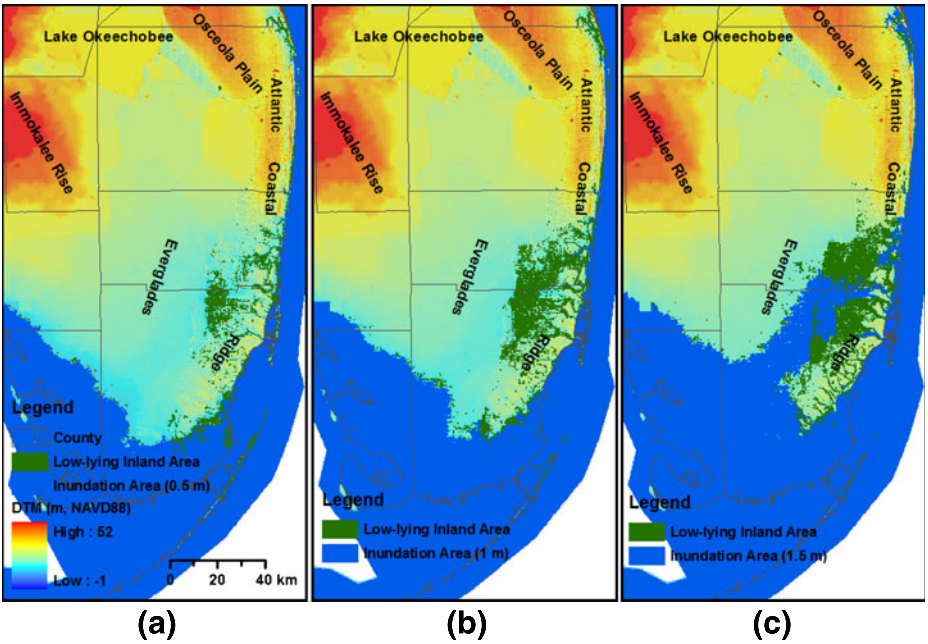


Fig. 6 The inundation map for south Florida with **a** 0.5 m, **b** 1 m, and **c** 1.5 m sea-level rises. Sea level is referenced to NAVD88 vertical datum. *Inundation Area* represents land areas inundated directly by the projected rising sea level, while *Low-lying Inland Area* delineates areas which are below the projected rising sea level, but are separated from the *Inundation Area* by elevation barriers

by thin linear features such as highways with higher elevations. It would be difficult to protect these low-lying inland areas from increased storm surge flooding by enhancing these thin separators. In addition, saltwater intrusion through porous limestone and sand would reduce the freshwater supply from the surficial Biscayne aquifer which provides most freshwater for public usage for the three counties (Renken et al. 2005). Therefore, although the 1 m sea-level rise does not cause direct inundation of a large amount of population and property, the maintenance of habitability at low-lying inland areas vulnerable to storm surge flooding and saltwater intrusion would be extremely challenging.

A 1.5 m sea-level rise would cause calamitous inundation throughout South Florida. The majority of barrier islands and mainland low elevation areas east of the Atlantic Coastal Ridge would be inundated by the Atlantic Ocean. Saltwater would reach the western portion of Miami-Dade County and southern Broward County from the Gulf of Mexico by flooding through the Everglades trough (Fig. 6c). Most of Everglades National Park would be under saltwater. About 58% of the land area of Miami-Dade County would be inundated directly by saltwater, altering the southern Atlantic Coastal Ridge into a chain of islands similar to the Florida Keys. Although this amount of sea-level rise would only cause a direct inundation of 14% and 20% of Miami-Dade County's population and property, the drastic reduction in land area, exacerbated storm surge flooding, and saltwater intrusion would make it impossible to support the entire population living on the remaining high ground. Saltwater would penetrate further inland in mid-Broward County through topographic lows across the Atlantic Coastal Ridge. Many local topographic highs would be fragmented into many small islands. Inland areas below 1.5 m in the western portion of Broward County would be separated from the Atlantic Ocean and the Gulf of Mexico by very thin linear topographic highs. By contrast, Palm Beach County would not be inundated significantly by the 1.5 m sea-level rise.

5.2 Non-linear processes of inundation

In comparisons of inundated area, population, and property for 0.5, 1, and 1.5 m sea-level rises, inundation appears to accelerate for equal increments of sea level (Table 3). All land area hypsometric curves for elevations have an S-shape, indicating that the majority of land areas are located in a band of mid-level elevations (Figs. 7a, 8, 9a). As a result, in low, middle, and high elevation zones, inundation will occur slowly, fast, and slowly, respectively, in response to a constant rate of sea-level rise. The separation of inundated coastal areas and low-lying inlands at lower sea-level rise scenarios and the subsequent merging of inundated coastal areas and low-lying inlands at higher sea-level rise scenarios further steepen changes of inundated area hypsometric curves. Thresholds, i.e., elevations beyond which inundation accelerates rapidly, are identified at 1.25, 1.5, and 3 m elevation in Miami-Dade, Broward, and Palm Beach Counties, respectively. The land area inundated by sea-level rise from 0 to 3 m in Palm Beach County, and from 0 to 1.5 m in Broward County, is about 5% of each county's area, while the land area flooded by sea-level rise from 3 to 5 m in Palm Beach County and from 1.5 to 3 m in Broward County are 75% and

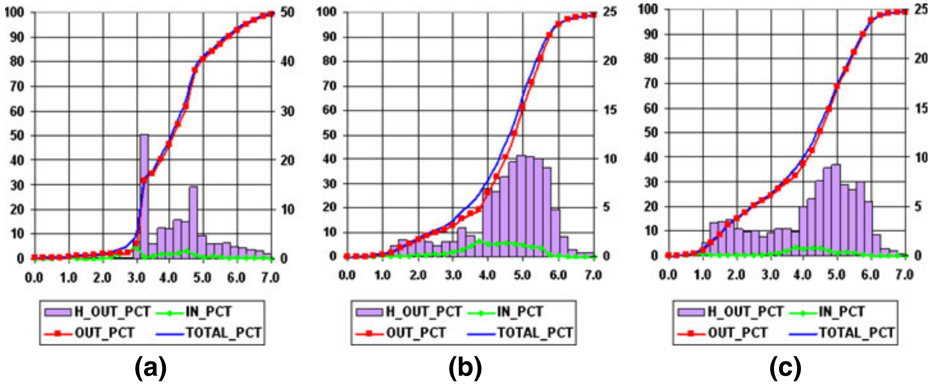
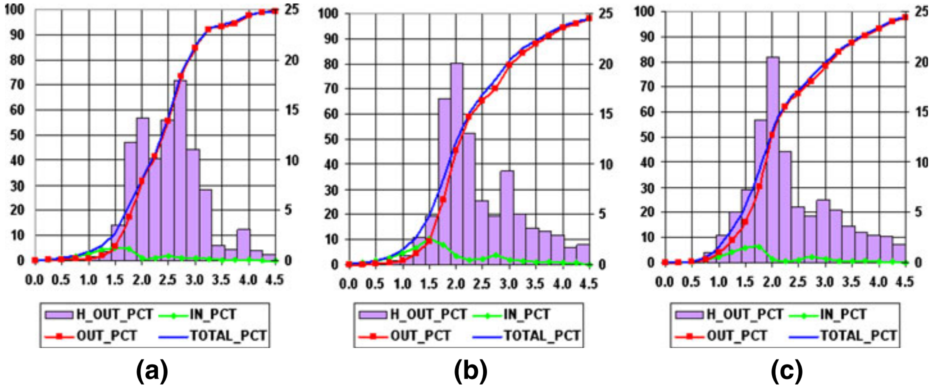


Fig. 7 Land area (**a**), population (**b**), and property (**c**) hypsometric curves for elevation in Palm Beach County. *X* axis represents the elevation (m) above the NAVD88. *Y* axis on the left side corresponds to variables *IN_PCT, OUT_PCT*, and *TOTAL_PCT*, and *Y* axis on the right side corresponds to variables *H_OUT_PCT*. *IN_PCT*: low-lying inland area, population, and property below a given elevation as percentage of the county's values. The inland area, population, and property which are located within inside polygons are not inundated by the ocean water as sea-level rises to the given elevation. *OUT_PCT*: land area, population, and property below a given elevation as a percentage of the county's values. The area, population, and property that are located within the outside polygon are inundated by the ocean water as sea-level rises to the given elevation. *TOTAL_PCT (IN_PCT + OUT_PCT)*: total area, population, and property below a given elevation as a percentage of the county's values. *H_OUT_PCT*: histogram for land area, population, and property within outside polygons between two adjacent elevations as the percentage of the county's values

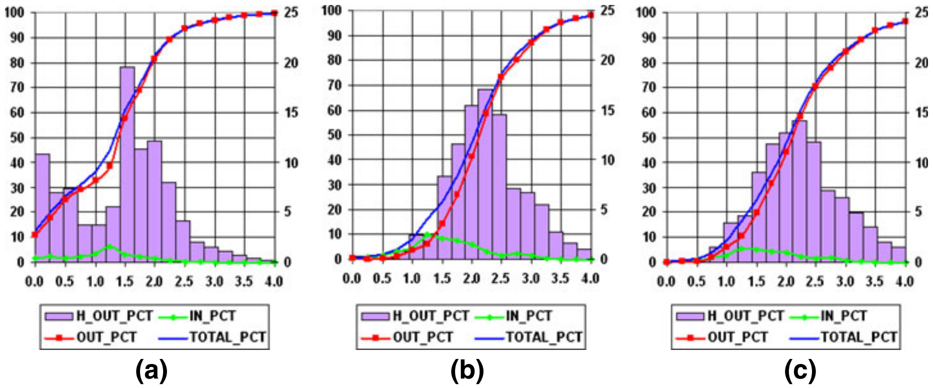


(a) (b) (c)

Fig. 8 Land area (**a**), population (**b**), and property (**c**) hypsometric curves for elevation in Broward County. Variable definitions as in Fig. 7

79% of each county's area, respectively. In Miami-Dade County, about 11% of the land area, most of which is located in Everglades National Park, is already below 0 m elevation. Changes in flooded land areas before and after the elevation threshold in Miami-Dade County are less dramatic than in the other counties, because of the considerable area already below the elevation threshold. The inundated land area resulting from a 0 to 1.25 m sea-level rise is about 27% of Miami-Dade County's area, while the inundated land area resulting from a 1.25 to 2.25 m sea-level rise is about 50% of the county's area.

The effect of inundation thresholds is evident along a profile across Monroe, Miami-Dade, and Broward Counties from Cape Sable to the Atlantic Coastal Ridge (Fig. 2b). The elevation of the marl ridge at Cape Sable reaches about 2 m and then drops to near or below zero in the marsh depression behind the ridge. Elevation rises from 0 to 1.5 m from 45 to 70 km along the profile, and then becomes a nearly flat terrace occupying the area from 70 to 105 km. Elevation rises again to more than 3 m



(a) (b) (c)

Fig. 9 Land area (**a**), population (**b**), and property (**c**) hypsometric curves for elevation in Miami-Dade County. Variable definitions as in Fig. 7

from 105 to 150 km with large fluctuations. The elevations of several locations within this section are below 1 m. Therefore, once the sea-level rises 1.5 m above its current level, there is no topographic high that can block saltwater from the Gulf of Mexico from inundating western portions of Miami-Dade County and Broward County.

Population and property hypsometric curves for elevation exhibit non-linear behaviors similar to area curves, but with considerable differences in processes (Figs. 7–9). The non-linear inundation processes for population and property are not as dramatic as that for land area in Palm Beach County. The inundated land area between 0 and 3 m elevation in Palm Beach County is a small portion of the county's area, whereas 12% and 23% of the county's population and property are located in this area. This is due to high population and property density in the low elevated barrier islands and coastal areas east of the Atlantic Coastal Ridge. The dramatic increase in inundated land area by sea-level rise from 3 to 3.25 m does not cause a rapid rise in inundated population and property because most areas in this elevation interval are located in the Everglades.

The threshold positions for inundated population and property hypsometric curves for Broward County are close to the threshold position for inundated area (1.5 m elevation). However, 9% and 16% of the county's population and property are located in the inundated area between 0 and 1.5 m elevation, compared to only 5% of the county's area located in this area. The increases in inundated population and property are less dramatic than that in inundated areas beyond the 2.25 m elevation, indicating that population and property are denser at higher elevations. The population and property hypsometric curves for Miami-Dade County are characterized by more regular S shapes. The inundated population and property impacted by a 1 m sea-level rise are only 4% and 6% of the county's population and property, respectively, although the corresponding inundated area occupies 33% of the county's area, located primarily in the Everglades and in the southern end of Miami-Dade County. These differences in land area, population, and property hypsometric curves are important in determining the human carrying capacity of the land above a given elevation.

5.3 Effect of accelerated sea-level rise on inundation

Accelerated sea-level rise in the next century further amplifies the non-linear inundation process as shown in Fig. 10. The faster sea-level rise accelerates, the sooner the inundation threshold is reached. For Palm Beach County, the inundated areas for scenarios of 2.5 and 3 m sea-level rise by 2100 comprise less than 5% of the county; however, under these same scenarios, 34% and 54% of the county's area would be inundated by 2120.

Increases in inundation areas in Broward County for six scenarios of sea-level rise are gradual before 2070. The thresholds of inundation processes occur between 2070 and 2120 for scenarios of sea-level rise from 1 to 3 m, respectively. For these scenarios, the inundation proceeds with gathering pace after the threshold is reached as inundated areas increase from 5% to 32% within 10 to 20 years. In contrast to Palm Beach where most topographic lows are located in the non-residential Everglades and are protected by the wide Atlantic Coastal Ridge, the populated low elevation areas west of the relatively low and discontinuous coastal ridge in Broward County are soon inundated as the sea level exceeds the threshold (Figs. 1 and 6). More than

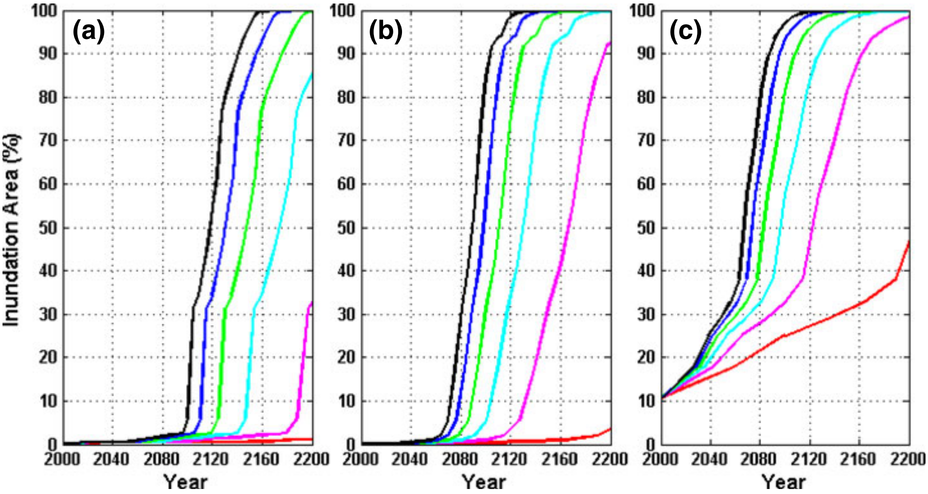


Fig. 10 Land area hypsometric curves for time for scenarios of 0.5 m (*red*), 1 m (*purple*), 1.5 m (*light blue*), 2 m (*green*), 2.5 m (*blue*), and 3 m (*black*) sea-level rise by 2100 in Palm Beach County (**a**), Broward County (**b**), and Miami-Dade County (**c**)

45% of population and 50% of property are located within 32% of the inundated area (Fig. 9). Rapid inundation in Miami-Dade will start between 2060 and 2090 for scenarios of sea-level rise from 1.5 to 3 m. In contrast to Palm Beach and Broward Counties where less than 5% of the inland is inundated before the threshold is reached, about 27% of the area is flooded with considerable speed before the threshold is reached in Miami-Dade County.

5.4 Effect of DEM resolutions

Measurements with vertical and horizontal RMS errors of 0.15 m and 0.45 m, respectively, can be routinely derived through airborne LIDAR surveys (Whitman et al. 2003). The improvement in accuracy allows us to produce DEMs with higher vertical and horizontal resolutions than those produced from older USGS topographic maps. However, a DEM with a finer horizontal resolution for a large area occupies more computer memory and requires more processing time when it is used to estimate inundation extents. A DEM with coarse horizontal resolution can significantly reduce time and complexity of delineating inundation areas. In order to investigate the effects of horizontal and vertical resolutions of DEMs on the delineation of inundation extents, 33 inundation areas for the elevation series from 0 to 8 m with an interval of 0.25 m were generated from both 30 m and 5 m LIDAR DEMs, and both USGS 30 m and 10 m DEMs for the area covered by FIU's LIDAR data set (Fig. 1). The statistics for a difference grid generated by subtracting the 30 m USGS DEM from the 30 m LIDAR DEM was also derived.

Table 4 shows that the RMS differences in inundated land areas for all three counties for 33 elevation intervals derived from LIDAR DEMs with horizontal resolutions of 5 m and 30 m range from 0.36% to 0.53% of the total area of LIDAR coverage in a county. The maximum differences in areas inundated by a series of

Table 4 The difference between inundation areas derived from 5 m and 30 m LIDAR DEMs

County	Total area (km^2)	Max diff (%)	Elevation (m)	LIDAR 5 m area (%)	LIDAR 30 m area (%)	RMS diff (%)
Palm Beach	556	2.95	5.75	85.09	88.04	0.53
Broward	844	2.22	2.00	53.50	55.72	0.49
Dade	873	1.64	2.75	76.12	77.76	0.36

Total area: total areas in Palm Beach, Broward, and Miami-Dade Counties covered by FIU LIDAR surveys, *Max diff*: maximum of the absolute values of the differences between the inundated area from 5 m LIDAR DEM and that from 30 m LIDAR DEM for a given sea-level rise (elevation), *Elevation*: corresponding elevation for Max Diff, *LIDAR 5 m area*: inundated areas from LIDAR 5 m DEM in percentage of the total area of LIDAR coverage in a county for a given elevation, *LIDAR 30 m area*: inundated areas from LIDAR 30 m DEM in percentage of the total area of LIDAR coverage in a county for a given elevation, *RMS diff*: root mean square difference in areas from 5 m and 30 m LIDAR DEMs for 33 elevation intervals from 0 m to 8 m with an increment of 0.25 m

sea-level rise from 0 to 8 m are less than 3% for these two DEMs. The maximum differences in population and property also exhibit a similar pattern because most LIDAR surveyed areas in three counties are occupied by residents. Compared to those for LIDAR DEMs, the differences in land areas for 33 elevation intervals from USGS 10 m and 30 m DEMs are even smaller, with RMS values less than 0.43% (Table 5). The maximum differences in areas inundated by a series of sea-level rises from 0 to 8 m are less than 0.65%. These indicate that the horizontal resolutions ($\leq$30 m) of DEM have little effect on estimating inundated areas, population, and property for a large area with hundreds of square kilometers. Thus, it is appropriate to use 30 m LIDAR DEM to calculate the total inundated areas, population, and property for a large area such as the entire county.

However, using high resolution DEMs is essential for implementing a sea-level rise related policy which involves individual properties. Figure 11 displays the 5 m and 30 m LIDAR DEMs, and 30 m USGS DEM for an area around the Fort Lauderdale Hollywood International (FLL) Airport. Many topographic low and high features in the 30 m LIDAR DEM are different from those in the 30 m USGS DEM, resulting in a dramatic difference in inundated areas for 1 m rise in sea level. In addition to the lower elevation accuracy of the USGS DEM, human modifications to the topographic features made during construction of the FLL airport are not reflected in the USGS DEM. In a comparison of the inundated areas in the 5 m and 30 m LIDAR DEMs, boundaries for individual residential buildings at the south of the FLL airport are obscured in the 30 m DEM. Clearly, the inundation map from the 30 m LIDAR DEM is not appropriate to determine whether an individual residential building is inundated.

Table 5 The difference between inundation areas derived from USGS 10 m and USGS 30 m DEMs

County	Total area (km^2)	Max diff (%)	Elevation (m)	USGS 10 m area (%)	USGS 30 m area (%)	RMS diff (%)
Palm Beach	556	0.36	0	3.27	2.91	0.23
Broward	844	0.63	1	8.38	9.01	0.36
Dade	873	0.65	2.5	64.56	65.21	0.43

The attributes of the table are the same as those in Table 4

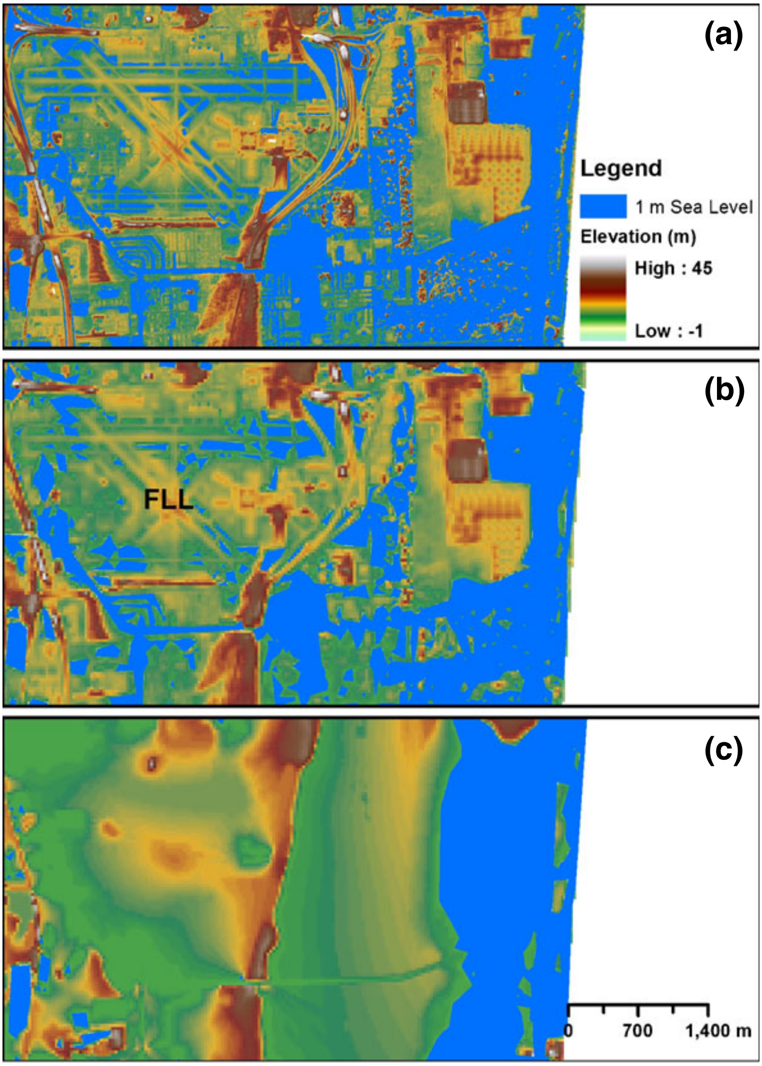


Fig. 11 Five meters (**a**) and 30 m LIDAR (**b**), and 30 m USGS (**c**) DEMs for the area around the Fort Lauderdale Hollywood International (*FLL*) Airport. The topographic modification by construction of the FLL airport is not presented in the USGS DEM. Details of topographic changes in 5 m LIDAR DEM that are important for analyzing the inundation of individual properties are smoothed in the 30 m LIDAR DEM

The vertical resolution of a DEM has more effect on delineating inundated areas than its horizontal resolution. The mean elevation differences between 30 m LIDAR and 30 m USGS DEMs are 0.21, 0.24, and 0.04 m for Palm Beach, Broward, and Miami-Dade Counties, respectively, indicating that USGS DEMs for Palm Beach and Broward Counties are lower in average than the LIDAR DEMs in the areas covered by LIDAR surveys. The RMS differences between 30 m LIDAR and 30 m USGS DEMs are 0.73, 0.74, and 0.83 m for Palm Beach, Broward, and Miami-Dade

Table 6 The difference between inundation areas derived from LIDAR 30 m and USGS 30 m DEMs

County	Total area (km^2)	Max diff (%)	Elevation (m)	LIDAR 30 m area (%)	USGS 30 m area (%)	RMS diff (%)
Palm Beach	556	9.90	4.25	33.39	43.29	2.76
Broward	844	29.45	1.25	17.83	47.28	6.54
Dade	873	10.39	1.50	27.43	37.82	3.99

The attributes of the table are the same as those in Table 4

Counties. These differences are approximately one-half of a 1.5 m contour interval that is the elevation RMS error of the 30 m USGS DEM. This result is similar to that derived by Titus and Wang (2008) who compared the LIDAR DEM for the Maryland coast and the DEM generated from USGS contours.

The RMS differences in inundated areas for 33 elevation intervals between 30 m LIDAR and 30 m USGS DEMs range from 2.8% to 6.5% of the total LIDAR surveyed area for a county (Table 6). Changes in inundated area frequency for each elevation interval from the 30 m USGS DEM are not smooth due to coarse vertical resolution (1.5 m elevation contours) (Fig. 12). The inundated areas for certain elevation intervals have notably larger values than those for adjacent elevation intervals. For example, the inundated area for interval 1 to 1.25 m is about 40% of the total LIDAR covered area for the Broward County. In contrast, changes of area frequencies for each elevation interval from the 30 m LIDAR DEM are gradual, leading to much smoother curves for inundated areas for given elevations. The largest discrepancy in inundated areas occurs at 1.25 m elevation in Broward County (Fig. 12b) and reaches 29% of the total LIDAR covered area (Table 6),

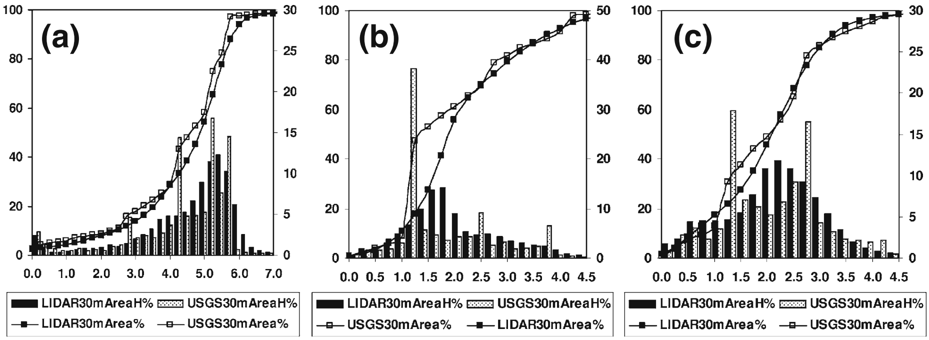


Fig. 12 Area hypsometric curves for elevation derived from 30 m LIDAR and USGS DEMs for Palm Beach (**a**), Broward (**b**), and Miami-Dade (**c**) counties. *X* axis represents the elevation (m) above the NAVD88. *Y* axis on the left side corresponds to variables *LIDAR30mArea* and *USGS30mArea*, and *Y* axis on the right side corresponds to variables *LIDAR30mAreaH* and *USGS30mAreaH*. *LIDAR30mArea*: inundated land areas (outside polygons) from the LIDAR DEM as sea-level rises to a given elevation as a percentage of the total LIDAR covered area for a county. *USGS30mArea*: inundated land areas from the USGS DEM as sea-level rises to a given elevation as a percentage of the total LIDAR covered area for a county. *LIDAR30mAreaH*: histogram for land area from the LIDAR DEM within outside polygons between two adjacent elevations as the percentage of the total LIDAR covered area for a county. *USGS30mAreaH*: histogram for land area from the USGS DEM within outside polygons between two adjacent elevations as the percentage of the total LIDAR covered area for a county

resulting in 165% difference between inundated areas from 30 m LIDAR and USGS DEMs. This discrepancy is mainly due to the elevation differences in LIDAR and USGS DEMs for the topographic lows in southern and eastern Broward County.

In Palm Beach and Miami-Dade Counties, where the LIDAR data set covers more topographic highs and has smaller discrepancies in inundated areas, the largest difference in inundated areas for given elevations is about 10% of the LIDAR covered area, leading to a 30% difference in inundated areas at an elevation of 4.25 m in Palm Beach County and a 38% difference at an elevation of 1.5 m in Miami-Dade County. Therefore, errors of inundated areas delineated using USGS DEMs can be considerably large, especially in topographic lows. Compared to inundated areas derived by the previous study using one degree USGS DEMs (Titus and Richman 2001), the inundated areas for a 1.5 m sea-level rise in the Everglades is much

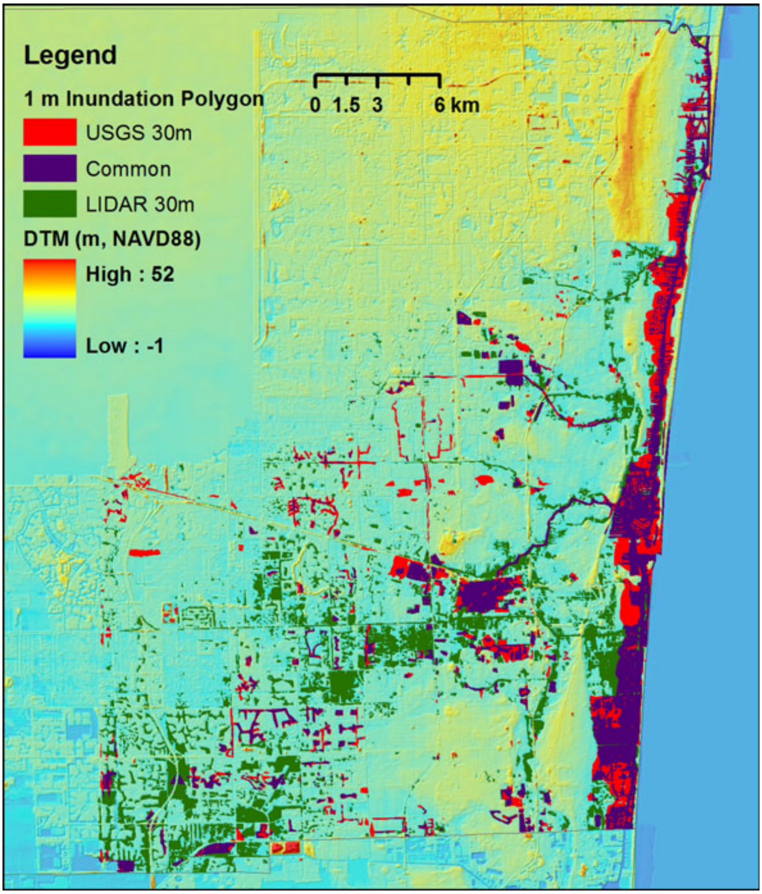


Fig. 13 Inundated areas (polygons) from 30 m LIDAR and USGS DEMs in eastern Broward County caused by a 1 m sea-level rise. The common areas between LIDAR and USGS inundation polygons are *colored dark purple*. Inundation polygons in the USGS DEM, but not in the LIDAR DEM are *colored red*, while inundation polygons in the LIDAR DEM, but not in the USGS DEM are *colored green*

less, but is considerably more in urban regions in southern Broward County and northern Miami-Dade County (Fig. 6), suggesting that accurate DEMs are essential for delineating sea-level rise inundation.

The discrepancy in inundated areas from LIDAR and USGS DEMs in Fig. 12 reveals aggregated errors in delineating inundated areas from USGS DEMs. However, it does not describe the spatial distribution of the discrepancy, which could uncover more errors. For example, Fig. 13 shows the inundation polygons for a 1 m sea-level rise from 30 m LIDAR and USGS DEMs in Broward County. The difference in inundated areas from LIDAR and USGS DEMs appears small, about 2.1% of the total LIDAR covered area in Broward County (Fig. 12b). However, using the common area between LIDAR and USGS inundation polygons as a base reference, we determined that inundation polygons in the LIDAR DEM, but not in the USGS DEM occupy an area about 126% of the common area, while inundation polygons in the USGS DEM, but not in the LIDAR DEM occupy an area 83% of the common area. Therefore, it is not only the difference in the total value of the inundated areas, but also the difference in the spatial distribution of the inundated areas that is important in documenting errors in the process of delineating inundation areas from USGS DEMs.

6 Discussion

Due to the limitations in our understanding of the effects of global warming, there remains large uncertainty in projections of sea-level rise for this century, which range from 0.18 to 5 m. As demonstrated by the case of South Florida, this uncertainty poses a great challenge for implementation of a policy to cope with the impact of sea-level rise on the coastal environment. A 0.18 m sea-level rise by 2100 would not cause a significant impact on South Florida, and a gradual change from the current policy is appropriate to handle this scenario. The comprehensive Everglades restoration plan should proceed as planned because the restoration of historic sheet flow across the Everglades will be helpful in the next several hundred years to reduce the impact of inundation by diluting the saltwater intruding the Everglades and Biscayne aquifer. In contrast, a sea-level rise of 1.5 m or more by 2100 would be catastrophic for Miami-Dade and Broward Counties and a drastic change in policy is needed. A strategic plan for shifting the economic core and population from South Florida to higher elevation areas in central and northern Florida would have to be implemented. The objectives of the comprehensive Everglades restoration plan would also have to be adjusted or even abandoned for the high-end scenarios of sea-level rise. Thus, there is an urgent need from a policy making perspective to reduce the uncertainty in sea-level rise prediction.

Both the public and government agencies are understandably reluctant to take action to reduce the impact of future sea-level rise unless direct and dramatic events actually occur. The large uncertainty in projection of future sea-level rise further increases this reluctance. However, if society is waiting for the arrival of extensive and direct evidence of accelerated sea-level rise impacts before response, non-linear inundation processes clearly show the danger of this approach. The slow inundation process occurring prior to reaching a critical threshold can give people the false impression that sea-level rise does not cause serious problems, whereas the rapid inundation that occurs once the threshold has been exceeded limits the adequacy of a late response. Construction of dikes to protect low-lying areas from saltwater intrusion would be extremely difficult in Broward and Miami-Dade Counties due to the highly porous limestone and sand of the Atlantic Coastal Ridge. In addition, as of 2000, approximately 4 million people resided in Broward and Miami-Dade Counties and between 1990 and 2000 the population increased 29% and 16%, respectively, with future growth expected. Changing policy to reverse this trend of population growth and the relocation of millions of people requires time and resources.

The non-linear inundation process and its amplification by accelerated sea-level rise is not unique to South Florida, and may be a characteristic of other low relief coastal areas such as the Mississippi delta, the Chesapeake Bay, and the Pamlico-Albemarle Peninsula of North Carolina, USA, and the Yangtze River delta in China. All should be investigated using DEMs with high vertical resolution. The effect of non-linear inundation on other processes related to sea-level rise such as coastal erosion, storm surge flooding, and saltwater intrusion also need to be investigated. To mitigate the societal impacts of non-linear inundation processes in low-lying areas such as South Florida, detailed monitoring and mapping of sea-level rise impacts, research on the human carrying capacity and resiliency of limited high land areas, as well as comprehensive planning for relocating population, economic foci, and endangered species in response to various scenarios of sea-level rise need to be undertaken properly.

7 Conclusions

The impact of inundation processes due to future sea-level rise in South Florida was quantified by applying a polygon-based method in GIS to DEMs with high accuracy generated from airborne LIDAR and height finder measurements. The results show that Miami-Dade County is most vulnerable to inundation, followed by Broward County and finally Palm Beach County. A 0.5 m sea-level rise at the end of this century would inundate a large area of Everglades National Park and the marsh areas in southeastern Miami-Dade County. The sea-level rise would not inundate a significant amount of population and property in the three counties. The direct impact of inundation on population and property can be mitigated by preventing saltwater flooding through canals. However, it is challenge to mitigate the impacts of increased surge flooding and exacerbated saltwater intrusion. A 1.5 m sea-level rise would cause catastrophic inundation to Miami-Dade County and southern Broward County, leading to direct flooding of 58% of Miami-Dade County's land by saltwater. The drastic reduction in land area, greatly exacerbated storm surge flooding, and saltwater intrusion would make it impossible to support the entire population living on the remaining high ground in Miami-Dade and Broward Counties. On the other hand, Palm Beach County would not be inundated significantly by 2100 even by a 3 m rise in sea level.

The inundation processes are non-linear as the sea-level rises based on analysis of land area, population, and property hypsometric curves for elevation. There are 3, 1.5, and 1.25 m elevation thresholds for inundated land areas in Palm Beach, Broward, and Miami-Dade Counties, beyond which inundation processes speed up rapidly even for a constant sea-level rise. The acceleration in global sea-level rise in this century can amplify the non-linear process by shortening the time to reach the threshold. The gradual inundation process before the threshold may give people the false impression that sea-level rise does not cause serious problem, while the rapid inundation after the threshold makes an appropriate response impossible. The effect of non-linear inundation has to be considered when policies for mitigating sea-level rise impacts are made.

Comparison of inundated land areas extracted from 550–870 km^2 5 m and 30 m LIDAR DEMs in three counties shows that the 30 m LIDAR DEM is sufficient for estimating the aggregated numbers for inundation areas and associated parameters at the county level. However, LIDAR DEMs with fine horizontal resolutions are needed to determine the inundation processes for individual properties. The elevation difference between the 30 m LIDAR and USGS DEMs has a great effect on estimating the inundated area, population, and property even over a large area, especially for areas with low elevations. A lack of updating topographic elevations in areas that have been modified significantly by human activity also makes USGS DEMs less reliable in inundation analysis. LIDAR DEMs are essential for deriving accurate estimates of sea-level rise impacts for low relief coastal areas such as South Florida. Inundation processes due to sea-level rise along the Florida coast have to be investigated using LIDAR data collected by a state-wide effort on mapping storm surge vulnerable areas.

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