Flood Risks to Urban Development on a Coastal Barrier Landscape of Lekki Peninsula in Lagos, Nigeria

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Flood risks to urban development on a coastal barrier landscape of Lekki Peninsula in Lagos, Nigeria

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ABSTRACT

Lekki Peninsula, which is home to the nouveau riche, is one of the barrier islands of the barrier-lagoon system of the Lagos coastline. The peninsula has been undergoing rapid urbanization since 1980 in total disregard of its physical characteristics. This study assessed landscape dynamics in the peninsula from 1984 to 2014 and evaluated risks to development from potential storm surge flooding. The datasets included baseline data on geographical indicators/island characteristics, satellite imageries and ancillary data. Storm surge flooding hazards and areas at risk were assessed in a Planar GIS environment and with two-dimensional (2D) hydrodynamic simulation using the Cellular Automaton Evolutionary Slope and River (CAESAR) model. Results reveal that the Lekki Peninsula which was a green zone had grown from about 0.5% built-up area in 1984 to about 18% built-up area in 2014. This growth was due to urban expansion and occurred mostly in areas of ecological assets including mangroves, swamps and vegetation. The highest growth in built-up area occurred in Eti-Osa Local Government Area (LGA). Generally, the peninsula has a low-lying topography with 37% of its area lying between 0.5 m and 3 m while 63% is between 3 m and 5 m above mean sea level. Potential inundation simulation with the CAESAR model for selected storm surge levels reveal that at surge heights of 4 m and 5 m, 25% (mostly in Eti-Osa) and 37% respectively of the peninsula are flooded with the latter choking off Epe Expressway on both ends. Initial ingress of inundation occurred in Eti-Osa LGA. In comparison to Planar GIS water levels, the CAESAR model reflected more realistic flood extents. The base flood elevation (BFE) and design flood elevation (DFE) are recommended to improve the sustainability and resilience of future developments along with the recognition of natural processes in future policy and development of the peninsula.

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1. Introduction

With rising sea levels from global warming, low-lying areas along the coast are expectedly at risk of flooding, flood damage and erosion [1]. Although coastal zones worldwide are under the influence of natural processes and anthropogenic action, they are still home to increasing human populations. Generally, coastlines are dynamic areas where the land, air and water zones converge. Within this evolving coastal landscape, there is a dynamic balance between sea level changes, wave action and sediment supply [2]. Located along these coastal zones are fragile, thin accumulations of sand and vegetation that constitute barrier island systems. Barrier islands are dynamic, fragile and relatively young coastal geomorphic features found in nearly 10% of the world's coastlines [3,4]. These sedimentary or depositional barrier islands are usually separated from the mainland by lagoons, bays or estuaries. Unlike stationary landforms on the mainland, barrier islands are naturally unstable. Barrier islands flood, erode, migrate and rebuild in response to hydrodynamic forces (winds, waves, tides, current action, and sea level rise), and episodic storm events [5]. For example, sediment accretion could occur on barrier islands due to the impact of overwash and inundation [6]. The future of these low-lying coastal barrier islands is uncertain as sea level rise is projected to increase (IPCC [7]; [8]). The physical characteristics of barrier islands are covered in detail by Feagin et al. [5], Mcharg [9], Ibe [10], Bush et al. [11], Zhang and Leatherman [12] and Taylor [13]. A typical barrier island has two coasts – the ocean side and the lagoon side (Fig. 1). Madagascar, Colombia and Nigeria each has 3% of the total worldwide length of barrier islands [3].

All over the world, humans have thronged to barrier islands for recreational activities, economic tourism and livelihood sustainability. For example, from Long Island Atlantic seashore (Long Island, New York) through Atlantic City (New Jersey), Miami Beach (Florida), Lido, Italy (barrier island protecting Venice Lagoon) to the remote Bazaruto Island in Mozambique, the intensity of man's utilization of barrier islands for development has ranged from extreme, with high rise structures, to negligible with grass huts and elevated fishing villages. Coincidentally, this quest for the oceanfront is occurring at a period of rising sea levels and eroding shorelines [3]. In many of these places, the intensity and type of development complicate barrier island dynamics and processes which in consequence become risks to the same human activities, often leading to a long drawn out and lopsided costly contest with the sea [14]. Generally, the impacts of urban development on coasts and barrier islands have been well covered in the works of Western Carolina University [2], Feagin et al. [5], Taylor [13], Stutz and Pilkey [5], Bush et al. [5] and Davis and Fitzgerald [16].

As one of the megacities in the world, Lagos was a former capital city of Nigeria and currently is the economic nerve center of Nigeria. Its strategic coastal location, economic potentials and growing population provide livelihood opportunities for the residents [17]. The population growth in the state has been rapid [18], and economically, it is the fastest-growing region in Nigeria [19]. However, its numerous urbanization challenges have made life very difficult for the teeming residents. The recent urban history of the state has been marked by gross infrastructural decay, accentuated by adverse weather events, due to its low-lying topography making it susceptible to flooding [20,21]. Lagos State is afflicted with the issues common to coastal cities worldwide along with population influx and the high demand for development and infrastructure. Rapid urbanization in a generally low-lying Lagos metropolis has resulted in extensive and unregulated wetland reclamation, sand filling of lagoon shores, encroachment on naturally occurring drainage channels and unplanned deforestation [22]. Increased flooding, local rise in sea levels, loss of valuable flora, fauna and wildlife, surface and groundwater pollution and increased urban slums were thus some of the manifestations of this unrestrained exploitation and development [22]. Brody et al. [23] posited that the high population density in coastal areas is associated with an increase in impervious surfaces, watershed alteration and reduced capacity of the environment to contain surface runoff. The physical/geomorphic, climatic and oceanographic processes of the coastal zone and barrier islands (wind, waves, storm surges, erosion, flooding, sediment transport and sea level rise) become enduring hazards when urban development is placed in their path [2,5,9,10,12–15]. This creates a drawn-out contest with these processes. Some effects of urban development on barrier islands especially that of Victoria Island (Victoria Beach) of Lagos have been covered in Obiefuna et al. [24]. It is no secret that residents of Lagos view the coming of the rainy season with misgivings and trepidation due to the harrowing experiences associated with it.

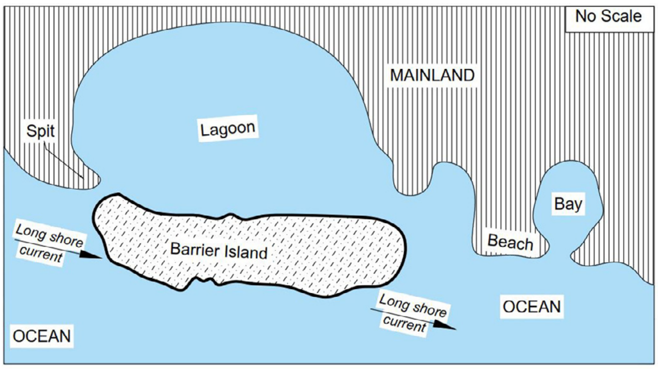

Fig. 1. A sketch of typical barrier island location on symbolic coasts.

On the south-eastern flank of Lagos metropolis is Lekki Peninsula, an area that has seen rapid growth in urbanization in recent times. The Lekki Peninsula barrier island is a dynamic growth area with vast amounts of undeveloped land in vicinities close to the highbrow Victoria Island. Its nearness to Victoria Island has predisposed it to the ever-increasing growth demands of the metropolis [25]. The peninsula possesses the characteristics of barrier islands globally. It is prone to swell-dominated wave regimes [3,27]. Due to the high energy wave regime, and strong west to east longshore current aided by rip currents ([10]; Plate 1a and b), its beaches are highly erosive.

Since 1980, the Lagos State Government has shown interest in an orderly development of the Lekki Peninsula. This manifested with the inception of the Lekki Peninsula Land Use Plan and Development Scheme within the purview of the 1980-2000 Lagos State Regional Master Plan. This initiative was sustained in principle through the land use provisions of both the Lagos State Regional Existing Land Use Plan 2002 and the earlier Revised Land Use Plan 2000/2001. Similar to the 1980 plan, these later planning documents were largely ignored as guiding documents in subsequent official land assignments, village excision and development [25]. Since then, considerable development has occurred largely in an uncoordinated manner and with minimal exercise of development control as urban development outpaced any comprehensive physical planning until recently. Rapid development is ongoing with the construction of Lekki Free Trade Zone (LFTZ) Phase I, the construction of Dangote Refinery and a mix of private, public and institutional development activities. A response to all these activities and ensuing problems was the government's initiative in the completion of an Infrastructure Master Plan and Land Use Plan for the region in 2009. This master plan proposed an intense development of the peninsula and proposed recreational/tourist uses along the Atlantic coastline in Ibeju Lekki. However, contrary to earlier studies including that of French et al. [26], it did not contain any recognition of the island's dynamic characteristics. Clearly lacking in official documents, government policies and actions on the development of Lekki Peninsula and Victoria Island (Bar Beach) barriers, is equally the recognition of the dynamic characteristics of these barriers. This is evident from previous massive erosion and flooding of Bar Beach resulting from anthropic shore protection and port development. Even in the massive reclamation of Eko Atlantic city project of 9 km^2 on Bar Beach [27], recognition of the area as part of the dynamic Victoria Island barrier, is still missing.

There is scarce evidence in the existing literature to indicate appropriate consideration for the dynamics, morphology and characteristics of the Lekki Peninsula and other barrier islands in Lagos as a defense for the mainland against the sea, or for the long-term sustainability of intense development in view of rising sea levels. Seemingly, in the scramble to develop the area, it is lost on collective consciousness that ocean waves, flooding and coastal erosion are constant features of barrier islands as exemplified in other coastal environments, on the previous Bar Beach, Victoria Island and on the peninsula [28]. Also forgotten is the historical knowledge that flooded communities from storm surges, coastal erosion, receding shorelines and frequently displaced coastal settlements have characterized the Atlantic shoreline of the Lekki Peninsula in past decades [29]. Due to the dynamic characteristics of the Lekki Peninsula, it is incumbent on the government to ensure adequate planning in developmental activities that consider the cultural and socio-economic disposition of the people [13] in order to improve the livability of the area. Despite the intensifying development, the precise vulnerability of the area to these threats (most especially, the threat of flooding) and the combined effect of island dynamics to aid solutions, remain spatially unknown or largely unreported in the literature. Although most storm surges on the Lagos coastline are experienced in the months of April – May and August to September [28,30], there is lack of data showing their areal extent on the Lagos barriers or on the Bight of Benin. This lack of spatial data on the Lagos coastline compelled the modeling of the spatial spread in the Gulf of Guinea of about 4m storm surge of 17th August 1995 by Folorunsho [31]. The modeled result of this storm surge height showed a spatial extent of the surge on the Gulf of Guinea as covering from Cote d' Ivoire through the barrier coastline of Lagos to Angola [31]. This underscores the need for a complimentary modeling to determine the landfall and probable areal extent of similar storm surge (such as that of August 17 – 18, 2012 reported in Sholademi et al. [32]) on the Lagos barriers including Lekki Peninsula.

Plate 1. Spilling breaker waves and beach size at Lekki beach - (a) Spilling breaker waves at Lekki beach; (b) Narrow beach at Lekki beach.

A literature survey on flood modeling within urbanized areas of Lagos State shows modest gains by researchers in assessing the social and environmental dimensions of the flood vulnerability. Thus, different perspectives are presented. For example, Nkwunonwo et al. [33] combined the cellular automata (CA) framework with a semi-implicit finite difference numerical scheme (SIFDS) to develop an urban flood prediction model for pluvial events for two local government areas - Lagos Island and Eti-Osa LGAs, both of which are highly urbanized sections of Lagos metropolis. The simulated results from their model were well correlated with actual flood depth with a correlation coefficient of 0.968. In earlier work, Mosuro [34] applied digital elevation model datasets in a hydraulic model to determine a floodplain inundation model suitable for predicting the propagation of flood for a part of Lagos metropolis. The risk levels of properties were mapped by associating the exposure indicators of flood depth and flow velocities to address parcel layers. Adelekan and Asiyanbi [35] examined perceptions of flood risk by residents in flood-affected communities of Lagos megacity. Their approach used a combination of theoretical and non-theoretical techniques including perceptions of vulnerability and flood risk by residents, and a psychometric paradigm approach. Their study showed a high-level perception by the respondents, including feelings of worry and dread with regards to the flood risk. Relatedly, Ajibade et al. [36] explored the heterogeneous experiences of the impacts of flood in three coastal neighborhoods of Lagos based on a bio-psychosocial model of environmental, socio-economic, demographic and behavioral factors. Their study demonstrated that the flood impacts were a result of the complex interplay among these factors. Both Nkwunonwo et al. [33] and Mosuro [34] are among the limited studies that simulated pluvial flooding in parts of the metropolis. Previous assessments by Ibe [10], Awosika et al. (1992, 1993a, 2000), French et al. [26], Nwilo [28], Popoola et al. [37] and Mehrotra et al. [38] drew attention to the dangers of storm surge and sea level rise on the Lagos barriers including Lekki. However, data on the physical extent or landfall, and points of ingress of these scenarios especially at the local council level to facilitate emergency planning are scanty in the public domain. To this end and in part-response to the call by Alves et al. [39] for the use of hydrodynamic modeling for addressing coastal hazards in West Africa, the present study explored a low-cost approach using some geo-indicators [15] and free online data/hydrodynamic software to assess the risks faced by existing and continuing developments on the Lekki Peninsula to the risk of flooding from storm surge as a case study for other Lagos coastline barriers. It is geared towards demonstrating a low-budget, reproducible analyses on coastal hazards and risks which can be integrated into coastal spatial planning and monitoring for the Peninsula and sister barrier islands on Lagos coastline. In addition, the study investigated the utility of the derived information for safeguarding existing and proposed developments on the developing barrier islands of Lagos. This was in response to concerns on the nature of land cover changes in the area between 1984 and 2014 along with hazards and risks to urban development posed by some of the peninsula's physical characteristics as ideas towards effective coastal zone development and management. The risk posed by erosion has been reported in Obiefuna et al. [24].

2. Materials and methods

The methodology workflow is as shown in Fig. 2. This procedure involves baseline data acquisition, data conversion and pre-processing, image classification, land cover change detection analysis, and hazard/risk evaluation.

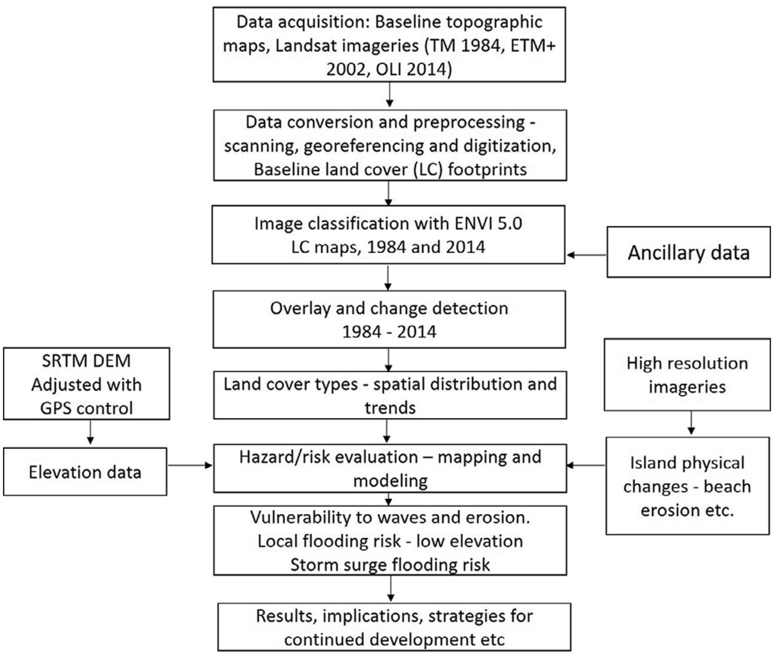

Fig. 2. Flowchart of study methodology.

2.1. Study area

Lekki Peninsula is a rapidly urbanizing area on the south-eastern side of metropolitan Lagos (Fig. 3). It is the location of the Lagos Free Trade Zone (LFTZ) as well as the Dangote Refinery complex under construction. On the west, it is bounded by Victoria Island and Igbosere Creek. Within the peninsula are the Kuramo Waters and Five Cowrie Creek. The Five Cowrie Creek connects to the Commodore Channel. Commodore Channel is the only western connection of both Lekki and Lagos Lagoons to the Bight of Benin/Atlantic Ocean. The Lagos and Lekki Lagoons are located to the north of the Lekki Peninsula and Ogun State is along the eastern border. On the southern axis is the Bight of Benin/Atlantic Ocean. The Lekki Peninsula has an areal extent of about 980km^2, and is geographically located between longitudes $3^{\circ}25'50''E$ - $4^{\circ}21'20''E$ and latitudes $6^{\circ}22'00''N$ - $6^{\circ}37'10''N$. Two climatic seasons are distinguishable in the area: a dry season from November to March and a wet (rainy) season from April to October. There are three main Local Government Areas (LGAs) within the peninsula namely: Eti-Osa, Ibeju-Lekki and Epe.

The Lagos coast consists of west-east trending barrier islands which include the Badagry Island/Lighthouse Beach backed by Badagry Creek, Victoria Island backed by Five Cowrie Creek and Lekki Peninsula backed Lagos and Lekki Lagoons. The Barrier-Lagoon Complex consists of narrow beach ridges, which are aligned parallel to the coast and its sediment composition is characterized by medium to coarse-grained sand [28]. On geology and physiology, opinions differ on whether the barrier islands of Lagos evolved from spits or submergence of beach or dune ridges. From a geomorphological perspective, Ibe [10] posits that these barriers are part of the low-lying Barrier-Lagoon complex which extends from the Nigeria/Benin border eastwards for about 200km. Geomorphologically too, they are part of the Guinea Current Coastal Zone which consists of low-lying sandy barrier islands, behind which is a complex lagoon network stretching from Cote d'Ivoire to Nigeria's Niger Delta [28,40]. As stated by Alves et al. [39], the Bight of Benin coast, which is part of the GCLME region and of which Lagos coastline is a part, represents one of the longest systems of beach-ridge barrier-lagoons in the world. The morphology of the Barrier-Lagoon complex was determined by the several interrelated coastal processes [10]. Characterized by erosive beaches, there is an absence of 'exoreic' rivers flowing through the hinterland to replenish sand lost due to longshore current action. This according to Ibe [10], explains the absence of spits and barriers developing presently. Also, the west to

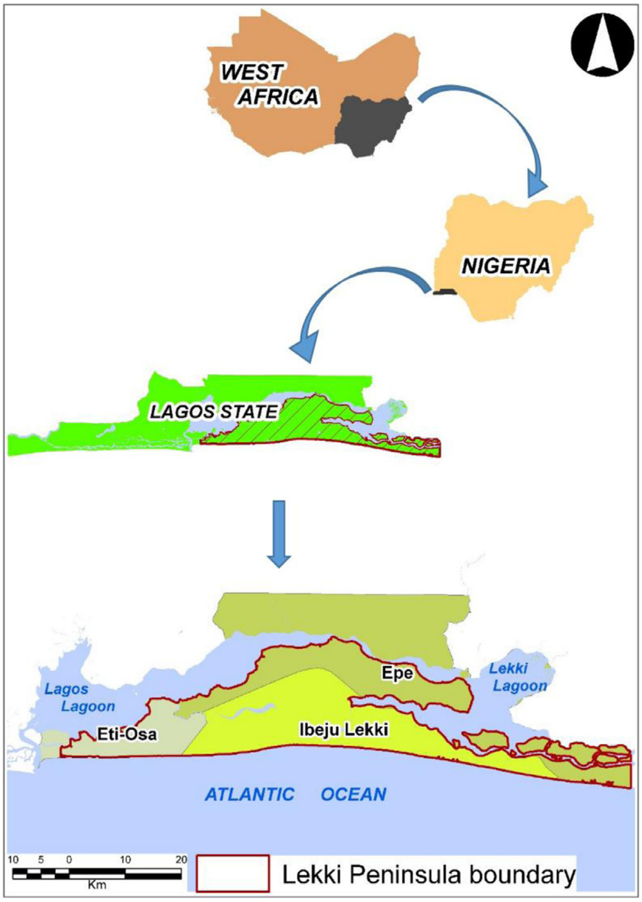

Fig. 3. Lekki Peninsula and Local Government Areas.

east longshore current is very active. Thirdly, the complex has a narrow, steep continental shelf of about 30km wide and which is indented by gullies and submarine canyons including the Avon Canyon (located at 3°55′E, 6°10′N) and the Mahin Canyon further east. Due to the narrowness of the continental shelf, waves reach the shore at higher heights and this leads to loss of nearshore sediments to the canyons and gullies. Lastly, there is intense wave action along the beaches, and this is influenced by the prevailing south-westerly winds. The barrier beaches constitute a narrow belt largely composed of sandy accumulations with an average altitude of 0.75–5 m above sea level and width varying between 2 and 8 km [22].

The geological formations of the Lekki Peninsula are composed of sediments laid down under fluvial, lacustrine and marine environments. These sediments vary widely in thickness and lateral extent [41]. The surface geology is composed of Benin formation (Miocene to recent), recent littoral alluvial, lagoon and coastal plain sand deposits [42,43]. A common feature of the alluvium sediments found in the area is that they are largely composed of sands, littoral and lagoon sediments. These sediments range in size from coarse to medium-grained, clean, white loose sandy soil which grade into one another towards the lagoon and near the mouth of the larger rivers. Litho-stratigraphic information from boreholes in the peninsula shows that a typical stratigraphic section consists of unconsolidated dry and wet sand, and organic clay deposits. The deposits are sometimes interbedded in places with sand-clay or clayey-sand and mud with occasional varying proportions of vegetable remains and peat [43].

2.2. Data acquisition and conversion

The data utilized for this research include baseline datasets on geographical indicators/island characteristics, satellite imageries and ancillary data. Baseline data on land cover and topography was derived from ten 1:25,000 topographic maps of 1984/85. The maps were acquired from the Office of the Surveyor General of the Federation (OSGOF). These maps, with very scanty elevation data, were scanned, georeferenced, manually digitized, mosaicked and edited in the AutoCAD Raster Design software environment. The digitized data were transferred to ArcGIS software and harmonized in the Universal Transverse Mercator (UTM) coordinate system. Additionally, reasonably cloud-free multi-date Landsat imageries of 1984, 2002 and December 2013/January 2014 were acquired from the United States Geological Surveys (USGS) online data center (http//glovis.usgs.gov). For elevation data, freely available 90m SRTM Digital Elevation Model (DEM) v4.1 was downloaded from the website of the Consultative Group for International Agricultural Research (CGIAR-CSI).

2.3. Image classification and land cover change

Six land cover classes consisting of urban or built-up area, bare land, mangrove, swamp, other vegetation and water body were identified on the Landsat imageries for classification. A hybrid classification scheme involving first an unsupervised and then supervised (parallelepiped) classifications were used to classify the imageries in ENVI 5.0 software. The classification output was exported to ESRI shapefile format and transferred to ArcGIS for further editing, areal geometry calculation and preparation of land cover maps.

2.4. Flood hazard/risk evaluation

Storm surge flooding hazards and areas at risk were assessed through a Planar GIS environment and two-dimensional (2D) hydrodynamic simulation. From literature [10,28,30,31,38], high energy spilling breaker waves which dominate the peninsula coastline are driven by the south-westerly winds. These winds generally attain 75–210 cm height between May and October. Furthermore, storm surges on the Lagos barrier coastline occur in the months of April–May and September–October during which high waters can exceed 4m above the low water mark. Based on these, surge heights of 2 m, 3 m, 4 m and 5 m above mean sea level (m.s.l) were appropriate for evaluating the vulnerability of the peninsula to wave overtopping and storm surge flooding. Due to lack of current published data on both local and eustatic sea level rise (SLR) on the Lagos coastline, the effect of SLR on storm surges and storm surge height was adduced from the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) which projects a maximum SLR of 0.9–1.0 m by 2100 for such coastal areas. To simulate 2D hydrodynamic flow and inundation, the CAESAR (Cellular Automaton Evolutionary Slope and River – [44]) model version 6.2 m was utilized. The simulation followed the submission by Ferreira [45] that $risk = hazard \times territorial\ exposure$, with storm surge heights of 2 m, 3 m, 4 m and 5 m. The SRTM DEM was simultaneously exposed to these hazards, first in Planar GIS water levels as benchmark and then in the CAESAR hydrodynamic model as demonstrated by Bates et al. [46].

Inundation in Planar GIS water levels or ‘bathtub’ method without hydraulic connectivity was simulated by intersecting the planar water surface heights of 2 m, 3 m, 4 m and 5 m each with the SRTM DEM to isolate possible flooded areas. A grid cell or area thus was flooded if the elevation fell below the intersecting plane or flood height. Secondly, the SRTM DEM was exposed in the CAESAR model to simulate areas potentially inundated by the same surge heights. The height of 5 m was arrived at by simply using the known surge height of 4 m for the area and accommodating a maximum SLR of 1 m. Inundation was through hydrologic connection to the ocean and the neighboring flooded cell. The underlying assumptions in the hydrodynamic simulation are that flows are in the form of still water flows without wave propagation effects; whereas still water flows entail an overflow mechanism in which overflows occur when bank full depth is achieved. The details for the model execution are covered in Coulthard [44] and the CAESAR model Tutorial version 6.2 m. However, the necessary steps in simulating the inundation potential involved the following: resampling of the SRTM DEM from 90 m to 50 m; the main direction of flow in CAESAR is set from left to right or west to east; running the model in flow and reach mode only with default time step; a wall or barrier of 10 m was constructed next to the coastline on the left or west end of the rotated island to prevent water flowing off into the ocean; the right edge or lower edge of the wall formed the points for the input discharges; input discharges corresponding to surge heights were simultaneously introduced at the input points (50,000 m^3 corresponding to surge height of 2 m or 'low' surge, 100,000 m^3 corresponding to surge height of 3m or 'moderate' surge, 500,000 m^3 corresponding to surge height of 4 m or 'high' surge and 1,000,000 m^3 corresponding to surge height of 5 m or 'extreme' surge); and the input discharges were in the form of still water flows involving overflow mechanism and without wave effects.

The average simulation time for each discharge on a core i7 laptop with 8GB RAM was 3 hours for 'low - high surges' and 2 hours 20 minutes for 'extreme surge' by which time output discharge occurred on the opposite end. The outputs were saved in ASCII format at the end of each model run. These were then converted to raster files in ArcGIS and raster calculator was used to calculate flooded area extents. The need to establish points of ingress of inundation landward was met by saving the progress of the 5 m surge height every 10 minutes of the model run. This pinpointed the time of ingress and the systematic spread of inundation. Subsequently, the maps of planar GIS water levels of 3 m and 5 m were overlain with those of the same levels from the CAESAR model to compare flood extents and demonstrate the effect of hydraulic connectivity. To demonstrate the potential for inundation especially 'high' to 'extreme', to impede vehicular flow in and out of the Lekki Peninsula, a shapefile of road network was overlaid on the inundation maps to show areas of potential bottlenecks or chokepoints in movement on the major route, the Lekki-Epe Expressway.

3. Results and discussion

3.1. Land cover change analysis

The land cover of the Lekki Peninsula for the respective years is shown in Figs. 4a, 4b and 4c while the results of the temporal changes in land cover are shown in Table 1 and illustrated in Fig. 5. Urban development or built-up areas which were less than 0.5% or 4.31 km^2 in 1984 had ballooned to 18% or 176.65km^2 in January 2014. As a marine environment, its critical feature, the mangroves which occupied 4.6% in 1984 had shrunk to 3% in 2002 at 0.91 km^2yr^{-1}, further sliding to 1.4% in 2014 at a faster rate of 1.4 km^2yr^{-1}. Across the three LGAs, Eti-Osa was the most developed as its built-up area grew from a mere 3% in 1984 to 68.4% in 2014 (Table 2). Within the peninsula, areas of severe depletion of ecological assets are manifested. Eti-Osa LGA which was next to Epe in total area of mangroves in 1984 had this asset decimated from 15% to 5% between 1984 and 2002, and it reduced further to about 3% in 2014. Within Epe (Table 3), there was a severe decrease in mangroves as its stock of about 6% had only 2.4% or 8.85 km^2 left in 2014. The growth in built-up area within Eti-Osa occurred mainly in the areas of mangroves and vegetation as both declined cumulatively by 89.83km^2 between 1984 and 2014.

Table 1
Areal changes in land cover within the Lekki Peninsula, 1984–2014.

Land cover	1984		2002		2014	
	km^2	%	km^2	%	km^2	%
Built-up area	4.31	0.44	66.58	6.78	176.65	17.98
Bare land	7.74	0.79	30.27	3.08	43.31	4.41
Mangrove	45.59	4.64	29.23	2.97	13.79	1.40
Swamp	227.19	23.12	215.47	21.93	185.67	18.80
Vegetation	674.29	68.62	618.85	62.98	541.14	55.07
Water body	23.55	2.40	22.26	2.27	22.1	2.25
Total	982.67	100.00	982.66	100.00	982.66	100.00

Table 2
Areal changes in land cover within Eti-Osa LGA, 1984–2014.

Land cover	1984		2002		2014	
	km^2	%	km^2	%	km^2	%
Built-up area	4.2	2.94	61.9	43.34	97.67	68.38
Bare land	4.95	3.47	4.78	3.35	4.55	3.19
Mangrove	21.72	15.21	7.2	5.04	4.25	2.98
Swamp	12.03	8.42	11.56	8.09	10.52	7.37
Vegetation	93.59	65.53	52.66	36.87	21.23	14.86
Water body	6.34	4.44	4.73	3.31	4.61	3.23
Total	142.83	100.00	142.83	100.00	142.83	100.00

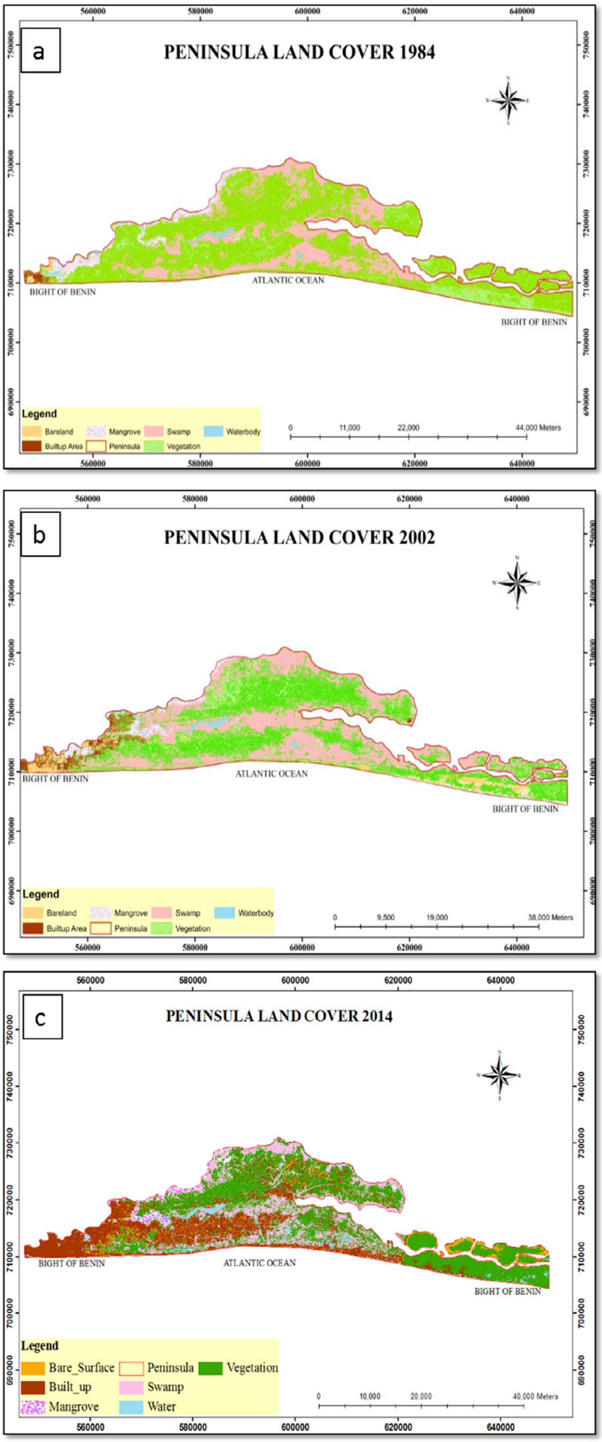

Fig. 4a, b, c. Land cover in the Lekki Peninsula - 1984, 2002 and 2014.

This growth in built-up area on areas of ecological assets and marginal lands is consistent with findings in Okude and Ademiluyi [47], and Obiefuna et al. [24,48]. Equally, the finding amplifies the concerns on the consequences of development in such areas as raised in those studies and in Aliu [19]. As mangroves and coastal wetlands protect coastal areas [49], their large-scale conversion and replacement with impervious surfaces would increase pluvial flooding with loss of flood storage areas [50], loss of tidal breeding grounds, altered associated marine processes and biodiversity among others.

Table 3
Areal changes in land cover within Epe LGA, 1984–2014.

Land cover	1984		2002		2014	
	km^2	%	km^2	%	km^2	%
Built-up area	0.11	0.03	4.67	1.25	19.67	5.28
Bare land	0.51	0.14	7.19	1.93	24.04	6.45
Mangrove	22.32	5.99	20.59	5.52	8.85	2.37
Swamp	70.75	18.98	63.9	17.14	45.21	12.13
Vegetation	270.61	72.60	268.12	71.94	266.75	71.57
Water body	8.42	2.26	8.25	2.21	8.20	2.20
Total	372.72	100.00	372.72	100.00	372.72	100.00

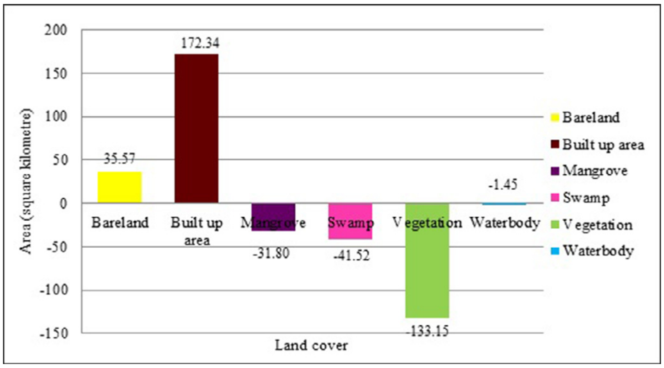

Fig. 5. Resultant changes in land cover in the Lekki Peninsula 1984–2014.

3.2. Analysis of potential flood extents

The spatial distribution of elevation reported previously in Obiefuna et al. [24] confirmed the Lekki Peninsula as generally low in elevation with 37% or 346.61 km^2 lying in the range of 0.5–3 m while 63% or 598.71 km^2 is in the range of 3–5 m above mean sea level (m.s.l). The lack of definitive watersheds and drainage basins from the drainage analysis attests to this low-lying nature. Eti-Osa LGA, the smallest and the most developed LGA in 2014 is the most low-lying with 14.4% of its area between 0.5 m and 1.5 m above m.s.l while 64.3% is between 1.5 m and 3.0 m above m.s.l. In contrast, Ibeju-Lekki and Epe LGAs have 1% and 1.7% respectively of their areas between 0.5 m and 1.5 m above m.s.l just as 28.2% and 27.4% of their areas respectively are between 1.5 m and 3 m above m.s.l.

3.2.1. CAESAR simulation

The potential inundation extents generated from CAESAR simulation for various water heights for surges from 'medium' to 'extreme' are shown in Figs. 6a, 6b and 6c. The potential area flooded by 'moderate' surge is 93.95 km^2 or 9.6%; 'high' is 231.49 km^2 or 24% while 'extreme' is 355.07 km^2 or 36%. With the 'high' surge of 4 m (Fig. 6b), most of Eti-Osa LGA is potentially submerged by upwards of 1m water depth. The western exits from Lekki - Epe Expressway in this area will be choked off by this water depth of 1 m. Interestingly in this scenario, the inundation in the east in Ibeju-Lekki spreads through the Lekki Lagoon northwards into Epe LGA to inundate the Lekki - Epe Expressway with about 1 m water depth, leaving LFTZ Phase I largely unscathed. The 5 m deep 'extreme' surge (Fig. 6c) shows that most of Eti-Osa and the eastern third of Ibeju-Lekki and Epe including the proposed Lekki airport location will be potentially inundated with 1–2 m water depth. Unless new elevated access roads are built, this scenario will choke off the existing access on both ends rendering vehicular access impossible. Under this circumstance, the mid-section of the island offers potential for minimally elevated access out of the island. This inundation also puts at risk government planned estates and projects of Beachland Estate, Maiyegun/Aro, the LFTZ and part of the proposed Lekki Airport. For the 5 m 'extreme' surge, Figs. 7a and b show the points of initial ingress and spread in the west and east. Inundation first ingresses landward in Eti-Osa LGA in the area marked 'A', being Kuramo Waters, old Maroko and the coastline east of these places. Later, it ingresses in the east into Ibeju Lekki LGA at 'B', a location near Ebute Lekki (Fig. 7b). Towards the end of the model run, inundation had potentially blocked Lekki-Epe Expressway in the west in Eti-Osa LGA while discharging into the Lagos Lagoon (Fig. 8). Translated to a 30-hour surge duration time frame adapted from Folorunsho [31], the 'extreme' surge initial ingress at 'A' occurred at about 17.14 hours while the subsequent ingress in the east at 'B' occurred at 21.43 hours, all from the inception of the surge. The discharge into the lagoons started at 25.71 hours.

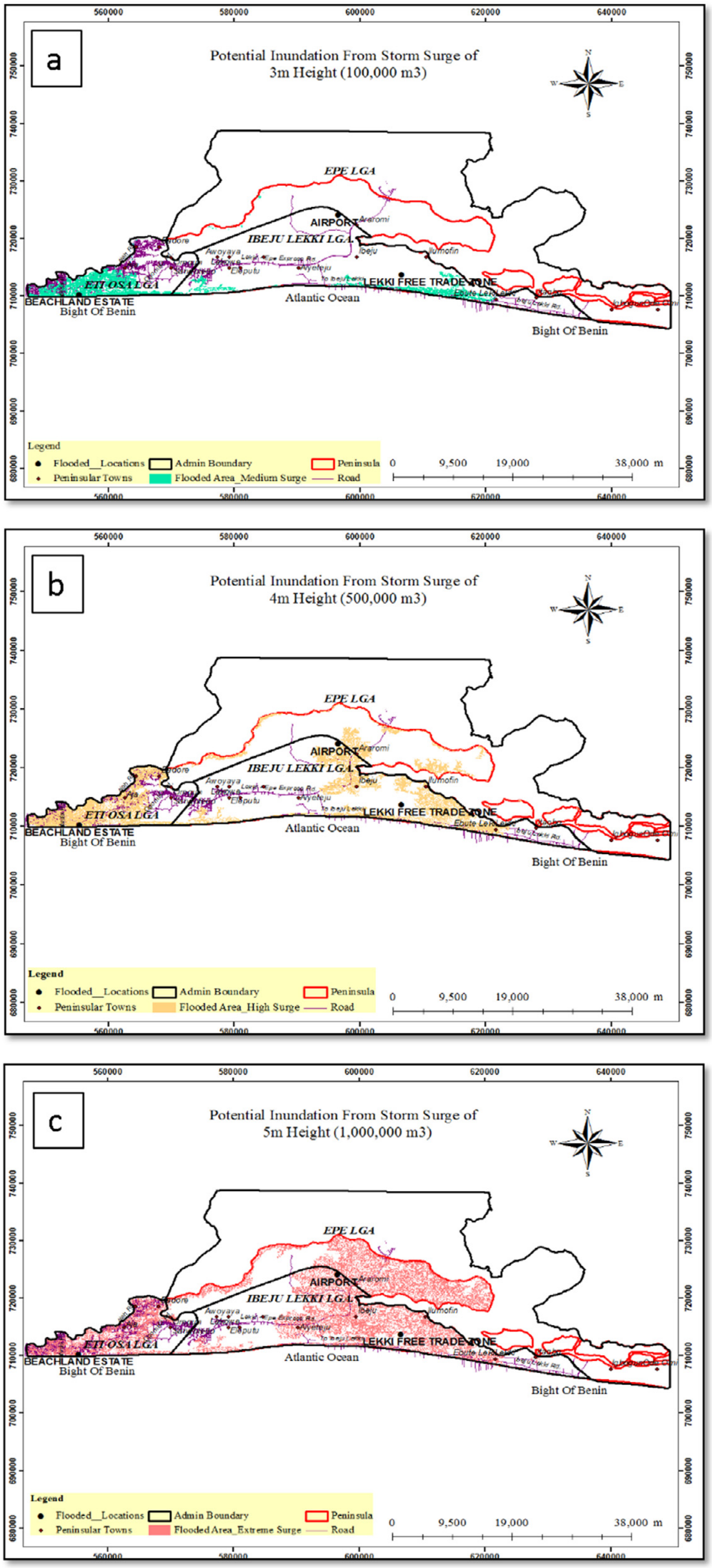

Fig. 6. a: Potential inundation from 'medium' surge of 3 m height – inundated area = 93.95 km^2 (Generated from CAESAR model). b: Potential inundation from 'high' surge of 4 m height – inundated area = 231.49 km^2 (Generated from CAESAR model). c: Potential inundation from 'extreme' surge of 5 m height – inundated area = 355.07 km^2 (Generated from CAESAR model).

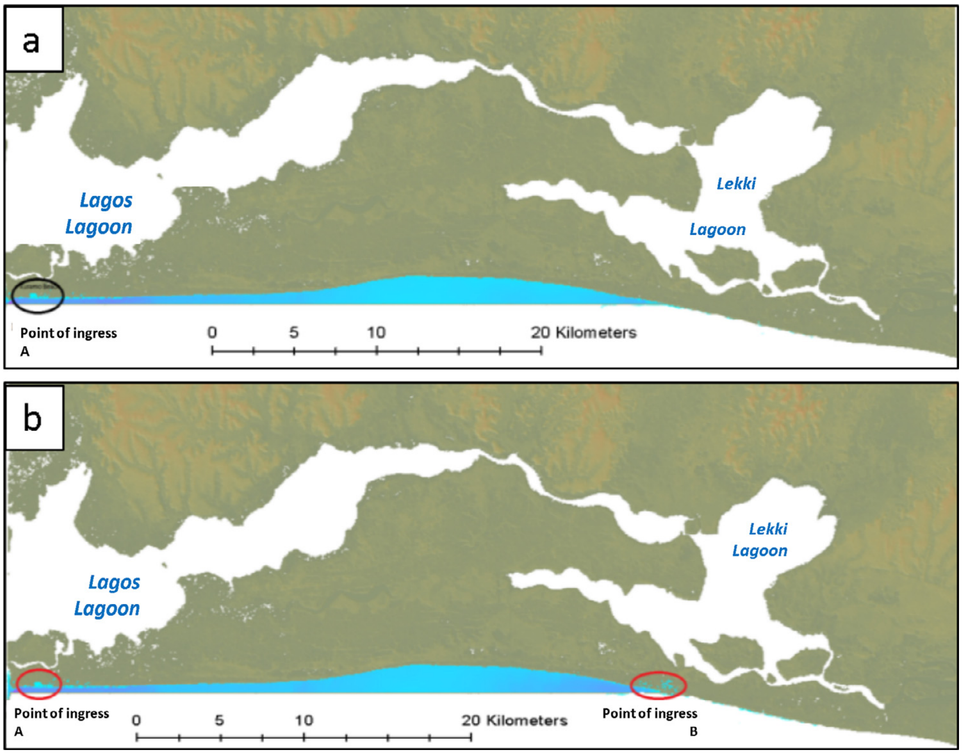

Fig. 7. a: Point A - initial potential ingress of 'extreme' surge at Kuramo Waters, Eti-Osa LGA. b: Points A and B - potential ingress of 'extreme' surge at both west and east in Ibeju-Lekki LGA.

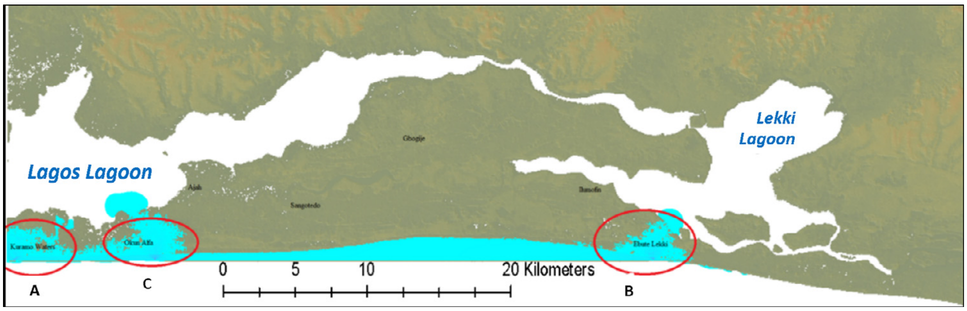

Fig. 8. Potential progress of inundation and discharges into Lagos and Lekki Lagoons with inundation in the west (points A and C) and east (point B) (Generated from CAESAR model).

3.2.2. Comparison with Planar GIS

The potential flood extents for scenarios of low to extreme flood from 'bathtub' or Planar GIS water levels were equally generated to compare or validate areal extents from the CAESAR model. Expectedly, the 5 m height planar water level potentially covers almost the entire Lekki Peninsula at 973.81 km^2 amplifying the low-lying nature of the island. Overlays of the 3 m and 5 m scenarios respectively on those from the CAESAR model show comparative extents and areas at risk as presented in Table 4 with only the overlay of 5 m scenarios shown in Fig. 9. Ostensibly, with hydraulic connectivity to the Atlantic Ocean as the source of inundation, the extents potentially flooded in CAESAR simulation for the two scenarios are considerably much lower by 47.8% (468.43 km^2) and 63.13% (618.74 km^2) respectively. This overlay amply affirms that the bathtub approach usually over-estimates flood extents although it has promising potentials as a tool for assessing pluvial flooding. With hydraulic connectivity, however, the CAESAR model results show more realistic flood extents which can be valuable for emergency planning.

Table 4
Comparative extents of CAESAR model potential inundation and Planar GIS water levels.

Surge height	CAESAR model		Planar GIS	
	km^2	%	km^2	%
Extreme - 5m	355.07	36.23	973.81	99.36
High - 4m	231.49	23.62	941.11	96.03
Moderate - 3m	93.95	9.59	562.38	57.39
Low - 2m	22.94	2.34	188.74	19.26

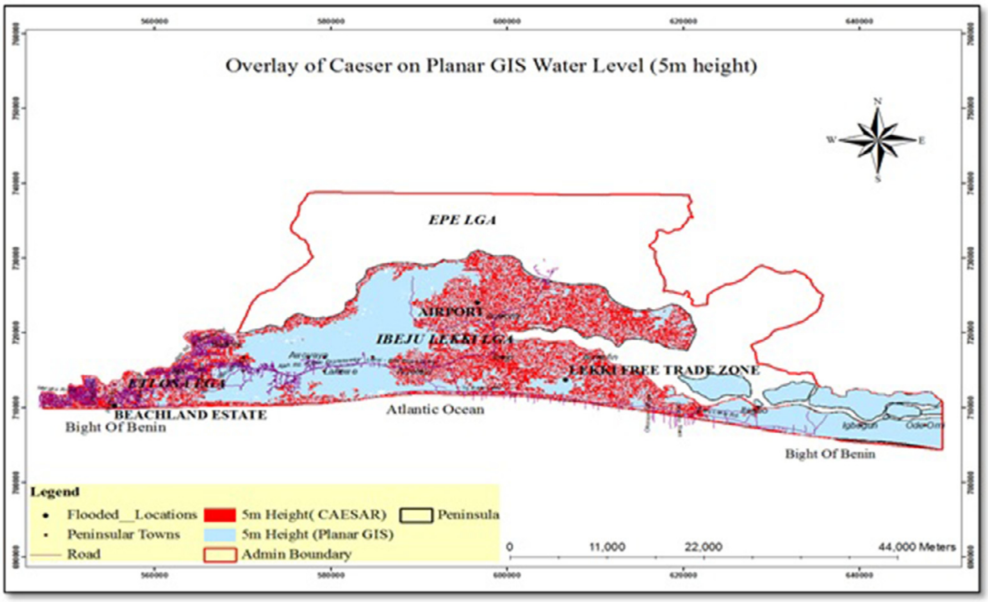

Fig. 9. Overlay of CAESAR and Planar GIS extents for 5 m surge height.

3.3. Matters arising from evaluated risks

The evaluated risks inherently have implications on the livability and continued habitation of the Lekki Peninsula. Livability refers to the quality of life a place offers as being influenced by land use and the built environment [51]. The conversion of protective ecosystems of mangroves and swamps abutting the lagoons to urban development means loss of storage areas for tidal overflow and pluvial flooding. With flood storage areas lacking, this means the floodwaters seek their levels thereby translating into potential flooding for areas previously unaffected with frustrations and misery for residents in the process. This is already evident in some parts of Ajah in Eti-Osa LGA where large tracts of wetlands were acquired for development by private developers and some houses built here have become submerged. With the rapid loss of the mangrove areas, tidal wetlands and the steady decline in vegetation assets comes the pressing need for more robust conservation of part of the remaining biodiversity. It is instructive that the only existing modest conservation effort in Lekki Conservation Center is today a lonely patch of biodiversity hemmed in on all sides by urban development. The remaining tidal wetland patches on the edges of the Lagos Lagoon need to be mapped and dedicated to conservation. Aquatic corridors for the inter-migration of aquatic animals between these patches and Lekki Conservation Center need to be established and safeguarded.

The analysis shows that most parts of the Lekki Peninsula are below 5m in height. Low elevation and drainage inconsistencies within the peninsula, therefore, present livelihood hardships through consequent flooding than the upland areas of the metropolis (Plate 2a-c). To achieve invert levels to enable gravity flow for the discharge of effluents into the lagoons is hardly possible. Even Lekki Phase 1, the first planned estate in the area relies as is common in the metropolis, on open-channel drainage system whose invert levels are inconsistent in some places to enable proper flow. Here also and indeed most of the developments on the peninsula rely on reinforced septic tanks for sewage which according to Dar al - Handasah [25], are generally evacuated frequently or emptied into stormwater/drainage canals and channels when they overflow. For the low-lying parts of the peninsula to have been spared from severe storm surge flooding is perhaps suggestive that the area has hardly been hit by surges of over 3.5 m height. If the predicted rise in sea level of about 1m is reached by the end of the twenty-first century or any time before, the situation might be different.

Among the requirements for flood resilient design and planning are the anticipated flood levels involving the base flood elevation (BFE) and the design flood elevation (DFE) as enunciated in Watson and Adams [52]. This specification is missing

Plate 2. Low elevation areas south of Lekki-Epe Expressway prone to flooding during rains/surge; (a) Maiyegun village; (b) Aro village residence prone to flooding (Note the water mark on the walls); (c) Ogombo - flooded community secondary school.

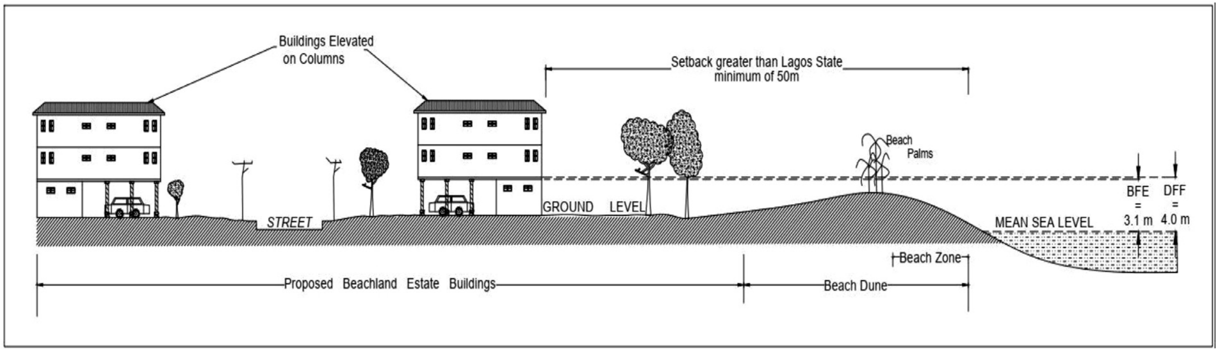

Fig. 10. A sketch of reduced exposure of buildings in the Lekki Peninsula to storm surge flooding through elevation of building/living quarters above the suggested BFE.

in the current Lagos State Planning Regulation of 2010. There is also no published information in the public domain on BFE and DFE or flood maps for insurance purposes for any part of the metropolis including the Lekki Peninsula.

For flood resilient new development in the Lekki Peninsula, the flood extents generated from inundation modeling can be combined with wave data contained in Ibe [10] and storm surge data reported in Folorunsho [30] and Awosika et al. [31]. Wave parameters and water depths observed on Victoria Beach as reported in Ibe [10] were highest in August and September. For August, the breaker heights ranged from 160 to 210 cm as water depth ranged from 189 to 265 cm. Similarly, for September, wave height ranged from 145 to 205 cm while water depth was from 169 to 241cm. Averaging these heights for the two months, the breaker height ranges from 152 to 207 cm while water depth ranges from 179 to 253 cm. Adding the two and deducting the normal mean sea level of 150 cm [30], above zero tide gauge results in a wave crest elevation range of 181–310 cm above m.s.l. Further, the storm surge heights of 3 m and 4 m used in inundation modeling and reported in Folorunsho [30] and Awosika et al. [31] also results in a range of flood elevation of 150–250 cm above m.s.l. An average of the former and the latter (that is, 181 + 150 and 310 + 250 cm) results in a range of 165–280 cm or 1.65–2.8 m wave crest elevation. According to Watson and Adams [52], a 100-yr wave crest elevation is used as base flood elevation for the National Flood Insurance Program and the Flood Insurance Rate Maps (FIRMS) in the United States. No record of such data for the Lekki Peninsula has been seen in the public domain during this study. Thus, allowing for a reasonable margin of safety and as 78% of Eti-Osa LGA and 37% of the peninsula are between 0.5 and 3 m height, it appears sensible to suggest 3.1 m above m.s.l as the Base Flood Elevation (BFE) for new developments in the area. Further allowing for a margin of safety of 60 cm or 'freeboard', the Design Flood Elevation (DFE) in consequence shall be 3.7 m above m.s.l. In providing for building settlement for shallow foundations, the DFE can be raised to 4 m. This is akin to flood-proofing as advocated in Alves et al. [39]. In this case, this entails raising the structures/living areas above the expected flood level.

However, these suggestions do not account for pluvial and other inland flooding as well as other uncertainties that may assail the Lekki Peninsula as an intensely developed barrier Island. For these reasons, it is wiser that new developments in the peninsula are elevated to a minimum of 3m above this suggested DFE. This way, the ground floor will be devoted to parking and gardens while living/working spaces are from the first floor as displayed in Fig. 10 and Plate 3. This is very ideal for the planned Beachland Estate on Lekki Beach as it is already exemplified in the Lekki Peninsula in the Chevron head office building where earth berms or mounds were deployed to elevate the buildings for flood resilience.

Inundation simulation with the CAESAR model amplified the risks to parts of the Lekki Peninsula from its low-lying nature. It showed that most of Eti-Osa LGA, and parts of Epe and Ibeju-Lekki LGAs are substantially at risk from the potential storm surge of 4–5 m water height. These inundation levels will potentially drown and choke off the main access

Plate 3. Elevated Chevron Nigeria Ltd Head office building in Lekki with earth berms above street level.

route of Epe Expressway in both west and east. Along with minimal inter-connectedness of feeder roads, these will impede evacuation in flooding emergencies. An urgent need arises for an alternative main access route to be elevated at least 4–5 m above m.s.l for safe access during flooding emergencies especially as the proposed 4th Mainland Bridge appears to have floundered. Also, the proposed Coastal Regional Road which the Lagos State government made feeble moves to free up in February 2020 from right-of-way encroachment by residential developers, needs to be elevated. This is to protect the road from the threat of storm surge flooding and perhaps coastal erosion already seen during the study to be threatening its alignment in Eti-Osa LGA around the end of Ligali Ayorinde Street. The new Ikoyi Link Bridge is a welcome development, but it needs to convey ensuing traffic much further down the lagoon coastline than it does presently.

A further consequential suggestion for flood resilient re-development of the affected existing low-lying developed areas is for the state to perhaps undertake to buy out the owners of these places in order to properly raise the levels to the recommended DFE. This may be too prohibitive and difficult especially for the excised villages with some ancestral homes in these locations. Alternatively, an advocacy approach with the phased implementation of sand filling is another track. Relocating the residents of these areas to locations of undeveloped and higher elevations in Epe and Ibeju-Lekki LGAs is a possible option. However, much of the undeveloped land in these places are already committed to planned uses such as the Lekki Airport and Free Trade Zone (LFTZ).

Other suggestions toward resilient future development on the Lekki Peninsula emanate from a mix of applicable structural and non-structural strategies being advanced [13,39,52] and pursued for new coastal developments in other countries of the world. These include the provision of shoreline protection and stabilization measures such as dune enhancement, groins, levees and dykes capable of reducing or diffusing storm surges through their elevation. Also included are the creation or restoration of natural assets such as wetlands which provide ecosystem services to absorb or diffuse surges and sea level rise impacts; possible provision of flood detention/retention, absorption and diffusion areas where space permits; provision of routes for emergency egress and access for first responders and post-event return; establishment of an early warning system, community emergency communication and procedures for emergency response and evacuation for a flooding event [52]. Incidentally, the existing infrastructure master plan of 2009 [25] has no provision or room for implementing flood detention or diffusion areas. As already reported in Obiefuna et al. [24] and Nwilo et al. [53], the construction of eighteen groins has been implemented on the shoreline of the Lekki Peninsula with palpable results.

4. Conclusion

This study has undertaken an inexpensive integration of satellite imagery, digital elevation data, remote sensing and GIS techniques with numerical hydrodynamic modeling to assess the dynamics of land cover and flooding risks to urban development on the Lekki Peninsula of Lagos State. This is a basis for understanding the sister developing barriers on the Lagos coastline and could serve as basis for studying similar developed/developing barriers on the Bight of Benin/GCLME region. With rising sea levels coupled with the rapid and intense development on some of the barrier island systems along the Lagos coastline, the need to understand some of the consequent environmental risks tied to their development has become imperative especially with the past experience from the sister developed barrier of Victoria Island. This is fanned by the current knowledge that to enhance livability and resilience on barrier islands and coastal zones, appropriate planning and development on them ought to be based on the understanding and accommodation of their dynamic physical characteristics within the context of human needs. Results from the study have underscored the area as low-lying and potentially prone to storm surge flooding of varying heights. The study has also established that some of the risks facing urbanization in the Lekki Peninsula are those tied to the natural and physical processes inherent in the formation of barrier islands. Other risks include the low elevation, storm surge flooding, beach recession and effects of global sea level rise. These risks should underpin any future policy, planning/development actions on the peninsula, on other barriers on the Lagos coastline and the Gulf of Guinea coastline to minimize such risks.

With the limited public knowledge and discussion on the inherent natural hazards on barrier islands along with the dangers of permanent human development on these otherwise dynamic geomorphic features defending the mainland, the study has attempted to raise awareness and help engender a better understanding of what happened previously on the sister barrier of Victoria Island. In addition, with spatial data scarcity (lack of vulnerability maps) on the landfall and reach of previous storm surges and while numerical modeling has enjoyed limited application in storm surge studies, this study has demonstrated its use as a storm surge predictive tool in line with the Sendai Framework of disaster risk reduction through preparedness.

To improve the resilience of proposed developments, the base flood elevation (BFE) and design flood elevation (DFE) has been suggested, which may also be applicable to other barrier islands in Lagos and West Africa with further inquiries. Other suggested actions for flood resilient development include structural and non-structural strategies being applied in other parts of the world. Regardless of the suggested measures and any other being implemented for the resilience of development in the Lekki Peninsula, it needs to be re-emphasized that low elevation, coastal erosion, flooding (pluvial and marine) are unchangeable natural processes of this barrier island and thus the life cycle of any barrier island. Protection measures can only buy time but do not stop their mobility. With sea level rise as predicted, these processes are expected to exacerbate. Part of the overall resilience strategy should therefore be the option of 'retreat' when possible. Despite the limitations imposed by the coarse SRTM DEM used for the hydrodynamic modeling, the study has advanced actionable procedures and spatial information which can be refined with finer grain elevation data such as is obtainable from airborne LIDAR (Light Detection and Ranging). This will help with evaluating development and pre-disaster risk assessment on both the peninsula and sister barriers on the Lagos coastline. Finer grain data will also enable the validation of the results of this simulation and the conclusions derived from it. Areas for further study include the numerical modeling of storm surge on the entire coastline of Lagos with the completion of Eko Atlantic City, to investigate surge behavior on Commodore Channel. This includes the investigation of social and economic impacts of the simulated potential inundation along with scenarios for emergency preparedness and evacuation in line with the Sendai Framework.

Finally, this study in part responds to the need and call by Alves et al. [39] for the use of numerical modeling to help predict extreme coastal flood events on the West African coastline for effective coastal management. It must be added that except for free online numerical models, many other models are not cheap and affordable by an unfunded individual researcher. As part of the barriers of the Bight of Benin/Gulf of Guinea, the recommendations and solutions offered here for the potential scenarios are applicable and can be inquired upon for similar low-lying, developed/developing barriers in the region.

Declaration of Competing Interest

The authors declare no conflict of interest.

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