Cover page

Meeting the Challenges of Flood Risk Assessment in Data Poor Developing Countries, With Particular Reference to Flood Risk Management in Lagos, Nigeria.

By

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Title page

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Abstract

Flooding poses significant threats to many urban areas globally. Realistically, flood risk assessment (FRA) which underlies solutions to these threats is often difficult to accomplish within the context of data poor developing countries (DPDCs), such as Nigeria, Mozambique and Bangladesh, and this highlight key issues, which are crucial for research. Despite the increasing vulnerabilities of people and urban assets, and the weak institutional capacity that prevails, previous research efforts relating to flood risk management (FRM) have failed to address this lingering issue of data paucity. Vulnerabilities of social systems in particular have not been assessed, although few discussions relating to vulnerability largely show that this concept is being considered, but within a limited scope and application. Although the level of awareness of urban flooding in the DPDCs is considerably poor, more scientific procedures, such as flood modelling, is lacking.

The present research is motivated by these issues, and therefore provides a possible workaround, using Lagos, Nigeria as a case in point. A critical review of flooding and current efforts to address flood risk in Lagos was undertaken. This is crucial to identify key objectives that will need to address present urban flooding challenges, and close the gaps in knowledge of FRM, between increasing urban flood risk and the means of protecting human lives and urban assets, to achieve a major sustainable urban development goal. Using the general view of vulnerability, proposed by Adger (2006) and IPCC (2007) in which vulnerability is defined on the basis of exposure, susceptibility and lack of coping capacity, social vulnerability to urban flooding in the area was evaluated. Indices of social vulnerability (SocVI) were constructed for the sixteen Local Government Areas (LGAs) that make up the Lagos city. A new flood model, *GFSP-1 (Geoinformation Flood Simulation Program 1)*, was developed by combining two conceptual parts – Cellular Automata (CA) and Semi-Implicit Finite Difference Scheme (SIFDS).

The new model was tested and validated in Portsmouth, United Kingdom, using a severe flooding event that occurred on September 15th 2000. This event was chosen since map of hotspots of surface water flooding and social media-based information, especially photographic images of the event, were available to enable a rigorous validation of the new model. Simulation of various spatial and temporal scenarios for the July 11th 2011 flooding in Lagos was also carried out. In both of the test cases, the new model required only a 2-m horizontal resolution airborne LiDAR DEM, Manning's friction coefficient, and a rainfall intensity value to simulate urban flood hydrodynamics.

The results emerging from the research are as follows. Firstly, the SocVI construct indicates a high level of social vulnerability to urban flooding in Alimosho, Kosofe and Agege LGAs in Lagos metropolis. Secondly, in relation to the new flood model, the results show that *GFSP-1* simulated flooding at locations similar to those depicted by the map of hotspots of surface water flooding in Portsmouth, and identified during the reconnaissance survey in Lagos. Simulated maximum flood water depths from ten sampled locations in Portsmouth and six in Lagos compared well with estimated maximum flood water depths. The Pearson correlation coefficient (r) between model predictions and estimated values is 0.986 for Portsmouth, and 0.968 for Lagos. This indicates optimal performance for the new model in terms of reconstructing the characteristics of urban flooding. Additionally, the plots of water depth vs. time which produce a smooth curve throughout the simulation, and the short time spent in the simulation show that the model's outputs are unconditionally stable, and inexpensive from a computational point of view. These are major issues of considerations in flood modelling research.

The challenges of flooding in the DPDCs will continue unabated unless significant improvements are made on current flood risk policy and management efforts. This will necessitate evolving new measures, by which the urgent needs to protect human lives and economic infrastructure in the DPDCs outweigh considerations for uncertainty and standardisation in FRM. These new measures will consider the critical understanding of the dynamics of urban flooding, and the factors that influence social vulnerability to the hazard in the DPDCs. While such understanding is underpinned by provision of data and mapping of urban flood hazard and risk, considering climate change scenarios, how to maximise the potentials within presently available datasets in the DPDCs should be explored as a major research opportunity. The present research explores this opportunity, and, through its objectives and findings, provides flood hazard underpinnings, as well as makes significant contributions to knowledge in the area of ameliorating the impacts of urban flooding in Lagos in particular, and data poor urban centers in general. It is fundamental to innovative FRM policy and practice within these areas, as well as existing strengthening existing flood risk adaptation efforts.

Table of Contents

Declaration

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

Word count: 56, 633 words

List of Equations

List of Tables

List of Figures

Abbreviations

1.	ArcGIS10.2	*Arc Geographic Information System software*
2.	ASTER	*Advanced Space-borne Thermal Emission and Reflection radiometers*
3.	CA	*Cellular Automata*
4.	CRED-EMDAT	*Centre for Research on Epidemiology of Disasters Emergency Database*
5.	CFL	*Courant Fredrick Lewy*
6.	DCs	*Developing Countries*
7.	DEM	*Digital Elevation Model*
8.	DRIVER	***DR**iving **I**nno**V**ation for crisis management for **E**uropean **R**esilience*
9.	DRR	*Disaster Risk Reduction*
10.	DSM	*Digital Surface Model*
11.	DTM	*Digital Terrain Model*
12.	ECFD	*European Commission Flood Directive*
13.	ESRI	*Earth System Resources Institute*
14.	FEMA	*Federal Emergency Management Agency*
15.	FMUS	*Floodplain management in the US*
16.	FRM	*Flood Risk Management*
17.	FRMN	*Flood Risk Management for Netherlands*
18.	GAUN	*General Assembly of the United Nations*
19.	GFDRR	*Global Facility for Disaster Reductions and Recovery*
20.	*GFSP-1*	*Geoinformation Flood Simulation Program 1*
21.	GIS	*Geographic Information System*
22.	HDI	*Human Development Index*
23.	IDE	*Integrated Development Environment*
24.	IDF	*Intensity Duration Frequency*
25.	IFRMEW	*Integrated Flood Risk Management for England and Wales*
26.	IMPULSE	*IMProving Urban flood management in Lagos via Systematic Efforts*
27.	LC	*Land Cover*
28.	LGAs	*Local Government Areas*
29.	LiDAR	*Light Detection and Ranging*
30.	LU	*Land Use*
31.	MATLAB	*Matrix Laboratory*
32.	NIMET	*Nigerian Meteorological Agency*
33.	OECD	*Organisation for Economic Corporation and Development*
34.	OOP	*Object Oriented Programming*
35.	RAM	*Random Access Memory*
36.	RCM	*Reduced Complexity Models*
37.	SI	*Standard International units*
38.	SIFDS	*Semi Implicit Finite Difference Scheme*
39.	SocVI	*Social Vulnerability Index*
40.	SRTM	*Shuttle Radar Topographic Mission*
41.	SWEs	*Shallow Water Equations*
42.	UNDP	*United National Development Programme*
43.	UNISDR	*United Nations International Strategy on Disaster Reduction*

Glossary

S/No	Terms	Meaning
1.	Adaptation to climate change	The process of change by which an human population and urban infrastructure becomes better suited to the variations in weather conditions.
2.	Boundary condition	A condition that is required to be satisfied at the edges of a region in which a set of equations or models is to be solved.
3.	Calibration of flood models	The process of setting the parameters of a flood model to provide a simulation result for an area within an acceptable accuracy or error limit.
4.	Cellular automata	A mathematical principle in which the behaviours of a set of cells within a cellular space is controlled by a set of rules at a given time.
5.	Coping capacity	The means by which people or organizations use available resources and abilities to face adverse consequences that could lead to a disaster.
6.	Digital Elevation Model (DEM)	A specialized database that represents the relief or overall topography of a surface between points of known elevation.
7.	Flood extent	This refers to the total surface area that has been inundated during a known flooding event. It is often determined by the flood return period.
8.	Flood modeling	This is a no structural flood risk management approach to reconstruct a particular flooding event in terms of its extent and depth, using a set of mathematical formulas.
9.	Flood risk assessment	A method to quantify or estimate the impacts of flooding. The result of such procedure informs a method of flood risk management and policy.
10.	Flood risk management	This is the procedure to reduce the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods.
11.	Global climate change models	These are quantitative methods to simulate the interactions of the important drivers of climate change, including atmosphere, oceans, land surface and ice.
12.	Hydraulic flood models	A mathematical expression, computer code or smart application that is used to reconstruct and analyse the dynamic behaviors of flood inundation.
13.	Light Detection and Ranging (LiDAR) data	The most accurate topographic dataset that is produced by sending to and receiving light pulses from the earth surface.
14.	Numerical flood models	A group of flood models that use some sort of numerical schemes or time-stepping procedure to reconstruct or analyse a historical flooding event.

15.	Paleofloods	Paleofloods are geological evidence that can be used to reconstruct the magnitude and frequency of recent, past, or ancient flooding events.
16.	Parameterisation	The means to describe or represent a phenomenon, for example urban flooding, in terms of parameter or variables to enable the analyses of that phenomenon.
17.	Rainfall intensity	The ratio of the total amount of rain (rainfall depth) falling during a given period to the duration of the period. It is usually expressed as mm per hour (mm/h).
18.	Reduced complexity Model (RCM)	Also known or the simplified 2-D flood models are based on simple mathematical complexity. They solve the simplified version rather than the full shallow water equations.
19.	Resilience to flood risk	This is the capacity to recover quickly from flood losses. It is often supported by strong social and institutional capacity.
20.	Sensitivity analysis	This is a way to determine how variations in one variable, which constitute a model, impact the overall predictions of the model.
21.	Shallow Water Equations	A set of equations derived from the Navier -Stoke equation, and that underlie the formulation of hydraulic flood models.
22.	Social media data	A set of data that are based on social media sources such as, twitter, Google, What Apps, etc.
23.	Social vulnerability	A vulnerability based of social and demographic variables such as poverty, age, gender, socio-economic status, etc.
24.	Social vulnerability Index	A metric, such as a number that can be used to indicate the vulnerabilities of two or more places based on social variables.
25	Social vulnerability Indicator	A factor or a variable that is used as a proxy for computing social vulnerability. For examples: poverty, age, gender, socio-economic status.
26.	Sustainable urban drainage system (SUDS)	This is an approach that mimics natural processes to attenuate flooding, prevent or reduce contamination, and enhance biodiversity and amenity value of the environment.
27.	Uncertainty in flood modelling	This is the degree of unreliability of a flood model. It accounts for the variations between model predictions and observed or real world data.
28.	Uncertainty analysis	This is a technique to determine the quantity or the value that accounts for variations between model predictions and observed or real world data.
29.	Urban flooding	This is the overflow of water in a built-up area caused mainly by climate change and poor drainage facilities.
30.	Validation of flood models	This is a technique to assess the degree to which a flood model accurately predicts measured or real word data on flood extent and depth.

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Dissemination

1. Nkwunonwo, U. C., Whitworth, M., & Baily, B. (in press). An efficient assessment of social vulnerability to pluvial flood risk in the Lagos coastal city of Nigeria. *Journal of Applied Geography*.

2. Nkwunonwo, U. C., Whitworth, M., & Baily, B. (in press). Urban flood modelling combining cellular automata framework with semi-implicit finite difference numerical formulation. *African Journal of Earth Sciences*.

3. Nkwunonwo, U. C., Whitworth, M., & Baily, B. (2016). A review and critical analysis of the efforts towards urban flood risk management in the Lagos region of Nigeria. *Natural Hazards and Earth System Sciences, 16,* 349-369.

4. Nkwunonwo, U. C., Whitworth, M., & Baily, B. (2015). A review and critical analysis of the efforts towards urban flood reduction in the Lagos region of Nigeria. *Natural Hazards and Earth System Sciences Discussion, 3,* 3897-3923.

5. Nkwunonwo, U. C., Whitworth, M., & Baily, B. (2015). Flooding and flood risk reduction in Nigeria: cardinal gaps. *Journal of Geography and Natural Disasters, 5(1),* 1-12.

6. Nkwunonwo, U. C. Whitworth, M., & Baily, B. (2015). Relevance of social vulnerability assessment to flood risk reduction in the Lagos metropolis of Nigeria. *British Journal of Applied Science & Technology, 8(4),* 366-382.

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8. Nkwunonwo, U.C., Whitworth, M., Baily, B., & Inkpen, R. (2014). The development of a simplified model for urban flood risk mitigation in developing countries. ASCE council on Disaster Risk Management monograph No. 9: Vulnerability, uncertainty and risk: quantification, mitigation and management. Second international conference on vulnerability and risk analysis and management (ICVRAM) and sixth international symposium on uncertainty, modelling and analysis (ISUMA). (pp. 1116-1127). Liverpool: American Society of Civil Engineers (ASCE).

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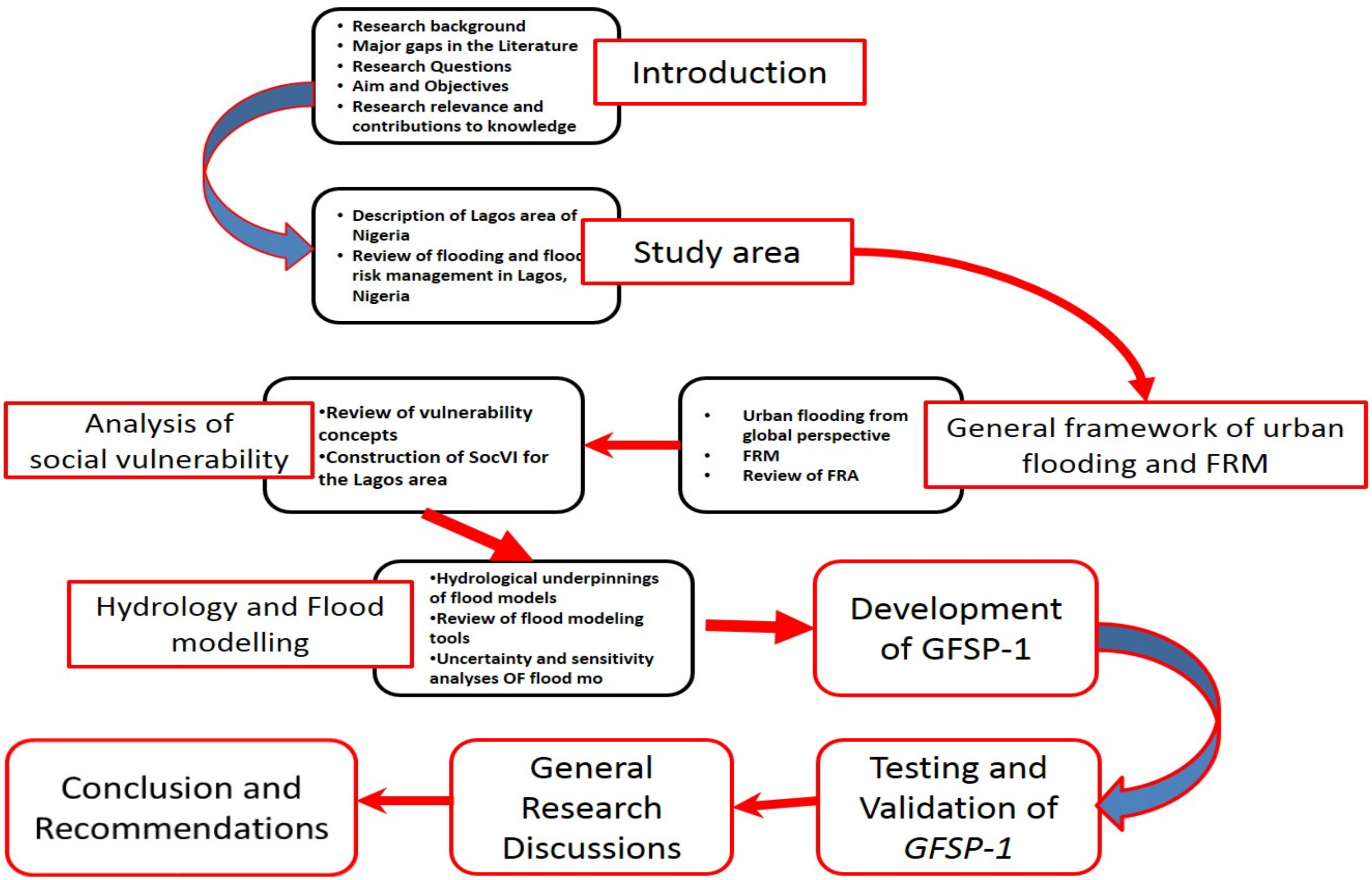
Framework of the present research, and the thesis structure



1 Introduction

This chapter presents the general background and context of the present research. It also describes the significant gaps identified in the literature, and outlines the key questions, which the research was designed to address. The main aim and important objectives of the research are highlighted, whilst its novelty and the contributions it makes to the science of flood risk management, and the possible future impact, are emphasised. Finally, the structure in which the rest of the thesis is organised is also presented.

1.1 The general background and research context

Flooding, in the general perspective, is arguably a naturally designed occurrence, which sometimes can be of significant benefits to ecological systems (Nguyen *et al.,* 2007). However, when such occurrence exceeds the capacity of a given community to cope, it becomes a hazard, which threatens human lives and properties. Looking at naturally-occurring hazards generally, flooding is the most common, accounts for more than 40% of all global economic losses, and affects both rural and urban settlements (Ohl &Tapsell, 2000; Ahern *et al.,* 2005; Di Baldassarre *et al.,* 2010). Over the last few decades, severe damage caused by flooding has been reported in the United States, Europe, Asia, Australia, Africa and the Caribbean (CRED/EM-DAT database).

Over the years, flash, fluvial and coastal flooding have caused severe damage to people and assets (Environment Agency (EA), 2000; CEA, 2007; Lumbroso & Vinet, 2011). Flash flooding usually is an unexpected event, mostly triggered by a sudden heavy rainfall, breeched levee and dam break. Fluvial flooding which is common among major rivers across the world, including the rivers Thames, Rhine, Mississippi, Yangtze and Niger, occurs when a river overflows its banks due to heavy rainfall or snow melt that raises the water level suddenly. Coastal flooding is considered when the sudden overflow of water (especially from rivers) inundates coastal areas. Whilst more than one-third of the world's human population and major cities are located within the coastal areas and small islands (Refer to: Small & Nicholls, 2003; Barbier *et al.,* 2008), a high level exposure and vulnerability of human populations and the built environment to flood risk can be an important research issue. The core urban areas are non-trivial issues in relation to these floods. Considering the recent increase in the number of cities being affected by flooding, rapidly growing urban areas are fast becoming hotspots of major flooding events (UNISDR, 2007; Jha *et al.,* 2011). This stimulates a renewed concern for urban flooding due to pluvial events which is now becoming more pervasive within flood hazard framework (Djordjević *et al.,* 2011).

Urban flooding is increasingly an important source of problem for many cities across the developed and developing world. As a consequence of its widespread nature and potential for large-scale damage, urban flooding is different from or worse than other hazards known to affect urban areas such as landslide and gully erosion (Dawson *et al.,* 2008). Its threats are often a function of the varying depths and spatial extent of flood water and the velocity with which it flows (Mignot *et al.,* 2006; Jha *et al.,* 2012). The flooding of 2007 that affected many cities within England and Wales, the 2010 flooding in Pakistan and the 2015 flooding in Chennai are some examples, which suggest that the environmental, human and economic impacts of urban flooding are significant, and this is due to the high concentration of people along with local social and economic infrastructure within the urban areas (Chen *et al.,* 2009). Despite the scale of impacts, and the frequency of occurrence of urban flooding, existing knowledge regarding the hazard is limited especially in data poor countries, for example the developing countries (DCs) such as Nigeria, Mozambique and Bangladesh. The hazard source, susceptibilities of urban areas, the link between them and sustainable urban development are not well-known.

Recent predictions made from global and regional climate change models, allied with upward trends in urbanisation and population growth, imply that the impacts of urban flooding are expected to worsen in the future (Grimmond, 2007; UN-HABITAT, 2008; Arnbjerg-Nielsen *et al.,* 2013; Kundzewicz *et al.,* 2014; Winsemius *et al.,* 2016). More recent reviews of flood hazard such as those of Jonkman (2005), Barredo (2007), Merz *et al.* (2010) and Kundzewicz *et al.* (2014) indicate that urban flooding has probably not received the attention it deserves in the literature. In the light of these expectations and limitations, a number of issues are crucial especially in the DCs. These issues include the lack of accurate and good quality data to analyse the hazard and communicate its risk effectively, poor perception of the hazard especially among the wider population in poor urban regions, along with limitations in the management efforts (Tingsanchali & Karim, 2005; Faulkner & Ball, 2007; Merz *et al.,* 2010; Dasgupta *et al.,* 2015; Koks *et al.,* 2015; Nkwunonwo *et al.,* 2016).

The lack of accurate and good quality data underscores the present situation in the Lagos metropolis of Nigeria with regards to urban flooding and efforts to address its challenges. Although the city's roles as a major social, political and economic hub for Nigeria and many African countries are significant, urban flooding, which appears to be an annual event (usually between July and October rainy season), remains a major threat to human, environmental and socio-economic development (Nkwunonwo *et al.,* 2016). With the exception of 1973, the drought year, Lagos flooding has occurred since 1960 with an increasing intensity and an increased severity of impacts (Oyebande, 1974; Odunuga, 2008; Etuonovbe, 2011). More concrete examples from several incidences of flooding in Lagos are reported in section 3.5 of chapter 3. However, over the last one and a half decades, considering available secondary data, severe urban flooding has affected hundreds of thousands of people through death and displacement from homes, and brought about economic losses estimated at millions of US dollars (EM-DAT, 2015). Private and public utilities including houses, network of roads and schools have been destroyed (IFRC, 2012; Oladunjoye, 2011; Adelekan 2015). A number of personal cars have been swept away by flood water, whilst the economic activities and the source of livelihoods of many residents have been interrupted (Adelekan & Asiyanbi, 2016).

Lagos has always been susceptible to various types of flooding which are well documented (Odunuga, 2008). However, pluvial flooding events (rainfall-related), which can be partly explained as the excess water, not absorbed due to apparent inefficiency of storm drainage systems, have arguably been more widespread (Olajuyigbe *et al.,* 2012), and thus is being considered in the present research. Admittedly, the lack of flood data and other relevant data to analyse such a hazard is an important problem for flood risk research in the Lagos area, but also for the DCs and globally. Absolute solutions to this problem have so far been unknown apart from utilising freely available global datasets, and adapting proven methodologies to local situations (Brown & Damery, 2002; Levy, 2005; Apel *et al.,* 2006). Although solutions of this type have been satisfactory on many occasions, there is an inherent epistemic uncertainty which is likely to overestimate or even underestimate the outcome of flood risk analyses (Beven *et al.,* 2016). The nature of urban pluvial flooding further underscores the limitations with such scale of datasets. Apel *et al.* (2009), Ernst *et al.* (2010), Marchi *et al.* (2010) and Wolski *et al.* (2017) have shown that high resolution datasets are required for the assessment of urban flooding, in order to give an accurate representation of flooding events. Within the Lagos context, despite the availability of airborne LiDAR (Light Detection and Ranging) data, which now addresses the need for a high resolution topography, the lack of a continuous rainfall record, arguably still presents significant research needs.

Oddly, the highest scale of rainfall data in Lagos is ‘daily total amounts’ (NIMET, 2012). This level of rainfall data is an important limitation to flood modelling, and vulnerability assessment, and therefore motivates various assumptions made in the present research to develop new models that function on the basis of available datasets. It is also a major challenge to the development of reliable Intensity-Duration-Frequency (IDF) models, mapping of flood hazard and flood risk, and thus creates significant gaps in the literature relating to a comprehensive assessment of flood risk in Lagos. In particular the IDF models (which establishes the relationship for precipitation variability for the flood risk assessment and mapping) being used in Lagos state were the ones developed by Oyebande (1983) and Dar Al-Handasah Consultants (1993). These models are obsolete while their suitability for accurate flood risk assessment (FRA) is questionable. In view of the fact that Lagos is also a coastal city bordered in the south by the Atlantic Ocean, expectations on the reliability of current flood defences are likely to be high, despite the limitations in the current IDF models. However, there are no investigations known to the researcher regarding the fragility or rigidity of these defences and integrating information regarding them into FRA has not been attempted. Flood hazard and flood risk maps are well-recognised tools for communicating flood hazard and risk, and improving the awareness of flooding in an area (Faulkner & Ball, 2007; McCarthy *et al.*, 2007; de Moel *et al.,* 2009; Ward *et al.,* 2013). However, these maps do not currently exist in Lagos and their availability and use have arguably not been adequately investigated (Adeaga, 2008).

In terms of parameterisation of urban pluvial flood risk, data relating to high resolution topographic and long term precipitation are essential but inadequate. An accurate assessment of urban pluvial flood risk also requires data about social and demographic variables, stage, storm drainage system, flood damage, and other datasets for model validation and sensitivity analysis (see table 1-1 for a list of these datasets and their usefulness in flood risk assessment).

Table 1-1: Parameters for flood risk assessment, their uses, and availability in Lagos

S/No	Parameters	Uses in flood risk assessment	Available in Lagos / what scale?
1.	LiDAR	To represent topography, and source for estimation of roughness coefficient for flood modelling.	Yes (1-m horizontal resolution)
2.	Precipitation	Input into flood risk models	Yes ('daily total amounts')
3.	Discharge/Stage	Initial and boundary condition for flood models	No
4.	Storm drainage system	Incorporated into flood models	Unknown
5.	Friction coefficient	Sensitivity analysis of flood models	Can be extracted from topography/ published works
6.	Flood damage	Validation of flood models	Yes, Media, Journalistic
7.	Social and Demographic	Analyses of social vulnerability	Yes - LGS, LCDA
8.	Flood depth/ extent	Validation of flood models	No. Can be extracted from **RADAR** based satellites

These datasets enable the three fundamental investigations, which are frequently undertaken in FRA - estimation of flood hazard, analysis of vulnerability and assessment of exposure (Crichton, 1999; UNISDR, 2004; Kron 2005; Birkmann, 2007; Koks *et al.,* 2015) (See figure 1-1 below). The aim of flood hazard estimation is to characterise flooding in terms of water depth, duration and velocity (Merz *et al.,* 2007). Vulnerability analysis with regards to flooding is essential to understand the sensitivities to flooding and lack of resilience of the elements at risk (Adger, 2006; Blaikie *et al.,* 2014). Exposure is analysed to identify the spatial and temporal characteristics of elements at risk (Barredo & Engelen, 2010; Gupta & Nair, 2010; Mazzorana *et al.,* 2012). The unexpected occurrence of flooding in relation to issued flood warning, the spatial extent of the floodplain, locations of residents relative to the source of flooding and the nature of the houses in which residents live are also analysed within the framework of exposure (Penning-Rowsell *et al.,* 2005). Additionally, current economic values of exposed elements are estimated and used to assess economic flood risk on the basis of fragility or stage-damage functions (Smith, 1994; Dutta *et al.* 2001). Unfortunately, these investigations have been largely constrained in Lagos. Other issue in addition to lack of relevant datasets is weak institutional capacity, which is also a major research problem considering the large scale human and economic impacts of urban flooding alongside abundant resources and potential that characterise the area and other DCs generally.

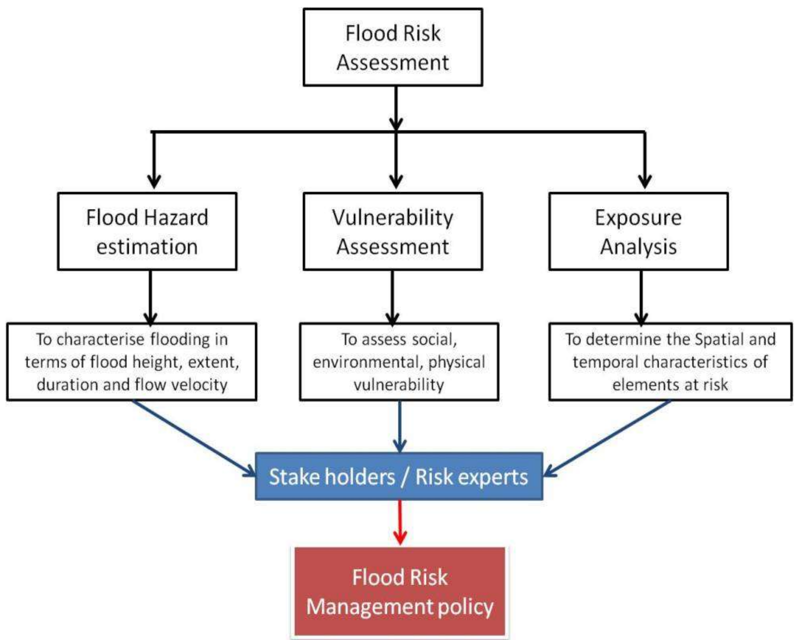


Figure 1-1: Flood risk assessment essentials

From the table 1-1 above, it is clear that for Lagos, most of the datasets required for FRA are either lacking or available at scales unsuitable for accurate FRA. Definitely, stake holders and urban residents in the Lagos area are not prepared to live with a future surrounded by an increasing threat of flood risk coupled with an unrealistic flood risk mitigation policy. The present research is in sympathy with this presentiment, and explores the potentials within freely accessible datasets to model pluvial flooding, and construct indices of social vulnerability for the Lagos area.

Flood modelling and vulnerability assessment can address the threats of pluvial flooding on human populations, economic activities and critical infrastructure (Bates & De Roo, 2000; Adger, 2006; Ne'elz & Pender, 2009). Despite this merit, and the particular implications and gaps which these procedures can fill in flood risk assessment within the Lagos context, they have been largely ignored (van de Sande *et al.,* 2012; Nkwunonwo *et al.,* 2014). In particular, the lack of vulnerability assessment is due to the conceptual disparity that exists in the current literature, in addition to lack of relevant datasets in the study area. Therefore, the present research, using the general view of vulnerability, proposed by Adger (2006) and IPCC (2007) in which vulnerability is defined on the basis of exposure, susceptibility and lack of coping capacity, evaluates social vulnerability to urban flooding in the study area, and constructs indices of social vulnerability (SocVI) for the Lagos area.

The lack of flood modelling in Lagos can be associated with some of the limitations in the existing flood modelling procedure which make them unsuitable for application in the Lagos context. In addition to the lack of calibration data, high computation cost of existing models which often stipulates high-end computer systems is a critical issue (Wheater, 2002; Mark *et al.,* 2004; Maksimović *et al.,* 2009). Most importantly, copyright restriction which is a major handicap to accessing these models' licenses and their technical supports, and the Lagos state government has arguably not demonstrated sufficient political will that can necessitate the acquisition of proprietary licenses for these models. Several studies have focused on finding ways of addressing the challenges with existing flood models especially as it applies to the means of reducing computation time while deriving stable solution of flow over a spatial domain (Bates & De Roo, 2000; Yu & Lane, 2006a; Almeida *et al.,* 2012). Two popular key strategies being adopted, which are crucial in meeting the challenges of flood risk assessment in data poor countries, are modification of existing models, and the development of new ones.

In particular, the development of a new flood model which was undertaken in the present research is of crucial importance towards addressing the gaps in relation to using previous flood modelling methodologies within the context of Lagos. This is allied with the need to demonstrate the extent to which novelty and innovation in flood modelling procedures can make contributions to the science of flood modelling in Lagos and other data poor communities. Moreover, the utility of 'daily amounts' rainfall data and air-borne LiDAR topographic data, both of which apply specifically to simulating pluvial flooding in Lagos, is of great research significance. The knowledge of these issues is relevant to calibration and uncertainty analyses of flood model, especially as it relates to resolving the sensitivities of simplified flood models to flood hazard physics.

The new model proposed in the present research combines Semi Implicit Finite difference Scheme (SIFDS) with Cellular Automata (CA) principle to simulate pluvial flooding. SIFDS integrates the merits of explicit finite difference scheme and those of implicit schemes, and was first used by Casulli (1990) to simulate hydrodynamics. Its prospects in simulating flood inundation have been significant, and have been extensively investigated in a number of studies involving two- and three-dimensional shallow water equations (see for examples Stelling & Duinmeijer, 2003; Kar, 2006; Casulli & Stelling, 2011; Dumbser & Casulli, 2013; Wong *et al.,* 2013). However, its performance in relation to improving the predictive standard required in urban flood modelling is not sufficiently known. Moreover, the response of flood physics to various models formulated by combining SIFDS with one or two other mathematical frameworks for example CA is an issue of research importance. CA is now gaining significant attention in the natural sciences to dynamically model systems whose states evolve with respect to time and space (Engelen *et al.,* 1995; Wahle *et al.,* 2001; Topa *et al.,* 2006; Cirbus & Podhoranyi, 2013). In the context of water flow simulation, CA can undoubtedly scale down the computation burden associated with physically based numerical models (Ghimire *et al.,* 2013). However, scale and homogeneity of input data remain a key issue in view of the recent research. Many available CA codes are limited in their application to external locations despite varying urban geomorphologies. Whilst research into the use of CA to model urban flooding is still emerging, more investigations are required to validate the assumption that CA based flood models can be reliable alternatives to the inflexible physically based distributed and lumped flood models.

1.2 Research questions

This research was intended to be a contribution to the solution of the widespread urban flooding in the Lagos metropolis of Nigeria. From a general research perspective, the achievement of this goal requires a robust and empirical research method. Therefore in view of the critical issues emerging from the research background and gaps identified in the literature (using section 1.1), the following key research questions have been addressed:

1. What specifically limits the assessment of the flood risk in the Lagos area?

2. Given the different distributions of social factors such as poverty, family structures, gender, etc., across the 16 LGAs in the Lagos metropolitan area and the scale of data available, is it possible to evaluate social vulnerabilities to urban flooding?

3. How is it possible to overcome the present problems with flood models which make it difficult to apply the flood modelling techniques to assess urban flood risk in the Lagos area?

4. Is it possible to analyse the flood risk over a selected specific area in Lagos in terms of the flood water depth, extent and duration?

5. In terms of convergence, unconditional stability and computation cost of flood models, what are the strengths and weaknesses of CA principles and semi-implicit time discretisation scheme for modelling urban flood hazard in Lagos?

1.3 Statement of aim and objectives

The main aim of this research was to critically analyse current approaches to urban flood risk assessment in the Lagos metropolis of Nigeria and to develop completely new models to address these inadequacies. On the basis of the widespread nature of urban flooding in Lagos, five key objectives have been addressed which include:

1. Provision of a review of literature relevant to urban flooding and management in the Lagos metropolis of Nigeria.

2. Critical evaluation of social vulnerability, and construction of indices of social vulnerability (SocVI) for the 16 Local Government Areas (LGAs) in Lagos city using national demographic and global elevation dataset and GIS mapping of these indices to delineate their variations across the LGAs.

3. Development of a new physically-based deterministic flood simulation model based on cellular automata (CA) principles and semi-implicit time discretization approach.

4. Testing of the new flood model using Portsmouth flooding of September 15th 2000, and simulation of the July 11th 2011 historical flooding event in Lagos in terms of various spatial and temporal variation on the basis of available meteorological and flood event data.

5. Make recommendations to the Lagos state government and other key stake holders towards improved flood risk policy in Lagos.

1.4 Novelty, contributions to knowledge and possible research impact

1. The present research provides a knowledge base relating to urban flooding in the Lagos area, in terms of the specific causes, widespread impacts and management efforts. This is achieved through discussions, which relate to flooding and its management within a global framework, as well as a critical review of urban flooding and flood risk management efforts in Lagos.

2. The present research provides a critical evaluation of social vulnerability to urban flooding in Lagos, as well as constructs new indices of social vulnerability (SocVI) for the 16 LGAs in the Lagos metropolis, by adopting a part of methods described in the Human Development Index of the United Nations (UNHDI, 2006) and Patnaik and Narayanan (2009).

3. The present research develops a new open source application (research code), *GFSP-1*, for flood modelling in urban areas, by combining CA principles and a SIFDS. Whilst flood modelling has never been attempted in any study to date in the Lagos area, the integration of CA and SIFDS is innovative and makes new contribution to the science of flood modelling and flood risk assessment.

4. In view of these contributions, the present research proposes a new concept known as IMPULSE (**IMP**roving **U**rban flood risk management in **L**agos via **S**ystematic **E**fforts) which might redefine flood risk management for Lagos. IMPULSE would involve various applications of *GFSP-1* flood model and SocVI for urban flood risk management in Lagos, and this is the possible impact of the present research.

1.5 Thesis structure

Chapter 2 presents a complete review of flood risk assessment methodologies. Chapter 3 provides an extensive description of the Lagos metropolis of Nigeria and a review of the literature relevant to urban flooding and its management in the area. Chapter 4 presents the critical evaluation of social vulnerability. In particular, it discusses how social vulnerability indices (SocVI) for sixteen LGAs in Lagos area have been constructed and mapped in the present research. Chapter 5 considers the science of hydrology and contains a review of the various flood modelling tools for flood risk assessment and other hydro-related activities. Also presented in this chapter is general discussion on CA framework and the calibration of models along with significant challenges. The development of the new model, *GFSP-1*, which forms part of the critical foundation of the present research is described in chapter 6. Testing and validation of the new model using a test case in Portsmouth, Hampshire, United Kingdom is shown in Chapter 7. The simulation of a July 2011 historical flooding event in Lagos on the basis of the new flood model is also described. The general discussions relating to the present research are presented in chapter 8. These discussions include the implications of those gaps identified in the review of Lagos urban flooding and flood risk management, social factors that predispose social systems to urban flooding in Lagos, and the strengths and weaknesses of *GFSP-1* using the results of the test cases. Chapter 9 presents the general conclusion and key limitations of the present research. The chapter also contains some recommendations and directions for further research. Appendices include an overview of the model simulation code (in MATLAB programming language), and other documentation relevant to the research.

2 Complete Review of Flood Risk Assessment

This chapter presents a review of the current approaches to Flood Risk Assessment (FRA), which is integral to Flood Risk Management (FRM). Arguably, these subjects have not been sufficiently discussed in the flood hazard literature, especially those that focus on the developing countries. Taking into consideration the importance of FRA, in its current science, in the effective management of urban flooding in Lagos, this review, which is drawn from a synthesis of literature spanning over many decades of research, is of great significance to the present research.

2.1 Flood risk assessment (FRA)

Within the wider research community, efforts to tackle urban flooding which promote sustainable urban development are targeted to gain a better understanding of flood hazard and risk in the general sense, to develop robust but low-cost methodologies, and to enhance the availability of good quality flood data (Merz *et al.,* 2010a; Löwe *et al.,* 2015; Mason *et al.,* 2016). Community-based approaches towards reducing the impacts of flooding generally have been proposed (Guarín *et al.,* 2004; Allen, 2006; Van Aalst *et al.,* 2008; White *et al.,* 2010; Zhang *et al.,* 2013). Integration of urban growth and climate change scenarios into flood risk management models is also attempted (Wilby *et al.,* 2008; Price & Vojinovic, 2008; van Herk *et al.,* 2011; Zhou *et al.,* 2012; Khan *et al.,* 2016).

These efforts are underpinned by flood risk assessment (FRA), which is a systematic procedure to identify, analyse and quantify the real and expected damage threats of flooding. Driven by a shift from the ideology of flood hazard prevention to that of flood risk mitigation, such a procedure is increasingly the critical component of flood risk management, and a vital tool for the formulation of flood risk mitigation policies at national, regional and global scales (Bocchiola *et al.,* 2003; UNISDR, 2004; EC, 2004; Samuels *et al.,* 2006; Merz *et al.,* 2010; Brémond *et al.,* 2013). FRA been implicitly suggested by the draft statements of all the UNISDR disaster frameworks along with a number of theoretical issues arising from the Yokohama strategy (Smith, 1994; Askew, 1999; Mercer *et al.,* 2010). The Global Facility for Disaster Reduction and Recovery (GFDRR) in its 2014 report, titled "understanding risk in an evolving world", attributed the success of a decade activity by Hyogo Framework for Action (HFA) to accurate and actionable risk assessment. World Bank (2012) highlighted the role of risk assessment in its recent global disaster report, which suggests that risk assessment is fundamental to five key areas of risk management policy framework – risk identification, risk reduction, preparedness, financial protection and resilience construction. Unfortunately, within this framework, quantitative risk assessment of all environmental hazards is lacking (Smith, 2013). This highlights the importance of the present research with regards to meeting the challenges of flooding in data poor urban communities.

Based on the data requirements, and levels of complexity in implementation, FRA methods can be generally divided into three types – index system-based assessment, historical flood hazard-based assessment and simulation-based assessment methods (Cheng *et al.*, 2010; Li *et al.,* 2013). Index system-based and historical flood hazard-based assessments are difficult to validate (Bocchiola *et al.,* 2003). Simulation-based assessment method is increasingly being applied although lack of data and computational complexity are major setbacks, especially with regards to urban flooding (Hirabayashi *et al.,* 2013). Table 2-1 shows the data requirements for each type of FRA.

Table 2-1: Types of Flood Risk Assessment
Most information contained in the Index system-based was obtained from Li *et al.* (2013)

	Index system-based	Historical flood hazard-based	Simulation-based
Data Requirements	**A. <u>Hazard index</u>** 1. Annual maximum daily rainfall 2. Rainfall in flood season 3. Water area ratio 4. City area ratio 5. Topographic slope **B. <u>Exposure index</u>** 1. Per capita fixed assets 2. Population density 3. Per capita secondary and tertiary industrial output value 4. Primary industrial output value in unit area **C. <u>Vulnerability index</u>** 1. Flood mitigation standard 2. Density of drainage system 3. Post-disaster reconstruction capability 4. Social variables data	1. Type of flooding • Fluvial • Pluvial • Coastal origin 2. Source of flooding 3. Flood damage information 4. Long term precipitation data	1. Precipitation data 2. Discharge information 3. Catchment boundary information 4. Efficient hydrological/hydraulic model 5. Storm drainage system data 6. Roughness coefficient 7. Validation data • *Measured water depth* • *SAR Satellite data* • *Existing flood maps* • *Social data information*

From the table 2-1 above, the various types of FRA are not mutually exclusive, given the intersection on data requirements. In addition to this, combining two or more FRA type can help to minimise the uncertainty in FRA, and this presents significant research needs in relation to a realistic FRA (Samuels *et al.,* 2006; Merz *et al.,* 2010; Hammond *et al.,* 2015). Nevertheless, how to actualise such a hybrid approach is an important consideration, which underscores the importance of the present research, in using an assortment of approaches to overcome the challenges of FRA for data poor urban localities.

FRA for urban areas provides a standard that can be used to measure the similarities or dissimilarities in flood risk arising from various sources of flooding (Popovska & Ivanoski, 2009). It is a challenging task due to the multi-facetted nature of flooding in urban areas (Dawson *et al.,* 2008; Kubal *et al.,* 2009). Uncertainties and the lack of time series stage data and good quality damage data (which are used with flood depth in fragility curves to assess economic values of flood risk) are major constraints (Middelmann-Fernandes, 2010). In many studies, FRA does not often include social and environmental impacts but exclusively considers economic damage, and this is increasingly popular in various FRM procedures throughout Europe and the United States (Haque & Etkin, 2007; Merz *et al.,* 2010). Whereas FRM should be based on a comprehensive assessment of flood risk combined with thorough investigation of uncertainties associated with risk assessment technique, FRA is often restricted to fiscal losses and comprehensive approaches which try to integrate economic, environmental and social impacts are less available (Apel *et al.,* 2004; Schanze, 2006; Merz *et al.,* 2010). Particularly, environmental and social impacts are frequently omitted due to a lack of suitable data (Ebert *et al.,* 2009).

A realistic FRA is characterised by a critical understanding of the risk concept, characterisation of flooding, spatial and temporal scales of flood damage, basic economic principles and typologies of flood damage (Merz *et al.,* 2010a; Marchi *et al.,* 2010; Kaźmierczak & Cavan, 2011; Penning-Rowsell, 2015; Shah *et al.,* 2015). Whilst the research community has yet to adopt a unanimous view of risk despite many years of debate, various frameworks in the literature give rise to heterogeneous methodologies of risk assessment (Van Ogtrop *et al.,* 2005; Solín & Skubincan, 2013). Such inconsistencies largely constrain cross disciplinary approaches to flood risk management in many contexts (see Scheuer *et al.,* 2013; Gober & Wheater, 2015). This is an important issue for the present research.

Fundamental to any risk assessment is the knowledge of "risk", which is the chance or probability of an event and its outcome. Risk is an important subject in the theory and practice of many disciplines including natural hazards, engineering, health and social sciences, crime, terrorism, etc. It is not the intention of this study to provide a thorough discussion on risk. However, risk forms an inseparable part of humanity and other environmental systems since it combines opportunity with uncertainty and shapes physical, natural and human environments (Renn, 2008; Smith, 2013). Different ideas of risk which emerged in the literature are generally based on the realists and constructivists perspectives of exposed systems under consideration, and their consequences (Renn, 2008; Wachinger *et al.,* 2010). The 'realists' believe in the existence of identifiable (perceivable or objective) risk in the real world (Rosa, 1998; Rosa, 2008). Such perspective aims to surround any possible risk of an activity or an event with awareness and knowledge. The problem with this framework arises when information required to objectively define the idealized risk is lacking. 'Constructivists' argue that risk does not exist in the real world "but that they are subjectively and socially constructed" (Jasanoff, 1998). In other words, if risk forcing factors are modelled and handled, risk becomes zero. This perspective is much applicable in managing financial risk. However, risk from the point of view of natural hazards which most times are difficult to predict will undermine this framework.

Aside these two frameworks, the majority of risk experts perceive risk in terms of "anticipated variability" which suggests a predictable departure of an occurrence from the expected outcome (Jüttner *et al.,* 2003). In an interdisciplinary review of risk, Renn (2008) provides some inclusive grouping of varieties of risk that may assist in the practice of risk management. The review shows that risk has been extensively discussed within the context of natural hazards, in which it is conceptualised as a function of probability of hazard occurrence and its consequences (Alexander, 1993;

Brooks, 2003Van Westen *et al.,* 2006; Giuliani & Peduzzi, 2011; Schmidt *et al.,* 2011). That is, Risk = Hazard * Vulnerability. Although a third element, exposure of the system at risk, is oftentimes included in risk definition (Crichton, 1999), an ideal risk definition within natural disasters framework is still debatable. There is a current consensus that risk in natural hazards always involves interactions between natural and human factors (Eiser *et al.,* 2012). This is of critical importance in conceptualising urban flood risk, and developing efficient techniques for its assessment and management (Zevenbergen *et al.,* 2015; Hammond *et al.,* 2015).

Efficient flood assessment technique and management policies rely adequately on proper characterisation of flooding (Carrera *et al.,* 2015). Most of the well-known flood management measures in the US and Europe, especially the Netherlands, are based on the idea of defences that "have virtually no chance of being exceeded" (Newton, 1983). Such defences are being developed on the basis of actual and/or expected flooding events, which characteristics in terms of return period were determined a-priori (Reis & Stedinger, 2005). The problem to be encountered within this framework is the lack of a standardised scheme for characterising flooding events. Although various sources of flooding, including flash, fluvial, coastal, pluvial and urban, are well-recognised, in most studies, floods are being characterised on the basis of their return periods, water depth and extent as well as velocity (Scawthorn *et al.,* 2006; Marchi *et al.,* 2010). This suggests that to facilitate urban flood risk assessment, more research efforts are needed to develop methodologies which are capable of deriving these variables for events of differing recurrence probabilities.

Besides characterising flooding events, knowledge of the type of flooding impacts is also relevant towards choosing a suitable flood assessment technique. In flood risk science, the negative impacts of flooding are often classified in terms of tangible and intangible damage. Tangible damage such as damage to properties and infrastructure are those that can be associated with monetary values. Intangible damage is difficult to express in monetary terms and may include depression, anxiety and loss of life. Categorisation of flooding impacts as direct and indirect damage is also applicable. Direct flood damage includes those which result from direct contact with flood water. When direct flood damage is tangible, a broader classification, direct tangible flood damage, applies. Indirect tangible flood damage is a secondary consequence of direct flood impacts and may include economic disruption, individual misfortune and an increase in water-borne diseases (Samuels *et al.,* 2006; Meyer *et al.,* 2012; Hammond *et al.,* 2015).

Direct tangible flood damage including damage to agricultural products, cultural heritage, etc., appears to be the focus of many flood risk assessment studies (Samuels *et al.,* 2006; Brémond *et al.* 2013; Hammond *et al.,* 2015). This remains a major gap in the current literature considering other types of flood damage which are also fundamental to flood risk assessment. Estimation of intangible flood damage is complicated and this remains an important gap in FRA. Several authors however, have proposed methods for estimating intangible damage. For example the concept of 'anxiety-productivity-income' which assumes that anxiety is a function of flood water depth and duration (Lekuthai & Vongvisessomjai, 2001; Price & Vojinovic 2008). The 'Risk-to-life' model, uses flood characteristics and an estimate of the number of people exposed to flooding to assess the possible mortality, was proposed in Jonkman *et al.* (2008). A comprehensive review of other current methods to assess intangible flood losses can be found in Jonkman (2008) and Hammond *et al.* (2015).

Merz *et al.* (2010) argued that knowledge of the spatial and temporal scales of flood damage, and basic economic principles, is essential for proper assessment of flood risk. For urban FRA, the spatial and temporal scales of flood damage serve as a key tool for defining the purpose, accuracy specification, the choice of data and appropriate method for flood damage estimation (Merz *et al.,* 2010). The dynamic nature of risk evolution supports the temporal scale of flood damage (Mazzorana *et al.,* 2012). In fact the risk of urban flooding in an area the next time flooding will occur can be higher or less depending on the rate of modification of land use and land cover. Furthermore, some flood consequences such as health effects seem to linger on. Within this context, time frame becomes an important factor in flood damage estimation. Spatial scale of flood damage is similarly crucial, and flood damage estimations in most cases have been carried out in three discrete levels: micro, meso and macro levels (Merz *et al.,* 2010). Micro level damage estimations are based on single element at risk; for example an isolated property or a community. Meso level estimations consider clusters of spatial features such as administrative units. Damage estimations at the macro level appear to be more encompassing and large areas such as mega cities, regions or counties are considered. As a result of the lack of detailed damage data and flood risk assessment tools such as flood modelling to characterise urban flooding, meso and macro assessment of urban flood risk are lacking in Lagos.

Basic economic principles are clearly connected with especially economic FRA due to the need to establish a common economic standard, and to remove confusions that are likely to be met in the process of figuring out the worth of damaged features (Merz *et al.,* 2010). Economic principles can assist to minimise these errors and ensure that only actual or post- flood event damage are associated with economic values. In FRA research, four basic principles are being followed in order to carry out reliable damage estimation. They include: (1) definition of appropriate temporal and spatial boundaries of the study, (2) evaluation of all tangible costs, including the cost of emergency services, (3) estimation based on depreciated values, instead of full replacement costs, and (4) definition of element at risk based only on stock values (Messner *et al.,* 2007; Merz *et al.*, 2010). Research in economic flood damage assessment indicates a long history of application of these principles (Jonkman *et al.,* 2003; Apel *et al.,* 2009; Hammond *et al.,* 2015). However, these principles have yet to be easily applicable in urban FRA, in the estimation of indirect flood losses such as those involving property destruction and business interruption, as well as indirect intangible losses (Gall *et al.,* 2009). Considering the data poor urban localities where such indirect intangible flood losses are significant, this limited application of basic economic principles becomes a research issue.

2.2 Review of current practices in flood risk assessment

Over the years, various FRA approaches, which have emerged in the flood hazard and risk literature generally consist of three aspects: (1) flood hazard identification and estimation, (2) vulnerability assessment and (3) damage evaluation (Smith, 1996; O'Brien, 2000; Thieken *et al.,* 2006; Covello & Merkhoher, 2013). Ologunorisa & Abawua (2005) argued that a fourth aspect which addresses the need to take post-audits of all risk assessment exercises is equally required in FRA. Of these three aspects, flood hazard estimation is a critical issue, which has received much attention in the literature due to the significance of water depth in many economic assessments of flood risk which rely heavily on stage-damage functions (Smith 1994; Merz *et al.,* 2010; Zhou *et al.,* 2012).

One of the simplest approaches to FRA involved a multi hazard risk assessment in which flooding is treated alongside other known hazards within a spatial domain (Granger *et al.,* 1999). Ferrier & Haque (2003) implemented this idea in a study which was aimed to provide information for emergency response. Risk was conceptualised as a product of frequency of hazard occurrence, exposure and vulnerability. Hazard was given a score ranging from 1-10 based on historical evidence of hazard occurrence at various districts. Vulnerability and exposure were scored similarly but based respectively on the severity of impact on the community and different level of perception of risk. The overall scores (risk rating on a 0–1000 scale) were obtained by multiplying all the individual scores and plotting them on the risk assessment table. In addition to being flexible, simplicity is a major advantage in using such an approach. It is easy to incorporate hazard assessment results into a GIS for mapping and to compare relative risks from other sources. However, a number of gaps were identified (Zevenbergen *et al.,* 2008). The method was somewhat generalised and while inadequately objective, insufficient local information arguably undermines its applicability in many places (Grünthal *et al.,* 2006).

FRA is progressively moving from simple approaches to methods which are multi-dimensional and cross-disciplinary (Thieken *et al.,* 2006; Merz *et al.,* 2010; Skakun *et al.,* 2014; Hammond *et al.,* 2015). This is due to the increasing frequency of occurrence of flooding in the urban areas and the degree of impacts associated. Within the recent methods, climate change, which is an important issue further highlights the need to strengthen the assessment of urban flood risk from pluvial sources, especially in the DCs (Gouldby *et al.,* 2008; Falter *et al.,* 2013). Climate change affects the failure of existing flood defences, so that the standard of protection (SOP) of structural measures to be adopted within an urban framework is now a major input in FRA (Hall *et al.* 2003; Vorogushyn *et al.,* 2010; Falter *et al.,* 2013). This is increasingly of concern in economic assessment of flood risk which reflects a significant progress within FRM research (Van der Sande *et al.*, 2003; Buchele *et al.,* 2006; Zhou *et al.,* 2012; Ji *et al.,* 2013).

Unfortunately, most of the existing methodologies are based on a large scale (regional and national) assessment of flood risk, and consider flood water from fluvial and coastal sources (Hall *et al.* 2003; Vorogushyn *et al.,* 2010; Falter *et al.,* 2013). However, for the DCs, data relating to sewers, urban drainage systems, and the major components of the hydrological cycle including rainfall, runoff and infiltration, are fundamental to the assessment of urban flood risk from pluvial sources, and these data are not readily available (Douglas *et al.,* 2010; Blanc *et al.,* 2012). As a result, efforts are being made to develop techniques which are efficient, and also retain the ability to fit available datasets (Hall *et al.,* 2003; Apel *et al.,* 2006; Apel *et al.,* 2009; Gall *et al.,* 2009; Kubal *et al.,* 2009; Woodward *et al.,* 2011; Neuhold & Nachtnebel, 2011).

In developing such robust and alternative techniques to address flooding in urban areas, researchers are identifying the need to incorporate climate change scenarios into FRA (Milly *et al.,* 2002; UNISDR, 2004; Prudhomme *et al.,* 2010; Eum *et al.,* 2010; Zhou *et al.,* 2012; Kundzewicz *et al.,* 2014; Chen *et al.,* 2015). To investigate the potential impacts of changing climate change on flood risk, Eum *et al.* (2010) integrated climate change assessment with hydrologic-hydraulic modelling for floodplain mapping in Upper Thames River basin. The study utilised 43 years of historical data at 15 stations in the study area and global circulation model predictions. The results of the study show that climate change conditions increase the spatial extent of flood impacts with increased magnitude of water depth, and thus caused increased level of risk to public infrastructure. To further validate this finding, reservoir management system was integrated into FRA under climate change scenario (Eum *et al.,* 2012).

Similar objectives underlie studies by Bowering *et al.* (2014) and Chen *et al.* (2015). A combination of damage-frequency, flow-frequency, stage-damage curves and climate based floodplain maps derived from hydrologic and hydraulic analyses were used in Bowering *et al.* (2013). The index of risk calculated for each asset was aggregated and summed up by spatial unit and presented in the form of risk tables and maps. Results of a case study in the city of London, Ontario, Canada, indicate that the 100 year climate change scenarios accounts for the most critical flood situation. Chen *et al.* (2015) utilised spatial gridded data, including climate, hydrology, topography, vegetation and soils, processed in a GIS environment. The aim of the study was to develop a spatial multi-criteria decision making model for regional scale flood risk assessment using the Bowen Basin and its surroundings in Queensland as a case study. Several indices were derived based on time series of observations and spatial modelling, taking account of topography, extreme climate events and hydrologic scenarios. These indices were weighted using the analytical hierarchy process (AHP) and integrated in an AHP-based suitability assessment (AHP-SA) model, to derive a regional flood risk map, which represent likely impacts at different climate risk levels.

Critical information regarding the costs of existing urban assets and present condition of drainage facilities is fundamental to the application of such climate based FRA in the development of climate change adaptation and emergency response management policies (Caradot *et al.,* 2011; Peck *et al.,* 2014). The assumption that service levels of urban drainage systems are likely to be affected by expected increases in runoff and peak volume driven by climate change and urbanisation was investigated by Zhou *et al.* (2012). The authors proposed an integrated approach, which incorporates climate change impact assessment, flood inundation modelling, and economic tools, for economic assessment of pluvial flood risk in urban areas. The results of assessment for a Danish case study were based on basic cost functions with particular focus on direct tangible damage. However, such a framework can serve as an important decision support tool in relation to SUDS.

The majority of these FRA methods that include climate change scenarios assessed flood risk on the basis of stage-damage function or fragility curves (Jonkman *et al.,* 2008; Vorogushyn *et al.,* 2010; De Risi *et al.,* 2013). Stage-damage functions defined from the first principles are rational tools that describe the relationship between elements at risk and depth of flooding (Smith, 1994). This provides potential tools for assessing direct and indirect tangible flood damage and has been applied extensively in many case studies around the world including the US, UK and all over Europe (Merz *et al.,* 2004; Merz *et al.,* 2007). Many studies conclude that using these curves is only the first stage in assessing flood losses since the curves have to be combined with field surveys of properties at risk, hydrological information to give ex-post or ex-ante predictions of flood damages (Smith, 1994; Hammond *et al.,* 2015). However, whilst stage-damage functions nonetheless benefits from large databank, for the DPDCs, instrumental measurement to obtain flood water depth, for most extreme events has generally been impracticable (Vojinovic & Tutulic, 2009).

Another major limitation of stage damage curves arises from the neglect of water flow velocity which also influences flood damage (Jonkman, 2007; Merz *et al.,* 2010). There has been limited application in Africa and Asia which arguably has been due to the paucity of data relating to flooding (Kreibich & Thieken, 2008; Apel *et al.,* 2009). In addition to these limitations, stage-damage curves also suffer from other issues that constrain their wider application. These include hard decisions on what to include in constructing the curve, what values should be allocated to items, the number of varieties of building to be used (Smith, 1994). There are remarkable differences in the direct damage of individual properties which suggest the need for considerable smoothing and extensive interpolation and extrapolation of the raw data (Smith, 1994).

To improve the potential of stage-damage functions at FRA, flood water depth and water flow velocity can be modelled through the use of numerical and other mathematical frameworks (refer to chapters 6). Statistical modelling techniques are being considered (Newton, 1983; Li *et al.,* 2012). Some of the modelling techniques being applied include stochastic differential equations (Shuhai, 1994; Jiang, 1998), event-based probabilistic approaches (Torres *et al.,* 2014), information diffusion theory (Feng & Luo, 2008), fuzzy logic analyses and modelling (Chen & Guo, 2005; Li *et al.,* 2012; Ahmad & Simonovic, 2011; Li *et al.,* 2012; Zou *et al.,* 2012; 2013) and regression and multi-variate statistical analyses (Kim *et al.,* 2012; Merz *et al.,* 2013; Chinh *et al.,* 2015). The idea of multicriteria method of risk assessment has been extensively discussed and implemented (Meryer *et al.,* 2009a; Kubal *et al.,* 2009; Jiang *et al.,* 2009). Spatial and temporal variability of uncertainty in urban FRA have also been studied (Ahmad & Simonovic, 2013). The overall aim of these approaches is often to estimate a certain magnitude of flooding, to enable the design of flood defence structures that are unlikely to be breached by any future flooding events (Newton, 1983). A major issue, which presents obvious imitations with the use these techniques in the Lagos area, and perhaps in many DPDCs, is the lack of data relating to historical and pre-historical flooding events (Newton, 1983; Swain *et al.,* 1998; England *et al.,* 2003; George, 2010; Renard *et al.,* 2013).

Despite these recent developments, a key issue that has continued to emerge across various areas of FRA is data limitation. Thus, several data sources are being exploited. Benito *et al.* (2004), Greenbaum (2007), Cunningham *et al*. (2011) and Díez-Herrero *et al.* (2013) combined palaeofloods techniques in different geomorphological settings with historical flood data for extreme flood risk assessment. The idea of insurance related flood risk index (IRFRI) was presented in Ni *et al.* (2010) and used to assess flood risk in China. Cunningham *et al.* (2011) used storm surge data for improved assessment of flood risk. Kwak *et al.* (2012) proposed a new approach based on MRI-AGCM outputs and used it for FRA in Asia-Pacific region. Arrighi *et al.* (2013) and Arrighi *et al.* (2016) adopted a census data for assessing the damage done by flooding to art works in Florence, Italy. Balica (2012) applied a flood Vulnerability Index for FRA in Nzoia River, Kenya. Escuder-Bueno *et al.* (2012) presented a quantitative flood risk analysis methodology for urban areas with integration of social research data. Koks *et al.* (2015) demonstrate how a joint assessment of hazard, exposure and social vulnerability provides the most valuable risk assessment method. Vojinovic *et al.* (2016) proposed a holistic approach to FRA that combines quantitative and qualitative paradigms. This approach was developed and applied in the Ayutthaya region in Thailand, which is a UNESCO World Heritage Site.

The potential of remote sensing and GIS are also being exploited to improve FRA, through provision and geospatial analyses of satellite images to extract flood water depth. On the basis of GIS, key areas of research within FRA framework include presentation and visualization of result, database management, improved spatial analyses and modelling, alongside system coupling (Abdalla *et al.,* 2006; Xinyu *et al.,* 2009; Chen *et al.,* 2011; Yerramilli, 2012). GIS was used to carry out a community-based FRA for urban areas of San Sebastian, Guatemala in Guarín *et al.* (2004). Su *et al.* (2005) introduced a grid-based GIS approach to regional flood damage assessment in Shih-Jr city in northern Taiwan. Harvey *et al.* (2008) proposed the reframe: a software system supporting FRA. Shan *et al.* (2009) proposed a GIS-based neural networks assessment model of flood and waterlog disaster in Poyang, China, while Wang *et al.* (2011) developed a spatial multi-criteria approach based on GIS for FRA in the Dongting Lake Region, Hunan, Central China. Maantay *et al.* (2010) used GIS to estimate vulnerable urban populations for flood hazard and risk assessment in New York City. Combined approach of AHP and GIS for FRA and flood plain management in Huaihe River Basin, China and Taiwan respectively was studied by Chen *et al.* (2011) and Liu *et al.* (2008). Yerramilli, (2012) introduced a hybrid approach that integrates HEC-RAS and GIS towards FRA in the city of Jackson, Massachusetts.

Remote sensing has proved to be a logical alternative source of flood data for flood risk assessment (Tralli *et al.,* 2005; Bates, 2012; Mason *et al.,* 2014; Chohan *et al.,* 2015). Infrared, microwave and radar based imagery characterised by increased capability to penetrate clouds and soil and delineate flooded and flood prone areas are now being made available at various locations (Dano-Umar *et al.,* 2011). There has also been a significant improvement in the topographic data made available through the provision of airborne LiDAR data. Huang *et al.* (2008) assessed flooding risk in Lixiahe region of Jiangsu Province. Four images of 1991 AVHRR, 2003 and 2007 MODIS were used to extract water logging inundated water of three years, and three inundated water maps were overlaid to estimate the impacts of flooding frequency. Ho & Umitsu (2011) investigated micro-landform classification and flood hazard assessment of the Thu Bon alluvial plain, central Vietnam via an integrated method utilizing remotely sensed data. Skakun *et al.* (2014) undertook a FRA in Namibia using a time series of satellite image. Researchers are proposing the use of the new TANDEM-X-global DEM to improve the accuracy of DEMs produced for flood modelling studies (Mason *et al.,* 2016). TANDEM-X-DEM produced by DLR (German Aerospace Centre) with a spatial resolution of 0.4 arc second (10-12m) globally was designed to replace SRTM for large scale hydraulic modelling.

Notwithstanding these prospects, the science of remote sensing has yet to be fully understood, whilst the cost of data acquisition, validation of data and benchmarking are among the key issues that still linger with regards to the ubiquitous application of remote sensing technology in flood risk assessment (Tralli *et al.*, 2005). Moreover, given the lack of quality precipitation data in the DPDCs, it is now crucial to investigate how to utilise these remote sensing datasets in hydrodynamic flood modelling, to determine flood water depth and extent. Hypothetically, flood modelling, which has the capability to simulate flood data, along with the potential to predict future flooding events (refer to: Gall *et al.,* 2009; Bates *et al.,* 2010; Gibson *et al.,* 2016) can be explored to provide a logical solution to these limitations. This idea is fundamental to the present research. However, with the availability of remote sensing datasets, a lack of political will, unclear institutional arrangement, and the laissez-faire attitude of the general public to urban flooding in the DCs are issues that still need to be considered. So, the development of a new flood model is expected to improve the knowledge of urban flooding in the areas.

2.3 Summary

Flood risk assessment (FRA), which is a procedure to identify and quantify the risk associated with flooding is considered as a critical component in the risk-based management of urban flooding. Within this framework, FRA is underpinned by three important investigations - flood hazard estimation, vulnerability assessment and exposure analyses. How to accurately carry out these investigations across various local, national and regional scales is a crucial research questions, which is somewhat compounded by the lack of quality datasets in the DCs. However, despite numerous methodologies that exist in the literature alongside widespread application, the issues of risk conceptualisation, intangible flood damage assessment, a lack of flood damage data and occurrence of uncertainties are still issues of future research.

3 The Lagos Metropolis of Nigeria and a Critical Evaluation of Flooding and Flood Risk Management in the Area

This chapter presents a description of the Lagos metropolis of Nigeria. The critical dimensions of urban flooding, exposures and vulnerabilities of social and environmental systems in the area are discussed. Besides the general knowledge about Lagos, the geography, climate, geology and hydrology, topography and land cover, rapid population growth and urbanisation, culture, politics and the economy of Lagos, all of which play significant roles in the causes, widespread impacts and management of Lagos urban flooding, are described. Whilst these descriptive notes only relate to urban flooding, more comprehensive accounts of the Lagos area are available in a number of seminal sources (see for examples: Echeruo, 1977; Smith, 1988). The chapter also presents a critical review of flooding and flood risk management in the Lagos area.

3.1 The Lagos metropolis of Nigeria

The choice of Lagos as a case study for the present research was informed by three factors. Firstly, Lagos plays significant roles in the economic and political development of Nigeria. Secondly, rapid population growth and urbanisation in the area is a cause of major concern. Thirdly, previous studies claimed that most of the flooding in Nigeria occurred in Lagos, underscoring the need to develop robust and more realistic flood management policies (NIMET, 2012; Nkwunonwo *et al.,* 2015a).

3.1.1 Location and general information

The Lagos metropolis of Nigeria, which is made up of the more developed Mainland, and Lagos Island of Lagos state, consists of 16 Local Government Areas (LGA) – subdivided into 37 Local Council Development Areas (LCDAs). It is home to more than 16 million people (LSG, 2012). The city is located in south-western Nigeria on the West Coast of Africa within longitude 3^0 01'E to 3^0 40'E and latitude 6^0 23'N to $6^0$41'N (figure 3-1). It is bounded on the west by the Republic of Benin, to the north and east by Ogun State, with the Atlantic Ocean providing a coastline on the south. It covers approximately 1100 km^2 of low-lying coastal land and is surrounded by the sea, inland waterways and the Lagos lagoon. Based on demography, the city is the largest in Nigeria, second largest city in Africa and the seventh in the world, applauded as one of the megacities in the world. Keeping the megacity status, whilst contending with the challenges of urban flooding in tandem with other natural and environmental hazards is a crucial factor, which demonstrates the importance of the present research in the sustainable urban development of Lagos.

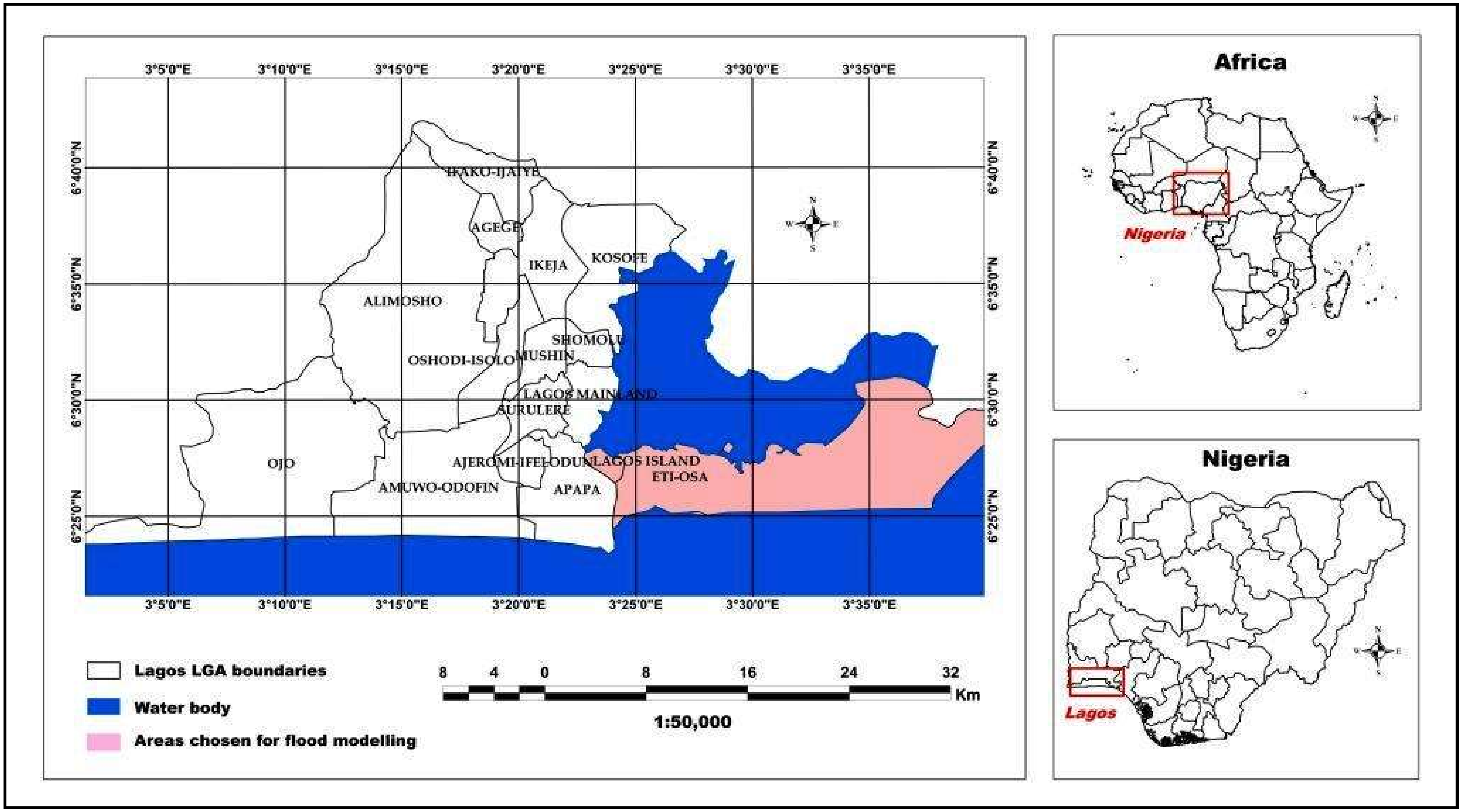


Figure 3-1: The Lagos metropolis of Nigeria showing the 16 LGAs, Atlantic Ocean and the Lagos Lagoon. Top right side shows Africa with the position of Nigeria while the lower right shows Nigeria given the location of Lagos.

3.1.2 Climate and vegetation

In the KÖppen climate classification system, the Lagos area has a wet equatorial climate, influenced by the equator and Gulf of guinea (Iwugo *et al.*,2003; Roth, 2007). The average annual temperature is about 27 °C, while the mean annual rainfall varies from one location to another. According to Iwugo *et al.* (2003), Ebute-metta, Yaba, Bariga areas record 1750mm, while Badagry, Epe and Agege record 1636.1mm, 1676.5mm and 1567.2mm respectively. A significant increase in the intensity and frequency of rainfall has been experienced in recent times (Odjugo, 2006). There is rainfall almost throughout the year. Rainfall pattern is described as double maxima (figure 3-2), heaviest between July and August, and tapers in intensity between October and November (Aderogba, 2012b). June is the wettest month of the year with an average rainfall of approximately 386 mm, producing quick runoff due to much pavements and poor drainage systems. Dry periods are experienced from December to March annually, and occasionally between August and September.

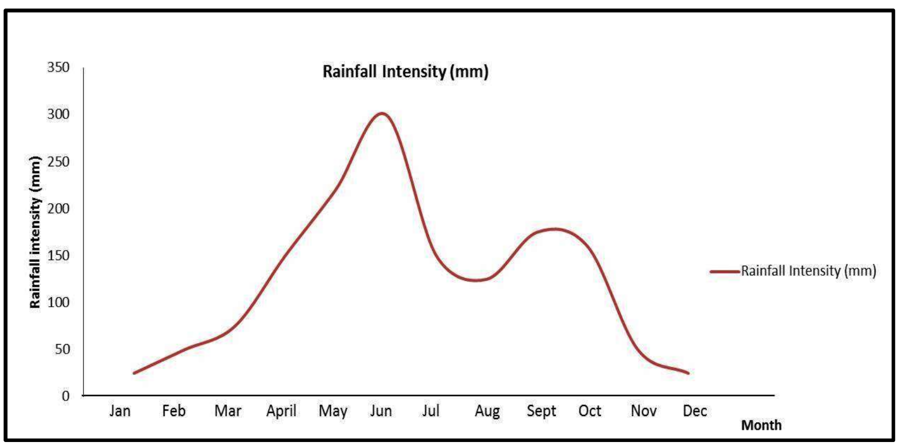


Figure 3-2: Annual rainfall pattern in Lagos showing the double maxima in June and October. Source: Adapted from Adedayo & Fashua (2012).

The natural vegetation of Lagos is dominated by depositional landforms, which include swamps, barrier island, low lying tidal islands, beaches, estuaries, wetlands and tropical swamp forest interlocked with marshes and lagoons (Sunday & Ajewole, 2006) (figure 3-3). In addition to the topography and relief, rock types and faults, the vegetation provides the area with a characteristic dendritic drainage pattern (Sunday & John, 2006). Unfortunately, this natural cover is being threatened by the increasing impervious surfaces caused by much built-up areas and tarred roads surfaces. Available research that addresses the effect of declining vegetation on urban flooding in Lagos is insufficient (Adelekan, 2010).

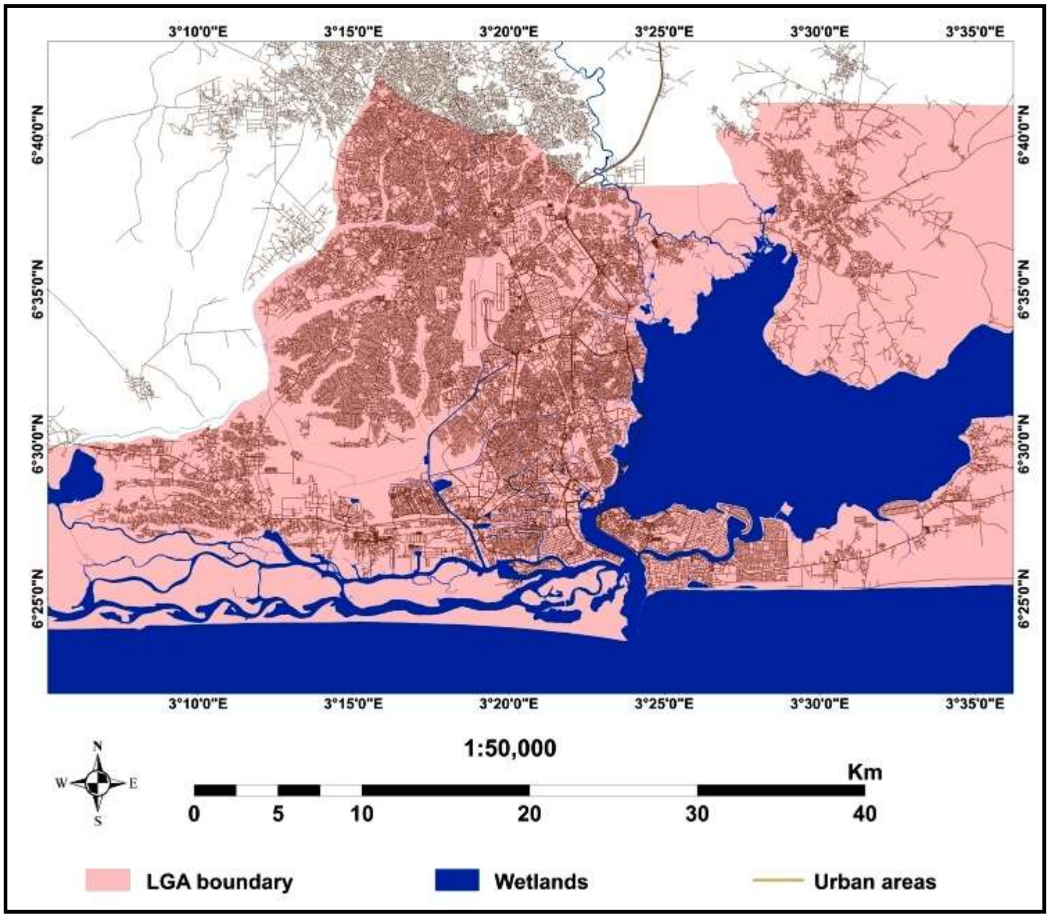


Figure 3-3: Natural vegetation of Lagos showing swamps and wetlands.

3.1.3 Geology

The Lagos metropolis falls within the eastern Dahomey basin (Longe *et al.,* 1987; Okosun, 1990). The area is comprised of mainly thick Ilaro formation which is overlaid by the coastal plain sands (CPS) which in turn underlay recent sedimentary formations: Cretaceous, Tertiary and Quaternary sediments (Billman, 1976; Atakpo *et al.,* 2011; Longe, 2011) (figure 3-4). The Cretaceous sediments are predominantly the Abeokuta formation which is the oldest unit that overlays the Precambrian crystalline rocks of the Basement Complex (Iwugo, 1986). Previous research has shown that these recent sediments form the water table aquifer which is manually exploited by hand-dug wells and shallow boreholes (Fayose, 1970; Iwugo, 1986). The CPS aquifer is a multi-aquifer system consisting of three aquifer horizons – the upper, middle and lower aquifers – separated by layers of silt or clay (Longe *et al.,* 1987; Onwuka 1990).

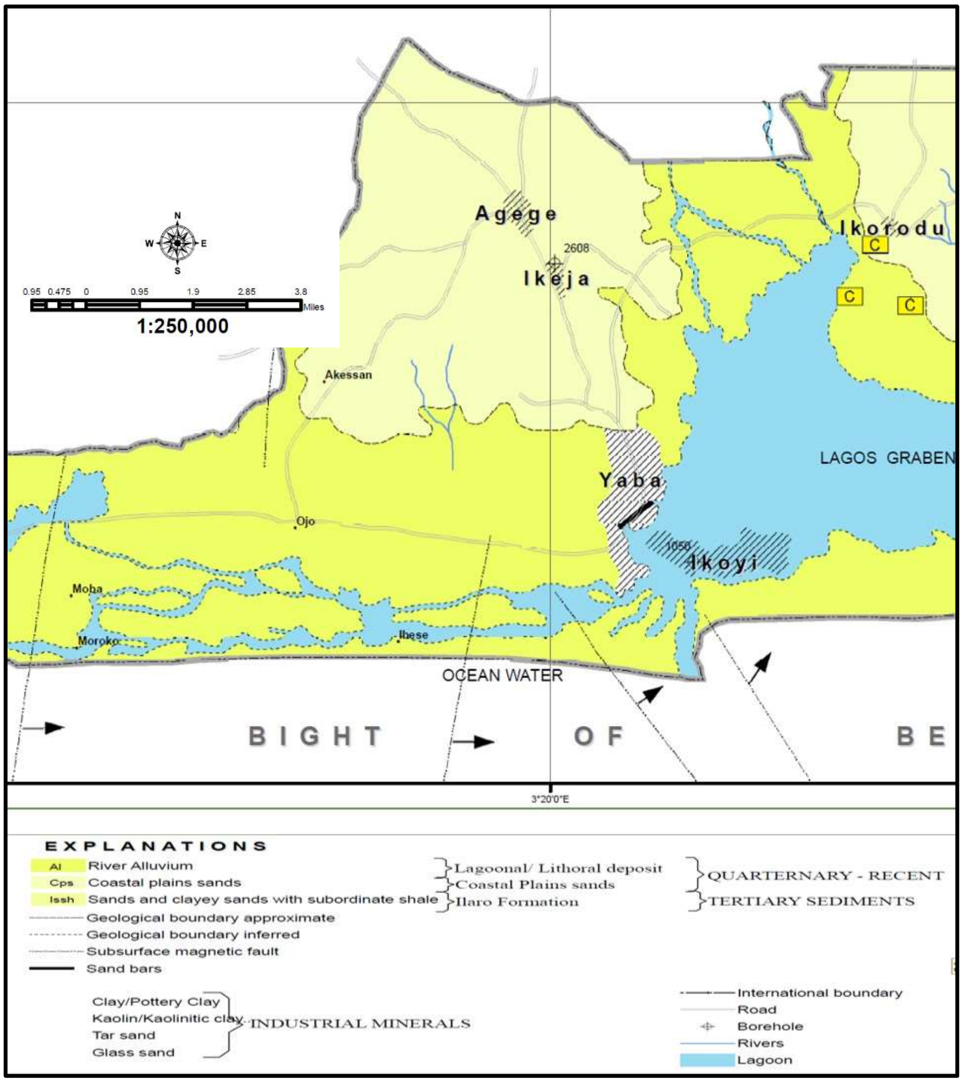


Figure 3-4: Geological map of the Lagos metropolis.
Source: Extracted from Geological and Mineral Resources map of Nigeria Nigeria Geological Survey Agency (NGSA, 2011)

3.1.4 Hydrology

The Lagos area is characterised by an abundance of aquatic environments with a rich supply of water resources (Akinyele, 2009). It is generally claimed that about 40% of the total land area of Lagos is covered by water and wetlands (Iwugo *et al.,* 2003). Due to the geological framework of the area, surface water and groundwater exist in large quantities, although groundwater is much more in abundance and mainly from semi-confined to unconfined aquifers (Longe & Balogun, 2010). However, there is still a limited supply of quality drinking water for a large section of the human populations (UN-WATER, 2007). Various actions have been undertaken to provide drinking water, including tapering of confined and unconfined aquifer and resorting to vendors – popularly known as 'sachet water' (Longe *et al.,* 1987). Research has shown that the aquifer is contaminated by anthropogenic activities, industrialisation and improper disposal of solid waste and non-biodegradable materials (Longe & Balogun, 2010; Atakpo *et al.,* 2011). The effects of these activities are also being associated with urban flooding in Lagos (Aderogba, 2012a).

Extensive investigations have been carried out with respect to the quality of ground water following the impacts of anthropogenic activities (Ehinola & Ogundele, 2010; Soladoye & Ajibade, 2014; Nkwunonwo & Awwal, 2015). Whilst the conclusion remains that the quality groundwater source is threatened, other local hydrological components which include infiltration, surface runoff, evapotranspiration and peak discharge are also undermined. As flooding is clearly a hydrological problem, therefore, to address the challenges, more research is needed towards the rate at which anthropogenic activities are modifying the local hydrology of Lagos.

3.2 Topography and land use

3.2.1 Topography

Besides the natural vegetation, the topography of Lagos is made up of a number of manmade features such as engineering, tourist and religious constructions as well as commercial and social amenities. Consistent urban growth has eclipsed natural topography making the area a dense network of complex morphological urban location (Agbola & Agunbiade, 2009). Alongside other features, the natural landscape of the area is primarily a flat surface (Aderogba, 2012a). The average gradient is less than 1: 100,000 with a minimum ground elevation of about 6*m (~20ft*) above sea level located at Surulere LGA, while the highest point is at Ifako-Ijaiye LGA, measuring about 80*m (~ 260ft)* (See the figures 3-5 and 3-6 below).

Figure 3-5: Elevation map of Lagos showing highest and lowest points.
Source: www.topographicmap.com

Due to the complex morphology and form of the Lagos area, a detailed representation of topography is fundamental to flood related studies (Bates & De Roo, 2000). The most up-to-date available data relating to detailed topography in the area is the airborne LiDAR dataset that was recently sampled. Although the present research utilised the dataset, the cost of acquisition and post-processing of the data were major challenges, which previous scientific investigations requiring topography had to overcome through the use of the historic and ageing large scale (1: 1000) topographic maps of Nigeria which are in various sheets (Nkwunonwo, 2013; Nkwunonwo & Okeke, 2013). Other data sources to delineate topography include routine local topographic survey and freely available global topographic datasets such as 90-m Shuttle Radar Topographic Mission (SRTM) and 30-m Advanced Space-borne Thermal Emission and Reflection Radiometers Global Digital Elevation Model (ASTERGDEM). However, it is being argued that these datasets are major sources of uncertainty in flood hazard assessment (Sanders, 2007; van de Sande *et al.,* 2012).

3.2.2 Land cover (LC) and land use (LU)

The natural and manmade topographic features in Lagos form the land cover (LC) and land use (LU) system. Following the Anderson (1976) classification scheme water body, vegetation, residential and industrial uses are the four main LC and LU, classes that have been identified in Lagos (Obiefuna *et al.,* 2012; Adepoju *et al.,* 2006; Nkwunonwo, 2013). The rate at which the natural LU and LC – vegetative farmlands and water bodies – are being modified mainly due to the rate of urbanisation is a major issue of concern (Odunuga & Oyebande, 2007; Obiefuna *et al.,* 2013). Apart from degrading the quality and natural form of the environment, LC and LU changes in Lagos has also been linked to the widespread urban flooding among other environmental hazards (Obiefuna *et al.,* 2013; Nkwunonwo, 2013). Critical to ongoing debates is the means to address the range of human necessities – food security, housing and economic power – without compromising the stability of the ecosystem (Nkwunonwo & Kolawole, 2010).

In section 3.5, LC and LU change investigation towards flood risk assessment in Lagos is discussed. However, it is intended in this section to highlight the rate of growth of urban areas in the Lagos. Figure 3-7 shows LC and LU maps representing four epochs in Lagos – 1990, 2000, 2006 and 2012.

Figure 3-6: Elevation map of Lagos, Nigeria, which displays range of elevation with different colours.

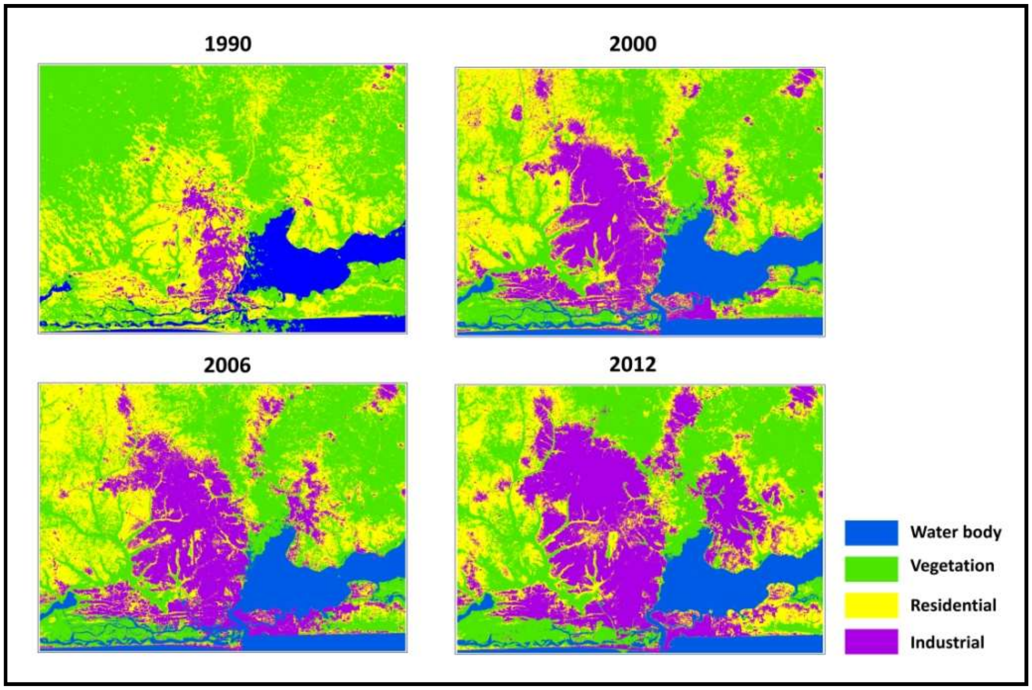


Figure 3-7: Land use (LU) land cover (LC) maps of Lagos metropolis covering the year: 1990, 2000, 2006 and 2012.

Figure 3-7 above illustrates a progressive growth in residential and industrial land classes, and a corresponding reduction in water body and vegetation land classes. Adepoju *et al. (*2006), Nkwunonwo (2013), and Obiefuna *et al.* (2013) are among several studies which quantitatively assessed this rate of LU and LC changes. Results indicate that the present urban areas, which include residential and industrial land classes, accounts for at least 54% of the whole Lagos area. Between 1984 and 2006, vegetation, especially mangrove wetlands decreased at the rate of 3.12km^2 per year, whilst Swamps decreased at the rate of 8.15km^2 per year (Obiefuna *et al.*, 2013). Although a more recent assessment of LU and LC changes in Lagos is lacking, the present situation in LU and LC changes, especially as it tends towards rapid population growth and urbanisation, is an important issue in relation to the present research, which argues that such changes form a major catalyst of social and physical vulnerability to urban flooding in Lagos.

3.3 Rapid population growth and urbanisation

Urbanization and rapid population growth combine with widespread flooding to intensity the threats on human population and urban assets. They are among the major evolving global concerns for the management of urban flooding (Cohen, 2006; Satterthwaite, 2009; Smit & Parnell, 2012). For Lagos, complex human settlements, overcrowding, pollution, illegal structures, wetland depletion, traffic congestion and complicated urban development are major issue in relation to urbanisation and rapid population growth (Obiefuna *et al.,* 2013). Others issues include poor living conditions, poor sewage, drainage and waste disposal systems, crime and a host of social and environmental disorders (Gabriel & Abraham, 2011). A great deal of the Lagos population currently lives within areas prone to flooding. Locally, the majority of these areas are slums, which provide provisional dwelling places to poor urban residents, but also increase the exposure and vulnerability to flooding of a large sections of the human population who lack resilience or capacities to cope with the flood hazard (Adelekan, 2010).

These problems – particularly slum development – suggest the need to intensify actions towards urban related challenges within the context of FRM in Lagos (Action aid, 2006; Adelekan, 2010). Slum development is a global issue and the UN-HABITAT (2013) estimates that 863 million people worldwide live in slum conditions. For Lagos, it is argued that more than 200 different blocks of slum settlements are scattered around the city while over two-thirds of the population of Lagos lives in slum conditions (Gandy, 2006; Morka, 2007; Agbola & Agunbiade, 2009; Lukeman *et al.,* 2014). This scenario underlines the importance of developing efficient adaptation measures through a proper assessment of social and physical vulnerability to urban flooding for the Lagos area.

3.3.1 Rapid population growth

Rapid population growth which arguably subjects Lagos area to lack of space for the myriad of human activities is a critical concern in relation to sustainable human and urban development (Oduwaye, 2009). According to recent reports, the population of

Lagos is presently estimated at 21 million, with a population growth rate estimated at 3.2% (Campbell, 2012; World Bank, 2013). These predictions of future population growth will be accompanied by climate change in the form of increased frequency and intensity of precipitation to worsen the severity of urban flooding (Aluko, 2010; UNDP, 2008). Barredo & Demicheli (2003) predict that up to 27 million people will inhabit Lagos by 2020. Lagos metropolis will account for Nigeria's position as one of the eight countries expected to account collectively for half of the total population increase in the world from 2005–2050, and will by 2100 record a population figure amounting between 505 million and 1.03 billion people (United Nations, 2004). It is estimated that Lagos is among the top 20 cities in the world with large human population exposed to coastal flooding presently and by 2070 (see table 3-1 below) (Nicholls *et al.,* 2008).

Table 3-1: Top 20 countries ranked in terms of population exposed to coastal flooding in the 2070s, including both climate change and socio-economic change) and showing present day exposure. (Source: Nicholls *et al.,* 2008, OECD, Paris)
* *Highlight is by author*

Rank	Country	Urban Agglomeration	Exposed Population (Current)	Exposed Population (Future)
1	India	Calcutta	1,929,000	14,014,000
2	India	Mumbai	2,787,000	11,418,000
3	Bangladesh	Dhaka	844,000	11,135,000
4	China	Guangzhou	2,718,000	10,333,000
5	Vietnam	Ho Chi Minh City	1,931,000	9,216,000
6	China	Shanghai	2,353,000	5,451,000
7	Thailand	Bangkok	907,000	5,138,000
8	Myanmar	Rangoon	510,000	4,965,000
9	USA	Miami	2,003,000	4,795,000
10	Vietnam	Hai Phòng	794,000	4,711,000
11	Egypt	Alexandria	1,330,000	4,375,000
12	China	Tianjin	956,000	3,790,000
13	Bangladesh	Khulna	441,000	3,641,000
14	China	Ningbo	299,000	3,305,000
*15	Nigeria	Lagos	357,000	3,229,000*
16	Cote d'ivoire	Abidjan	519,000	3,110,000
17	USA	New York	1,540,000	2,931,000
18	Bangladesh	Chittagong	255,000	2,866,000
19	Japan	Tokyo	1,110,000	2,521,000
20	Indonesia	Jakarta	513,000	2,248,000

The specific cause of rapid population growth in Lagos is not well-known. However, on the basis of population growth globally, birth rate and migration especially from other states of Nigeria and overseas are possible contributory factors (Zlotnik, 2004). From various census reports, Lagos population figures have grown from twenty-five thousand and eighty three persons in 1866 to more than sixteen million people (table 3-2) (NPC, 1991). Table 3-3 shows population distribution and other demographic variables across various 16 LGAs of Lagos metropolis with Eti-Osa LGA representing the largest land mass, while the population at Alimosho tops the list. The various levels of exposure and vulnerability to flooding which the variations in population and land use densities in LGAs indicate are major issue which highlight the relevance of the present research.

Table 3-2: Population figures of Lagos from 1800 till the most recent census of 2006. Sources: 1800-1952/53: Mabogunje (1968), Ekanem, (1963), The Population Census of Nigeria, 1963, 1973- 2006: Federal Office of Statistics, Lagos.

Year of Census / estimate	Area covered by census/ estimate (in sq. miles)	Population
1800	N.A	6,000
1850	N.A	18,000
1866	N.A	25000
1871	1.55	28,518
1881	1.55	37,452
1891	1.55	32,508
1901	N.A	41,847
1911	18.00	73,766
1921	20.17	99,960
1931	25.59	126,108
1950	27.22	230.256
1952/53	27.00	267,407
1963	27.00	952,752
1985	27.00	3,538,000
1988	27.00	2,788.736
1989	27.00	3,022,936
1990	27.00	3,063,594
1993	27.00	5,685,781
2006	386.00	8,049,430

Table 3-3: Demographic distribution by LGAs of the Lagos metropolis of Nigeria.
Source: Lagos state Local Government area abstract of Statistics, 2012.

S/No	LGAs	Land Area (SqKm)	Population (Male)	Population (Female)	Total Population	Population Density	% Total Population	% Male	% Female	Dev. Projects	Professionals	Gainfully Employed	No. Primary Health Care
1	AGEGE	17.00	564,239	468,825	1033064	60768.47	6.43	3.51	2.92	3	1286	136	21
2	AJEROMI-IFELODUN	13.90	723,644	711,651	1435295	103258.63	8.94	4.51	4.43	1	843	140	25
3	ALIMOSHO	137.80	1,099,656	947,370	2047026	14855.05	12.75	6.85	5.90	5	2444	2883	38
4	AMUWO-ODOFIN	179.10	301,012	223,959	524971	2931.16	3.27	1.87	1.39	1	764	1373	9
5	APAPA	38.50	264,728	257,656	522384	13568.42	3.25	1.65	1.60	17	858	1682	6
6	ETI-OSA	299.10	460,124	523,391	983515	3288.25	6.12	2.86	3.26	2	1451	4268	14
7	IFAKO-IJAYE	43.00	380,112	364,211	744323	17309.84	4.63	2.37	2.27	0	1454	1052	5
8	IKEJA	49.92	328,778	319,942	648720	12995.19	4.04	2.05	1.99	35	1238	1416	46
9	KOSOFE	84.40	527,539	407,075	934614	11073.63	5.82	3.28	2.53	16	1457	1717	8
10	LOGOS-ISLAND	9.26	461,830	398,019	859849	92856.26	5.35	2.88	2.48	7	1407	661	2
11	LAGOS-MAINLAND	19.62	326,433	303,036	629469	32083.03	3.92	2.03	1.89	9	1057	641	6
12	MUSHIN	14.05	684,176	637,341	1321517	94058.15	8.23	4.26	3.97	1	1357	24	13
13	OJO	182.00	507,693	433,830	941523	5173.20	5.86	3.16	2.70	2	1545	842	12
14	OSHODI-ISOLO	41.98	514,857	619,691	1134548	27025.92	7.06	3.21	3.86	5	1059	804	119
15	SHOMOLU	14.60	517,210	507,913	1025123	70213.90	6.38	3.22	3.16	2	1976	0	7
16	SURULERE	27.05	698,403	575,959	1274362	47111.35	7.93	4.35	3.59	4	1787	0	7
	Totals		***8360434***	***7699869***	***16060303***								

3.3.2 Urbanisation

Various studies underline the rapid rate at which major cities evolve from rural areas and small communities, as a result of migration, economic development and industrialization (Henderson, 2002; Weng, 2002; Foley *et al.,* 2005; Houet *et al.,* 2010; Satterthwaite *et al.,* 2010; Aluko, 2010; Saikiaa *et al.,* 2013). The Global Health Observatory (GHO) estimates that 54% of the world's population is presently living in cities (GHO, 2014). This number could rise to 70% by 2050 (UN-HABITAT, 2008). Sub-Saharan Africa, south-eastern Asia, eastern and western Asia appear to be the hotspots of urbanisation since nearly a decade ago, the rates of urbanisation in those places were estimated at 4.58%, 3.82%, 3.39%, and 2.89% respectively (UN-HABITAT, 2006).

These growth rates are often indices of increased risk of urban flooding (Kahn, 2009; Jha *et al.,* 2012). For example in England and Wales, 80,000 homes are at risk of urban flooding, which is estimated to cost about £270 million (approximately US$ 490 million) a year and could rise to between £1-10 billion (approximately US$ 1.5-15 billion) by 2080 (POST, 2007). About 80% of the US population resides in or around urban areas (McKinney, 2006). Approximately 7 million urban residents in the People’s Republic of China are presently exposed to urban flooding of coastal origin while about US$ 250 billion worth of assets are at risk from flooding in the Netherlands (Nicholls *et al.,* 2007). Although the present population in Dhaka, Bangladesh, exposed to urban flooding of coastal origin is nearly a million, more than 11 million people will be exposed by 2070 (Nicholls *et al.,* 2007). India, Japan and Nigeria are examples of countries in the DCs having cities each with a population of more than a million (refer to their national demographic database). Such population estimates not only highlights the urgent need for housing units, which escalates urbanisation, but also motivates research, mostly to formulate efficient flood risk management policy, and to enhance the capacities of human populations to cope with the present and future urban flooding events.

In Lagos, increasing needs for housing units is a critical issue, which escalate urbanisation rate in the area, and also influences the general morphology of the city

(Akiyode, 2012). Sessou (2013) claimed that more than one million, two hundred thousand houses existed in the area in 2012. Unfortunately, such urban growth is not accompanied by a corresponding urban planning scheme (Adeloye & Rustum, 2011). Moreover, little attention has been given to the reasons why routine city improvements recommended in Gabriel & Abraham (2009) are not often being considered. In view of the cluster of built-up structures, a number of concerns arise. Firstly, significant numbers of built-up structures either are unplanned or rarely adhere to local building regulations and town planning guidelines (Aluko, 2010). Secondly, while the condition of these buildings is not sufficiently taken into consideration in many flood hazard assessment discussions, there are speculations that a good number of them either have long since exceeded their life spans, or have been built with inferior materials or are built along natural drains and channels, thus, making them and their occupiers susceptible to flooding (Nkwunonwo *et al.,* 2015b).

3.4 Culture, politics and economy in relation to management of Lagos urban flood risk

3.4.1 Culture

Lagos is home to at least 250 ethnic groups of varying languages and customs with Fulani/Hausa, Yoruba and Igbo ethnic groups dominating (Fabusoro *et al.,* 2007; Akinwale 2011). This has significant implications in flood risk management when one considers the roles societal cultural background and historical experiences play in formulating policies for improved flood risk management (Samuels *et al.,* 2006). Nkwunonwo *et al.* (2014) argued that the concepts of ethnicity and 'unity in diversity' impact considerably on social vulnerability to flooding in Lagos. Strength, weaknesses and resilience of people are often determined by the uniqueness of their culture and ethnicity (Gandono, 1978; McCubbin & McCubbin, 2005; Ungar, 2008; Clauss-Ehlers, 2008). This is because different cultures and ethnic groups are characterised by specific occupations, nutrition and ancestral backgrounds and by extension the history of how they came through their historic events (Bonder *et al.,* 2004). Unfortunately, no research known to the author has been directed towards the influence of ethnicity and community livelihood on individual responses to flooding in Lagos.

3.4.2 Politics

It is claimed that demographic and economic developments contribute significantly to flood risk in urban areas (Samuels *et al.,* 2006). Thus, formal administrative structures and institutional framework are fundamental to efficient management of urban flood risk (EA, 2010). In Lagos, poor political will power is a major constraint towards addressing the challenges of urban flooding (Adelekan, 2015). Failures in infrastructural development and indeed poor urban planning are more critical issues (Adeloye & Rustum, 2011). The problems of political control and service delivery manifest each time a new team of politicians takes on the governance of the state (Fourchard, 2011). For example, during the first period of military administration (1967-1979), four areas received top priority: environmental services (water, sewage, and drainage), general administration, public transportation, and education. Under the succeeding civilian administration in 1979-1983, this order was generally maintained, except that expenditure on roads and housing rose considerably and edged education into fifth position (Olowu, 1990).

Between 1991 and 1993, when the Lagos state government was controlled by the National Republican Convention (NRC) and the local governments by the Social Democratic Party (SDP), there were several allegations by the SDP that the state administration was frustrating efforts at waste disposal by not settling bills due to the Waste Management Authority, for political reasons. With APC (All Progressive Congress) political party presently in control of Lagos state, much is expected in the areas of management of flooding and events related to climate change in the state. However, from the documented evidences of Olowu (1990), Peil (1991), Abiodun (1997) and Fourchard (2011), any efforts by the present administration to address the challenges of flooding are likely to be undermined in the nearest future if the incumbent party loses the next gubernatorial elections. Nevertheless, it is argued that efficiency and effectiveness in addressing the challenges of flooding and other climate change related events in the Lagos area would be largely improved if the administration and other political dimensions in the state were to be more stable.

3.4.3 Economy

Lagos area is characterised by various commercial and industrial activities, making the city the strongest economy in Nigeria in terms of gross domestic product (GDP). Lagos state accounts for over 60% of the nation's total industrial investment (Atakpo *et al.,* 2011). Measured by Gross Domestic Product (GDP), Lagos is among the richest states in Nigeria (see figure 3-8 below) and presently contributes more than US$ 74,674 to Nigeria's economy (Lagos Bureau of Statistics: LBS, 2012). This is attributed to a number of factors including the presence of sea-port – which is Nigeria's leading port and one of the largest and busiest in Africa – the presence of national and international airport, and the headquarters of Nigerian Stock Exchange (LBS, 2012). Other factors may include the large concentration of skilled and semi-skilled manpower, the presence of the head offices of almost all commercial banks operating in Nigeria, and a large road transportation networks linking Lagos to other parts of Nigeria.

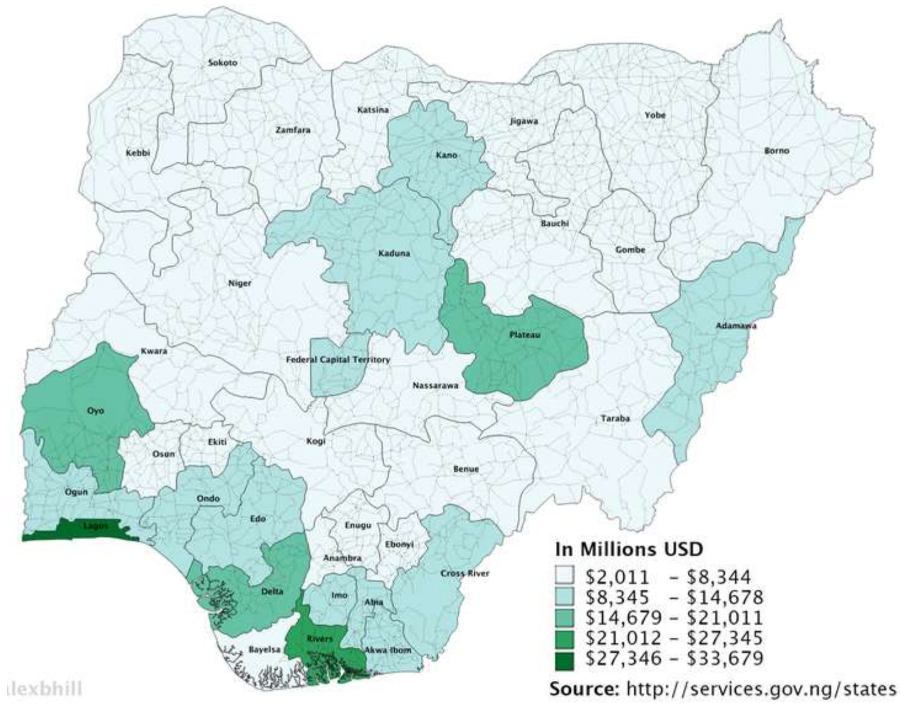


Figure 3-8: Nigerian states according to their Gross Domestic Products
Source: http://services.gov.ng/states

In view of the economy of Lagos area vis-à-vis the present efforts towards addressing the challenges of flooding, some critical issue come to mind. First, the area is poorly planned, which leads to widespread urban flooding (Adeloye & Rustum, 2011). Despite the financial development, annual investment in flooding is unknown, whilst research towards developing more current ways of addressing the challenges of flooding is poorly funded. In addition to these concerns, it is important to understand that if the area were poor so to speak, then the prospects of addressing the challenges of flooding and indeed other environmental hazards will continue to be elusive. However, while all sensible arguments point to corruption and political weakness as a possible cause of this failure (Nwabuzor, 2005). It is strongly recommended that reducing the vulnerabilities to flooding of social systems should be of utmost priority.

3.5 Review of flooding and flood risk management in Lagos

3.5.1 Flooding in Lagos

Flooding and flood risk management are issues of grave significance in Lagos (Aderogba, 2012a; Aderogba, 2012b). Various studies have claimed that flooding in the area has been devastating, affecting hundreds of thousands of people and causing widespread panic and considerable economic damage (Ajibade *et al.,* 2013; 2014; Adelekan, 2015; Nkwunonwo *et al.,* 2016). Two important examples are the flooding of 2011 and 2012. On the 11th July 2011, there was severe flooding event, which affected approximately five thousand people and resulted in about 25 deaths. The direct economic losses resulting from the event reached about 50 billion Nigerian naira (i.e. US$ 250 million). Public utilities including road networks, bridges and schools were destroyed. In addition, houses collapsed, private homes were submerged, while several cars were swept away by flood water (IFRC, 2011; Oladunjoye, 2011). Urban flooding claimed seven lives and caused severe damage to properties in June 2012. Economic activities and the source of livelihoods of many residents were affected (The Guardian, 2012).

3.5.1.1 Frequency of occurrence

According to FME (2012), Lagos is one of the few locations in Nigeria with more frequent flooding events (see figure 3-9). A number of floods have occurred in the Lagos area, although keeping track of events in the Nigerian context is challenging due partly to lack of relevant data collection capacities. As a result, data relating to hydrodynamics and historical flooding events are often lacking (Ajibade *et al.,* 2013). Table 3-4 shows a summary of major flooding events and associated consequences in the Lagos metropolis of Nigeria from 1968 to 2012. These data which appear to represent generalized flooding situations were obtained from a wide-range of sources including EM-DAT and Nigerian FME (Federal Ministry of Environment). It is argued that the conclusions that can be drawn about flooding in Lagos from these datasets relate to events of higher magnitudes and return periods (Guha-Sapir *et al.,* 2013). Only journalistic and non-quantitative evidence are available for lesser impacts and more frequent flooding events (see for example, IFRC, 2012). The problem with these forms of evidence is that they often do not have ethical and empirical groundings. For most of the events considered, data relating to flood duration and impacts in terms of number of people displaced, mortality and economic losses were not available. On the basis of this inconsistency, the effectiveness of flood management policies is being queried (Adelekan, 2015). In many cases, different types of flood damage were aggregated. Indeed, this situation adversely affects accurate flood damage estimation since a critical understanding of Lagos flood risk in the context of flood damage typology is difficult.

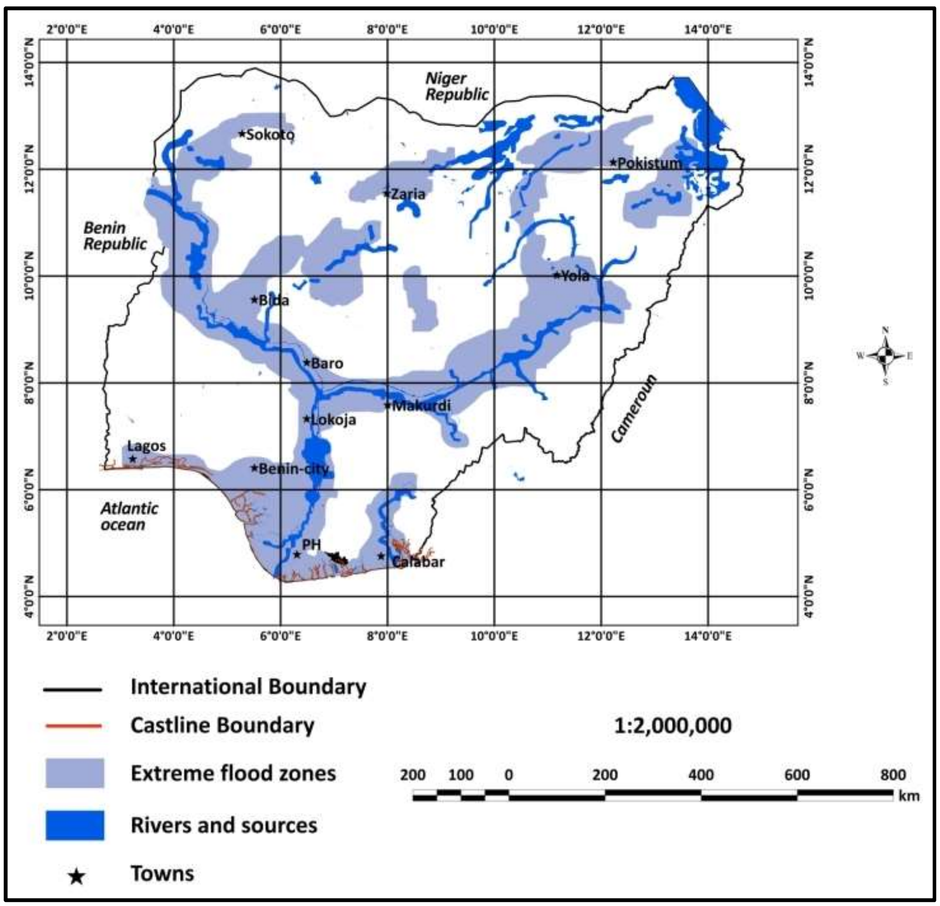


Figure 3-9: Spatial distribution of areas affected by extreme floods in Nigeria between 2000 and 2012. Source: Adapted from Federal Ministry of Environment (2012).

Table 3-4: A summary of major flooding events and associated threats in the Lagos metropolis of Nigeria from 1968 to 2012. Source: EM-DAT (2014), FME (2012) and other secondary sources.

*Grouped instead of treating as separate variables due to lack of data. N/A: *Not available*. Nil: *No information*.

S/No.	DATE	LGA(S) AFFECTED	DURATION (DAYS)	CAUSE (S)	NO OF PEOPLE DISPLACED	MORTALITY	ECONOMIC LOSS (₦)	AFFECTED HOUSES / OTHERS
1.	Oct, 2012	Lagos city*	Many days, unspecified	Heavy Rain	Thousands	>50	Millions, unspecified	Many*, including interruption of traffic and other activities
2.	July, 2011	Lagos island, Mainland, Mushin	2 days	Heavy Rain	10,000	100	Millions, unspecified	Many*
3.	Oct, 2010	Lagos island, Apapa, Kosofe,	Many days, unspecified	Heavy Rain	Thousands	20	Millions, unspecified	Many* including interruption of traffic and other activities
4.	July, 2009	Lagos city*	Many days	Heavy Rain	Many	Nil	Millions, unspecified	Many*
5.	Oct, 2008	Lagos city*	N/A	Heavy Rain	Not specified	No data	Millions, unspecified	Many* including interruption of traffic and other activities
6.	August, 2007	Ikorodu, Kosofe and Abeokuta	15	Heavy Rain	5000	17	Millions, unspecified	5000
7.	July 2005	Lagos city	5	Heavy storm	3000	25	Millions	N/A
8.	June, 2004	Lagos city	2	Heavy Rain	1000	Nil	Millions	Drainages
9.	July, 2002	Lagos city	3	Heavy Rain	200	2	Millions	Many*
10.	June, July Sept, 2000	Victoria Island & Ikoyi	2	Brief Torrential Rain	500	Nil	Millions, unspecified	Tens of thousands
11.	May, June, July, 1999	Mushin and Idiaraba	N/A				70,000,000	
12.	July, 1990	Lagos city	2	Heavy Rain	3000	5	Thousands	Many*, not specified
13.	July, 1990	Lagos city	2	Heavy Rain	500	Nil	N/A	Hundreds of inhabitants
14.	June, 1974	Idiaraba, Ikorodu, Surulere and Yaba	Many days, unspecified	Heavy rain	Thousands	Nil	N/A	
15.	June, 1972	Lagos Island	N/A	Heavy rainfall	Not specified	Nil	N/A	Traffic was disrupted, Few houses
16.	July, 1971	Lagos Island	5	Heavy rainfall	Not specified	Nil	N/A	Traffic was disrupted, Few houses
17.	July, 1970	Lagos Island	N/A	Winds, accompanied by short duration, high intensity rain	Nil	Nil	5000	Few
18.	June, 1969	Surulere and Yaba	10	Short duration, high intensity rain	Nil	Nil	N/A	Many*, not specified
19.	June, 1968	Lagos Island and Ijora.	N/A	Heavy storm	Nil	Nil	6000	Traffic was disrupted, Few houses

To qualitatively identify risk levels in this area, an approach used in 2005 World Bank Hotspot project was adopted (Dilley *et al.,* 2005). In this approach, records of flood events and affected areas were coupled with the population density of the local enumeration areas in Lagos and mapped in a GIS. The result of this analysis as shown in figure 3-10 indicates that Ajeromi-Ifeledun and Mushin areas are at a higher risk of flooding than the rest of the areas. This approach regardless of its simplicity, offers a potentially valuable insight into flooding pattern in Lagos. However, much uncertainty lies within the results and this suggests the need for more detailed research that will investigate the flood risk levels of Lagos using a more detailed quantitative dataset.

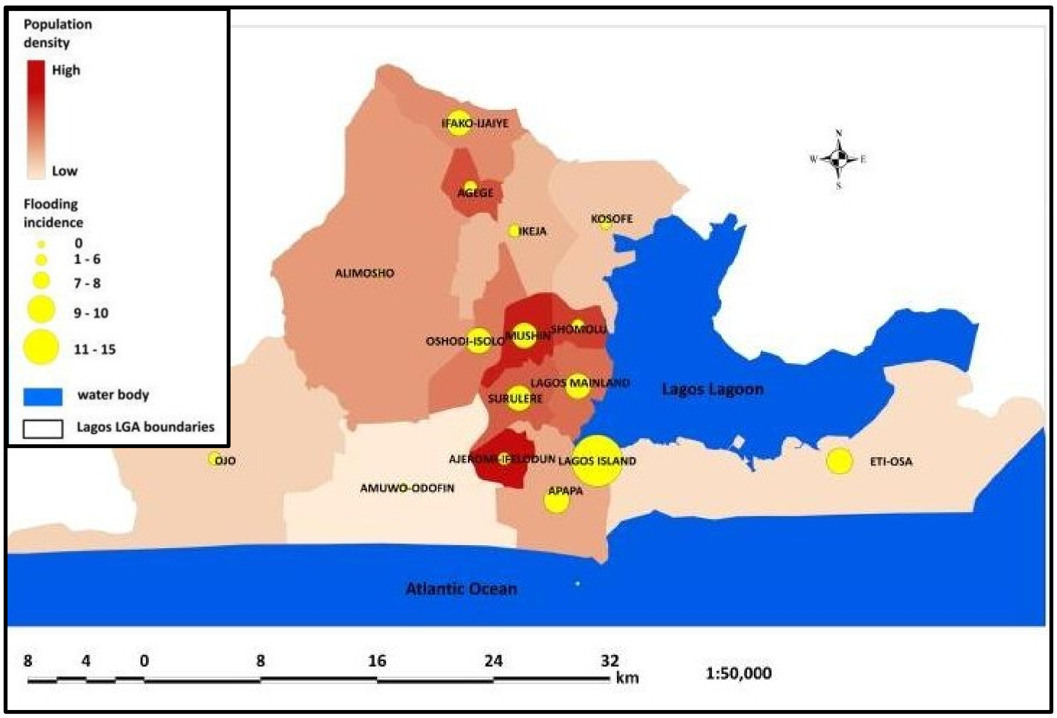


Figure 3-10: Flood risk levels in the Lagos area qualitatively determined by coupling population density with list of flooding events and locations.

3.5.1.2 *Specific causes*

Climate change through increased rainfall frequency and intensity, as well as sea level rise is generally highlighted as the major influential factor of urban flooding (Douglas *et al.,* 2008). Global rainfall datasets (for examples Global Precipitation Climatological Center: GPCC, International Precipitation Working Group: IPWG, 2016) show that the world is presently getting more precipitation than it did in the last 100 years. There is 6% precipitation increase in the United States - although the statistics varies according to region - and nearly 2% worldwide (IPCC, 2007; Kunkel *et al.,* 2010; USEPA, 2014 pg. 36). Climate change causes variations in air and ocean currents, and precipitation in the future is expected to increase in higher latitudes and decrease in areas closer to the equator (Trenberth, 2011). Recent global rainfall distribution shows that more high-intensity-shorter-duration and low-intensity-longer-duration rainfall events are now commonplace (Palazzi *et al,* 2013). Table 3-5 gives examples of these recent global rainfall patterns.

Table 3-5: Examples of recent global rises in rainfall frequency and intensity

Date/Year	Location	Rainfall Amount	Duration	Source
26 July 2005	Mumbai, India	994mm	24 hours	Gupta (2007)
June 2007	England and Wales	140mm	24 hours	EA (2010)
July 2010	Pakistan	274mm	24 hours	Gaurav *et al. (*2011)
June 2013	Alberta, Canada	>325mm	< two days	Pomeroy *et al. (*2015)
May 2010	Tennessee, USA	~ 345mm	< two days	Moore *et al. (*2012)
late December 2010	Queensland	400mm		Giles (2012)
In June 2011	Lagos, Nigeria	463.3mm	17 hours	Adelekan (2015)
November 2015	Chennai	~ 374mm	24 hours	Local media
Jun 2015	Accra, Ghana	torrential rainfall	two days	Local media

These pluvial events, albeit in combination with other factors, suggest that floods of significant magnitude and lower return periods are more likely to be expected in the cities. Within this framework, Kundzewicz *et al.* (2010) demonstrated that the 100-year control flood is now unlikely to support a realistic flood defence in many European countries, implying that for structural and non-structural measures to remain useful in flood risk management, redefining the 100 -year control flood by a factor of at least one has become unavoidable, an issue that is being debated across major flood risk management research (Wilby & Dessai, 2010; Wilby & Keenan, 2012; Kundzewicz *et al.*, 2014). Debates arising from the literature indicate that Lagos floods are mainly the consequences of climate change induced short-duration-high-intensity or long-duration-low-intensity rainfall (Ayoade & Akintola, 1980; Action aid, 2006; Adeloye & Rustum, 2011; Houston *et al.,* 2011a; Aderogba, 2012a; Adelekan, 2013; Oshodi, 2013; Ajibade *et al.,* 2013; 2014, Soneye 2014). Odjugo (2006) concluded that there are now more high intensity short duration rainfall events and more low intensity long duration rainfall events than there were three decades ago. Despite the recognised implications of these scenarios, a key issue within hydrological research, and by extension urban flood risk assessment, is the poor access to high quality data (especially in the DCs) and robust analyses techniques that accurately reflect the changing precipitation pattern (Min *et al.,* 2011, Zhang *et al.,* 2011; Marvel & Bonfils, 2013; Leidig *et al.,* 2016).

Urban flooding in Lagos is also influenced by topography of the area, poor urban planning, poor environmental management and a number of anthropogenic activities which modify the natural LU/LC system such as urbanisation and rapid population growth, and the indiscriminate disposal of solid waste (Adeloye & Rustum, 2011; Lamond *et al.,* 2012). Poor urban drainage systems are important issues in urban flooding given the importance of adequate drainage infrastructure in the quick evacuation of sewage and excess water during heavy storms (Cembrano *et al.,* 2004; Jha *et al.,* 2011). Other factors are the influence of canals, lagoons and beaches (Aderogba, 2012a; Aderogba *et al.,* 2012; Odunuga, 2008). Tidal and co-tidal influences and frequent incursion from the Atlantic into the lowlands during heavy storms also play important roles (Ojinnaka, 2013). The tendency for urban flooding to occur is also linked to other natural hazards such as tsunami, hurricane and typhoon. The hurricane Katrina of 2005 with its life-threatening surge that breached the levees protecting New Orleans and flooded nearly 80% of the city is a typical example. Similarly, the Japan earthquake and tsunami of 2011 which flooded over 560km^2 of land areas including major cities, and the tropical storm *Seniang* of 2014 which produced severe floods that affected cities and rural areas in Philippines (Rhykus, 2005; Jonkman *et al.,* 2009;

Okazumi & Nakasu, 2015). Besides these recognized sources, urban flooding has also been subject to fluvial and coastal flooding events.

These factors (schematized in figure 3-11), seem to influence the occurrence of the hazard and the exposure of elements at risk. However, in relation to the vulnerabilities of social systems to flooding in the area, the development of slum settlements and poor perception of flooding among local communities, urban residents and the general public are considered critical factors (Ayoade & Akintola, 1980; Agbola & Agunbiade, 2007; BNRCC, 2008; Odunuga *et al.,* 2012; Nkwunonwo, 2013; Oloke *et al.,* 2013).

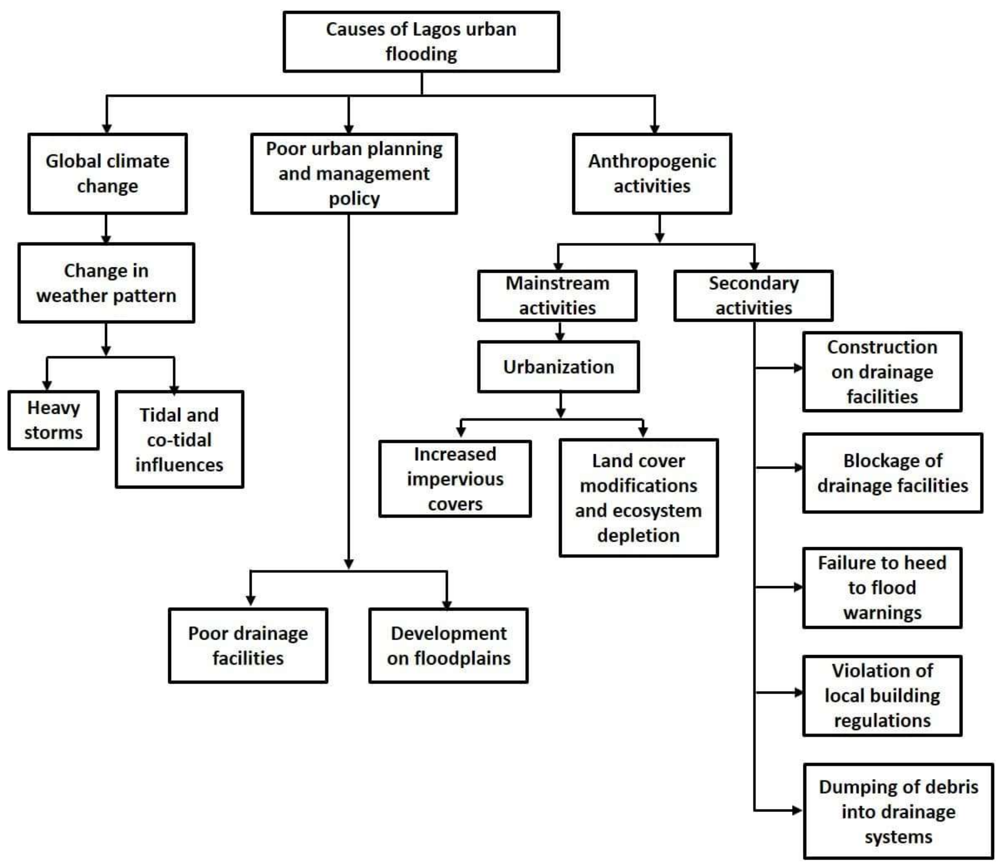


Figure 3-11: Main causes of urban flooding in the Lagos area of Nigeria showing global climate change, poor urban planning, urbanisation and anthropogenic activities.

3.5.1.3 Major impacts

Large scale impacts are reported of urban flooding within the DCs (Action aid, 2006; Lall & Deichmann, 2011). The July 2011 flooding in Lagos presents a clear example. Others are the 2010 Pakistan flooding, and the flooding of Accra and Chennai in 2015. The 2010 Pakistan flooding affected nearly one-fifth of the country's total land area (approximately 5400km^2), displaced about 20 million people, and caused 2,000 deaths (Gaurav *et al.,* 2011; Webster *et al.,* 2011). The economic damage resulting from the event was estimated at about US$ 1 billion (OCHA, 2012). Similarly, in Accra, Ghana, pluvial flooding, coupled with explosion at a gas station, resulted in the sudden death of over 200 people (Relief Web, 2015). Any connections between the flooding and the explosion have yet to be established. Causalities of the explosion were mainly individuals who took shelter at the station due to the rainfall (Reuters, 2015). Data relating to the actual impacts of the events are not available at the time of writing this thesis. However, many people were displaced from their homes, whist significant urban assets were damaged (IFRC, 2015). Red Cross assessment figures indicate that more than forty thousand people were affected by the flooding event. However, on the basis of IFRC needs assessment, an estimated CHF108115 (US$107000) was needed for reconstruction and recovery (IFRC, 2015).

The 2015 Chennai urban flooding was reputed to be the costliest for the year from the point of view of economic impact. Significant urban assets including major roads, city centers, schools and public offices were destroyed. The runway of the Chennai airport was flooded, whilst many economic activates were disrupted. About ten thousand people were evacuated from their homes. Flood water rendered many areas inaccessible. Indian local media reported about 70 deaths. Wall street Journal (2016) estimates the economic damage, to reach US$ 3 billion.

These impacts, both within the developed societies and the DCs (some of which are shown in appendix D: pages 337-339) underline the relevance of flood risk management, which has so far received significant attention in the literature. However, despite the ubiquitous nature of urban flooding and its impacts, the current methods to address the hazard reveal remarkable variations, travelling across regional, national and local scales (Samuels *et al.,* 2006; Zevenbergen *et al.,* 2008). Arguably, within the DCs this situation is underscored by a lack of proper understanding and application of the philosophy of flood risk management. Moreover, the current measures to tackle urban flooding are constrained by a weak institutional capacity, poor flood perception among the wider population, and the less availability of more scientific approaches, to assess and communicate urban flooding to various stake holders (Nkwunonwo *et al.,* 2016). Such constraints underpin the objectives of the present research, especially in the development of a new flood model and computation of social vulnerability indices, which can be considered as a minimum requirement towards a synergistic flood risk management policy.

To date, the impacts of flooding in Lagos (as illustrated in figure 3-12) raise concerns about a lack of early warning and evacuation systems. The general impacts (such as displacement from homes, mortality, physical injuries, disruption of economic activities, destruction of urban infrastructure and submergence of buildings) that relate to social systems directly have been extensively considered in the literature (Ugwu & Ugwu, 2013; Adigun *et al.,* 2013; Ajibola *et al.,* 2012; Aderogba, 2012b; Olajuyigbe *et al.,* 2012). However, there are reports that Lagos flooding causes severe additional impacts including the loss of social values, spread of vector-borne diseases, as well as air and water pollution (Adelekan 2010; Olajuyigbe *et al.,* 2012; Bashir *et al.,* 2012).

Olajuyigbe *et al.,* (2012) report that the flood hazard increases city-wide poverty as a result of the farmlands which are being destroyed and essential services which are often interrupted. Adelekan (2010) investigated these impacts using four poor urban communities in Lagos as case studies and identified three significant scales: individual, household and community. At the individual scale, the reluctance of friends and family to visit one another while in flooded houses affects social relationships. This has broad adverse implications on community lifestyle and further compounds depression among flood victims in Lagos. Food insecurity is equally an important issue at this scale as food items stored in individual homes are often lost during flooding. In addition, there can numerous health impacts including chronic skin infections from exposure to contaminated environmental systems and increased effects on those with an already poor health history.

Figure 3-12: Some flooding scenes examples in the Lagos metropolis of Nigeria. Upper left: residential building submerged. Upper right: commercial areas flooded. Lower left: Slum area flooded. Lower right: local community center affected by flood waters.
Source: Authors' images of flooding in Lagos, Nigeria.

Household and community scales of impacts are mainly indicated by the secondary effects of flooding in Lagos. Household impacts include deterioration of building quality, intrusion of contaminated water into apartments, lack of good drinking water and loss or damage to household properties including sanitation facilities. The community impacts include an unclean environment, disruption of movement and damage to public utilities. Urgent needs arise where community schools were flooded and schooling for children has been interrupted. This is an important issue within the context of human development. In many other DCs where it is also applicable, community leaders and the local authorities have often instigated measures to ensure that children's schooling is not interrupted despite the magnitude of flooding. In Bangladesh for example, a strategy known as 'floating schools' in which classrooms are constructed on boats is being put in place during flooding (Huq & Aslam, 2003). This enables provision of uninterrupted education for children who have been torn apart and whose education has been disrupted by flood catastrophes.

The impacts of flooding in Lagos also trigger concerns for environmental management, sustainable urban development, governance and the vulnerability of urban residents and local communities. Other factors of concern are humanitarian needs and services especially primary health delivery (Soneye, 2014; Ajibade, 2013; Lamond *et al.,* 2012). Needless to say, concerns for solid waste management are crucial as long as indiscriminate dumping of wastes in drainage systems remains prevalent within Lagos. One example of this is the water sold in polythene sachets which is the major source of drinking water for residents. It is perceived that many residents dispose of the containers which end up in drainage facilities. Being a non-degradable waste, it accumulates over time and blocks these drainage facilities. Unfortunately, little has been done to address such an important issue in flood control management.

3.5.2 The management and reduction of flood risk in Lagos

Discussion in this section first considers flood risk management (FRM) from a general perspectives, highlighting those relevant components, from which FRM within Lagos context will be examined. This will aid the understanding of the gaps and limitations in the current efforts to manage flooding in Lagos. In the flood risk science and management, FRM is a systematic measure taken to reduce the likelihood and/or the impact of flooding on people and assets, and to promote the UNISDR idea of "living with floods" (Pender & Faulkner, 2010; Merz *et al.,* 2010). The "living with floods" idea is discussed in the section 3.5.2.2. However, FRM coordinates various efforts on the basis of a holistic management cycle which incorporates preparedness, emergency response, recovery, prevention, protection and lessons learned (Samuels 2000; EC, 2004). Within this framework, a sound understanding of flooding (taken as the scientific aspects of urban flooding in the present research), accurate and actionable assessment of flood risk, knowledge-based decision and strong political leadership are fundamental (UNISDR, 2007; UNISDR, 2010). However, there are other key factors, which include operational legislation, enhanced technology, human commitment, clearly defined institutional roles, economic buoyancy and vendible research (Fratini *et al.,* 2012; Sayers *et al.,* 2013).

3.5.2.1 Global context of Flood Risk Management

There have been important differences in FRM policies at local, national and regional scales (Samuels *et al.,* 2006). This is important to the present research in relation to improving current flood management efforts in Lagos. Due to the lack of relevant data, technical requirements, characterisation of floods, inconsistencies in risk conceptualisation, and hydrological uncertainties, existing FRM methodologies have continued to widen the gap between theory and practice or application of FRM, especially in the DCs (Apel *et al.,* 2004; Hansson *et al.,* 2008; Sayers *et al.,* 2012; Shah *et al.,* 2015). Within the current FRM literature, absolute knowledge regarding how to bridge this gap is lacking. Global current FRM practices or "best practices" in FRM can be identified in a wide range of sources, covering global, regional and national scales (Hall *et al.,* 2003; EC, 2004; Ashley *et al.,* 2007; Terpstra & Gutteling, 2008; Galloway, 2008; Fratini *et al.,* 2012; Sayers *et al.,* 2013).

Within the global perspective of FRM, attention is drawn to the idea of disaster risk reduction (DRR), which the general assembly of the United Nations (GAUN) promotes through a number of historic initiatives and international disaster reduction policies. Three key initiatives within DRR are the ‘Yokohama Strategy and Plan of Action for a Safer World’ (YokS), Hyogo Framework for Action (HFA) (2005–2015), and Sendai Framework for Disaster Risk Reduction (SFDRR) (2015-2030). For detailed discussion on these initiatives, refer to: Schipper & Pelling (2006), de la Poterie & Baudoin (2015), UNISDR (2015) and Zia & Wagner (2015). However, their main objective is to minimize the impacts of disasters by a critical investigation of the underlying factors (UNISDR, 2010). With regards to urban flooding, these initiatives focus on three key activities: (1) Mitigation by reducing the frequency, scale, intensity and impact of hazards. (2) Preparedness by strengthening the capacity of communities to cope with hazards, lessening exposure to hazards and improving the intervention strategies of public and private partners in situations when a communities' capacities are overwhelmed. (3) Advocacy by the use of counter measures towards all factors contributing to the causes and magnitude of impact of hazards, as well as promoting community-based risk management (UNISDR, 2004). Whilst these objectives are the governing principle of various strategies within the global framework of flood risk management, how to achieve them, within the framework of Lagos urban flooding, is the main driver of the present research.

One of the strategies within the regional framework of flood risk management is the European Union Commission Flood Directive (ECFD), which is aimed to sensitize member states towards a regional flood risk management policy (CE, 2007). A necessary requirement within the directive is a preliminary assessment of flood risk through flood risk and flood hazard mapping of member states (de Moel *et al.,* 2009). This is much like the Floodplain Management in the United States (FMUS) and the United States Disaster Mitigation Act of 2000 (DMA). Within the DMA, communities are required to produce comprehensive mitigation plans for hazard, risk and vulnerabilities identified within their jurisdiction, in order to receive full federal disaster assistance (Burby, 2006). FMUS is a national strategy built on the ideology of integrated flood risk management. The strategy, which has been in place more than four decades ago, arises from the awareness that a great deal of the country's urban areas are located on or near floodplains (FEMA, 1992). The main aim is to reduce floodplain losses which include loss of lives and properties and loss of natural and cultural resources (FEMA, 1992).

Similarly, flood risk and water management strategy in Netherland (FRWMN), and Integrated flood risk management in England and Wales (IFRMEW) are important local strategies. FRWMN combines both structural and non-structural measures designed to protect the population within the dykes to against a 0.0001 percent (i.e. 1 in 10,000 year event) frequency of any event occurring (Jha *et al.,* 2012). Flood maps for different return periods, and a high level of responsibility within the private and public sectors are important components of the FRWMN (Terpstra & Gutteling, 2008; Kazmierczak & Carter (2010). IFRMEW stems from the realisation of the critical implications of climate change scenarios and urban growth (EA, 2010). Among other factors, a clear definition of flooding and impacts, continuous review of management system performance, iterative decision making are key features (Hall *et al.,* 2003). IFRMEW is characterized by clear legislation and institutional responsibilities, as well as sustainable urban drainage system (SUDS), which is promoted through formal building regulations in respect to evacuation of surface water (Pitt, 2008).

On the basis of these strategies, significant progress has been recorded in flood risk management research. For example within the ECFD framework the EU member states have benefitted from a number of initiative and advanced flood risk management methodologies. These include, but are not limited to, collaboration and data and knowledge sharing (EC, 2004; Merz *et al.,* 2007; Müller, 2013). Recently, Germany launched a project called DRIVER (**DR**iving **I**nno**V**ation for crisis management for **E**uropean **R**esilience) to facilitate the provision of radar-based imagery for flood hazard and flood risk management covering the EU member states and other disaster threatened countries across the world (Govers *et al.,* 2015). For the DCs in general, and Lagos in particular, these strategies can provide guidance, resources and technical support to advance local efforts towards urban flood risk management. However, the realization of these strategies has been criticised by Tsakiris (2014) who argued that the strategies require extensive data, whilst the means to produce risk maps from hazard assessment remain complex.

Although these strategies are, to some extent, beneficial to the DCs, limitations in the management of urban flood risk are still major research issues, given that a high concentration of resources in the DCs, to foster globalisation through tourism, economic affiliations and international trade, appear to be potentially at risk from urban flooding (Action aid, 2006). This motivates the present research. For example, China presently has one of the fastest growing economies in the world with extensive human and economic resources, partners with Africa, Asia, Europe, Middle East and the United States and supports global economy through proceeds from China's major cities (Xiaojuan & Hui, 2004). However, whilst flooding events in China has been severe, with significant impacts on urban assets, efforts to address the threats are at best limited (Shi *et al.,* 2005). Similarly, Nigeria and Libya are major actors in the global oil industry, whilst other Africa countries for example Morocco, Algeria, Tunisia, Egypt and Kenya, despite major political crises, play significant roles in tourism and global partnerships (Watts, 2004). Unfortunately, flooding and the lack of efficient FRM, especially in these countries' most economically viable cities, such as Lagos, Cairo and Nairobi, undermine the idea of sustainable urban development and resilient city (Action aid, 2006). Although FRM has evolved over many years, no decisive approach has been adopted regarding how to assist the DCs to build a more robust FRM system that will promote the development of regional potentials and sustain the idea of living with floods (Mirza, 2003; Osti *et al.,* 2008; Lumbroso *et al.,* 2008; Merz *et al.,* 2010; Bhattamishra & Barrett, 2010).

3.5.2.2 Living with floods

The UNISDR idea of "living with floods rather than fighting them" is the underlying framework of FRM, and the present research is designed to galvanise discussions towards improved flood risk management in Lagos based on this UNISDR idea. The "living with floods rather than fighting them" philosophy tends towards a policy whereby societies adapt to floods by being prepared and having the right attitude towards damage reduction (van Ogtrop *et al.,* 2005). It evolves from three key considerations: (1) the understanding that traditional flood control structural measures do not have all the answers to flooding; (2) the need for a people-friendly means of tackling flooding; and (3) the goal to lessen all impacts of extreme floods while at the same time exploiting all benefits of ordinary floods (UNISDR, 2004; Di Baldassarre & Uhlenbrook, 2012). Within this framework, integrated approaches which combine structural and non-structural measures are being considered (Hall *et al.,* 2003; Ashley *et al.,* 2012; Kazmierczak & Carter, 2010; Sayers *et al.,* 2015). Structural measures are technically-based and involve channelization, and the use of natural and man-made barriers to contain waters in rivers and seas. Non-structural measures are multi-disciplinary approaches such as flood hazard and risk mapping, land use zoning and planning, sustainable urban drainage system, flood vulnerability assessment, flood modelling, flood awareness campaign, flood insurance, flood forecasting, green infrastructure, relocation and resettlement plans, etc., (Merz *et al.,* 2007; Jha *et al.,* 2012; Smith, 2013).

3.5.2.3 Flood hazard and flood risk mapping

Flood hazard and flood risk maps are vital tools for FRM. They are visual representation of flood hazard and risk, useful for the communication of flood hazard and risk, decision-making towards flood management policy development and emergency planning (Plate, 2002; Büchele *et al.,* 2006). In Europe, the maps can be prepared based on specified flood frequencies or recurrence interval such as 1 in 10 years, 1 in 25 years, 1 in 100 years, or the more extreme 1 in 1000 year return period floods (Merz *et al.,* 2007). These maps are often characterised by type of flooding, depth of flood water, velocity and extent of flood water flow within an area (de Moel *et al.,* 2009).

A major factor limiting the widespread availability of these maps lies in the lack of detailed topographic data (Hsu *et al.,* 2011). In European Union Commission flood directive, the problem is that of data standard, as datasets are needed to be available in GIS layers in order to be used both for flood hazard and flood risk mapping (Tsakiris, 2014). Global flood hazard maps are being derived from the analyses of long term flood return periods using large scale physically based models of rainfall runoff and river routing algorithms (Pappenberger *et al.,* 2012). However, such data are not readily available at large temporal scales for many places. The use of fragility function to obtain flood risk map from flood hazard map is still location specific (Pistrika &Tsakiris, 2007). A great deal of uncertainty lies in the result of mapping flood risk using only water depth, and excluding other hydraulic parameters, such as water flow velocity (Hammond *et al.,* 2015). The influence of water flow velocity to flood damage has been well debated, although it is barely studied, and seldom considered in existing flood damage models (Büchele *et al.,* 2006; Merz *et al.,* 2007; Apel *et al.,* 2009; Kreibich *et al.,* 2009).

3.5.2.4 Sustainable urban drainage system

One important approach to drainage evolving in relation to a sustainable management of urban water is the sustainable urban drainage system (SUDS). Basically, SUDS mimic natural processes to improve surface water quality and enhance the amenity and biodiversity value of the environment (Butler & Parkinson, 1997; Charlesworth *et al.,* 2003; Barbosa *et al.,* 2012). Regardless of type - permeable pavements, green roof and rainwater reuse, infiltration trenches, SUDS attenuate flooding, prevent contamination of surface water (which often happen when traditional approaches involving mainly the pipe-based storm water systems, are employed) and promote recharging of groundwater resources (Graham, 2012). In the US, UK and many other developed countries, uncertainties in flood risk arising from projected climate change scenarios, and their implications in the management of urban flooding, and other urban water-related issues have been crucial in the implementation of SUDS (Abbott & Comino-Mateos, 2003; Wheater & Evans, 2009; Jha *et al.,* 2012; Zhou, 2014).

In spite of these prospects, SUDS are largely lacking in the DPDCs. Armitage (2011) investigated this issue, using South Africa as a case study, and implicated mainly the inadequacy of skilled personnel, to plan and implement SUDS in a timely and holistic manner. Mguni *et al.* (2016) examined the potential within SUDS to address the undesirable impacts of storm water management system on the urban environment. Although the study largely promotes the adoption of SUDS for the sub-Saharan African countries, institutional constraints and poor maintenance culture are major issues that need to be addressed. These issues, in addition to lack of relevant datasets, low prioritisation of storm water management in urban agenda, and lack of funds, highlight the present specific situation in Lagos with regards to SUDS. Literature evidence shows that the sustainability of drainage systems in Lagos remains an important problem that has received little attention in urban development studies. Existing storm drainage systems dates back to 1993 following the execution of the Lagos drainage sanitation project. However, as argued by Ahianba *et al*. (2008) and Benzerra *et al.* (2012), the drainage facility was designed only to meet the needs of wastewater and storm water transportation, highlighting key limitations within the context of urban water management, which is crucial to the present research. Whilst being often overwhelmed by heavy storms, which mainly influence urban flooding events, the lifespan of these drainage systems are arguably short since there are claims that they are easily broken and blocked by debris and other human activities (Douglas *et al.,* 2008; Adeloye & Rustum, 2011; Aderogba 2012; Benzerra *et al.,* 2012; Olukanni *et al.,* 2014).

3.5.2.5 Flood risk management in the urban areas

Urban flooding has not received as much risk management attention as fluvial and coastal flooding (Douglas *et al.,* 2010). The overall aim of flood risk management in the urban areas is to build a resilient city, to minimize human and economic losses (Godschalk, 2003; Vis *et al.,* 2003; Muller 2007; UNISDR, 2007 Zevenbergen *et al.,* 2008; Tingsanchali, 2012). This implies that as more urban residents can adapt to flooding, the more chances the society has to harness its natural potential in order to achieve sustainable urban development goals (Muller, 2007). Some authors argue that irrespective of the type of flooding, similar management approaches apply (Schanze, 2006; Gouldby *et al.,* 2008; Jha *et al.,* 2012). However, the range of factors that influence urban flooding, mostly a combination of physical processes, human activities and the complex geomorphological nature of urban terrain, underpins the need for developing specific management strategies for the hazard (Thieken *et al.,* 2005; Sampson *et al.,* 2011).

Tingsanchali (2012) articulated that urban flood risk management should be a proactive measure, which requires a combined participation from the public and private agencies, as well as the wider population. Considering the centrality of urban storm water in urban flooding, the author proposed a conceptual framework for urban flood risk management, which includes integrated flood management, total water cycle management and land use planning (Chanan & Woods, 2005; Tingsanchali, 2012). The overlapping principle within this framework involves acknowledging flooding as part of the overall water cycle, to improve on urban water management, and to drive a more comprehensive urban planning (Feilberg & Mark, 2016). Within this framework, institutional structure should be widened to enhance a city-wide performance in flood risk management in which various agencies become part of the management strategy (Tingsanchali, 2012). These ideas are more beneficial in the sense that whilst they seem to foster more flood risk management investment decisions, they also can remove the gaps in urban flood risk management in the DCs, caused by limited participation of private institutions and the general public.

Besides this general framework, there are some more recent ideas towards flood risk management in urban areas. For example the "digital city concept", which is based on a combination of various hydro-informatics tools (numerical models, flood forecasting and real-time warning systems), integrated with urban planning (Price & Vojinovic, 2008). The authors aggregated these tools within a GIS and used to manage the urban storm water. On the basis of source attribution of urban flood risk, Dawson *et al.* (2008) used drainage systems' failure, human and environmental factors, to support the development of integrated urban FRM system. Gupta (2007) utilized available information relating to drainage systems, and the details of the flooding, to formulate flood risk mitigation measures in the city of Mumbai, India. A multicriteria approach was used to formulate urban flood risk management systems on the basis of a set of variables such as demography, social vulnerability, land use classes and ecology which are often available for urban areas (Kubal *et al.,* 2009; Marlow *et al.,* 2013; Scheuer *et al.,* 2013). Within the project Collaborative Research in Flood Resilience in Urban Areas (CORFU), urban flood risk management is enabled by international collaboration, and proper assessment of future scenarios of geographic and socio-economic conditions, including urban growth (Khan *et al.,* 2016). This is especially useful for formulating policies for future urban flood mitigation and adaptation measures (Correia *et al.,* 1999; Wheater & Evans, 2009; Wakode *et al.,* 2014). However, whilst such prospects have been identified in the DPDCs, present challenges seem to overwhelm the opportunities especially in utilising free and open source (FOSS) geospatial datasets to model urban growth (Teeuw *et al.,* 2013).

Sayers *et al.* (2002) and Klinke & Renn (2002) proposed a risk-based approach to urban flood risk management. This approach considers the whole system of urban flooding including environmental, demographic, anthropogenic and climate change factors. Ganoulis (2003) and more recent studies such as Yohe & Leichenko (2010), Broekx *et* *al.* (2011) and Dawson *et al.* (2011) have utilized the risk-based approach to manage urban flood risk in various cities across the world. However, Maantay & Maroko (2009) investigated the approach and underlined the degree of uncertainty in the output caused by the disaggregation of especially demographic data. A new approach to flood warning, 'a trigger rainfall forecast', and a new method for identifying locations most at risk from pluvial urban flooding was recently proposed (Falconer *et al.*, 2009). Such novel tools are expected to provide risk managers and other stake-holders with enhanced capabilities for urban flood risk management.

These urban flood risk management strategies, which were reviewed in the foregoing paragraphs have one thing in common which is the use of integrated approaches. Fratini *et al.* (2012) and Wenger (2015) among other authors opined that integrated approaches consider FRM on the basis of required urban 'level of protection', which societies influence through a participatory process. However, the majority of these techniques are capital intensive. This is of critical importance to the present research, given that the difficulty in transferability and reusability of existing methodology seems to undermine a universal FRM in urban areas especially in the DCs, taking Lagos as a case study. Moreover, some issues such as the emotional, physical and social behaviours of urban residents can be critical factors in many phases of urban flood management (Zoleta-Nantes, 2002). In a recent urban flood management study in Heywood, Greater Manchester, United Kingdom, Douglas *et al.* (2010) report that flood victims were taken by surprise, while a lack of information and perplexity regarding what to do before, during and after the flooding event prevailed. This situation can complicate the understanding of what causes vulnerability and how to carry out emergency responses, as well as build the resilience of the city populace, to achieve the main aim of urban flood risk management (Zevenbergen *et al.,* 2008).

3.5.2.6 Flood risk management in Lagos

Unlike the majority of developed countries where FRM in urban area is underpinned by a general risk management framework, urban FRM in the data poor societies appear to be heuristic, unconventional and often disjointed. For the Lagos area, few recent practices presented by Oshodi (2013), which are general measures to tackle the challenges of flooding include the following:

1. The expansion of drainage infrastructure within the city heartland.
2. The annual debris removal from principal drainage facilities within the city heartland.
3. Providing advice to the inhabitants of flood plains and wetlands to relocate.
4. The demolition of homes in the flood prone areas.
5. Proposed resettlement scheme for the residents of Ogun river catchment areas.

Oshodi (2013) claimed that these practices are being carried out, although it could be argued that they are politically influenced. One example of this is the expansion and upgrading of the primary drainage facilities mainly being carried out in Bariga, Surulere, and Gbagada. The annual clearing of primary and secondary channels by Lagos State Government through the Ministry of Environment, is carried out principally in the metropolitan areas. Evacuation and resettlement are carried out for residents who live in flood prone areas. A proposed resettlement scheme for residents of Ajegunle community near Ikorodu was undertaken between October 2011 and January 2012 (Oshodi, 2013). The move was necessitated based on the belief that the current location of the community in the Lagos urban Master Plan was originally zoned as wetland for agricultural use. The area was a major catchment for Ogun River. It could be argued that the lack of clear implementation policy for the plan with enormous housing shortfall in the city to cope with rapid population growth and urbanisation has led to the conversion of the area into residential use. Significant environmental impacts are often associated with the use of land for purposes it was not originally allotted for. Flooding can be the case when such potentially inappropriate use affects ecological equilibrium. However, a detailed investigation is needed to validate this claim especially within the context of Lagos.

Major failures with these general measures arguably arise from the issues of continuity and the scope of application. These measures are often limited to the core urban areas of the city excluding the majority of the outskirts (Oshodi, 2013). Oshodi (2013) argued that many areas within Lagos did not benefit from the expansion of drainage facilities besides the project not being completed because of transition administration. These projects also suffer as new governments often abandon uncompleted projects of their predecessors. This shows potential urban mismanagement and a degree of limitation in urban development given that there are many abandoned projects and new ones are being considered. There are occasional inconsistencies in the annual cleaning of the channels. Sometimes this operation is delayed, a situation which paves the way for debris to accumulate in the channels. Coupled with careless attention to the channels after cleaning, accumulation of debris has led to the early collapse of the channels. This causes potholes on motorways and retention surfaces for water during flooding.

The problems of where to relocate to and the availability of support for relocation are overwhelming. Given the vast distribution of flood prone areas and the limited financial resources to facilitate resettlement, the choice of slum locations to resettle is complicated. Communities which cannot be resettled often face the risk of having individual homes demolished. Examples of this include the Agege and Ijeshatedo demolitions which happened in August 2011 and that of Ijora-Badia which occurred in 2010, 2012 and 2013. The demolishing of homes is understandably a distressing measure to those affected. It could be argued that a particularly controversial aspect could be the failure and neglect of the state government to provide any form of alternative housing arrangements to those whose houses have been demolished. There have been a few exceptional cases for example the Ijora-Badia World Bank assisted drainage channels project, which necessitated the demolition and burning of homes. Following a community led protest the affected families were awarded relocation assistance costs. On the basis of these potential government inadequacies, Ahonshi (2002), Kamunyori (2007) and Basinsksi (2009) cited in Lawanson (2015), argued that the achievement of government's urban sustainability goals (which includes the general flood management measures) in Lagos are often without regards to the needs of the poor residents of the area. At the same time, demolition and eviction frequently lead to forced social disconnection amongst families, compensation and legal process in favour of those affected can take a significant amount of time to complete. This is in part an aspect of social vulnerability which needs to be investigated within the context Lagos urban flooding. Under the circumstances of eviction and resettlement uncertainties, most people occupying the flood prone areas often seem to ignore government's flood risk mitigation policies and flood warnings. This leads to the persistence of large scale impacts of urban flooding in Lagos. However, despite numerous tensions, this issue has only received limited attention in the literature and in governance.

3.5.2.7 Institutional roles

One critical aspect of flood response is the institutional efforts which have been undertaken by local authorities and stakeholders. Odunuga (2008) recognized several flood preventive and curative initiatives ranging from community self-assistance actions to World Bank assisted programmes. Recently, key initiatives which include the Drain Dock and The Emergency Flood Abatement Gang (EFAG) were launched by the government of Lagos state to improve current efforts towards addressing the challenges of flooding. The ministries of Environment, Works and Health as well as the Lagos Metropolitan Development and Governance Project (LMDGP), have a number of initiatives aimed at controlling flood hazard in the area and these include shoreline protection, low carbon emissions, the school advocacy programme and the climate change club. Lagos is also the first region in Nigeria to carry out a detailed topographic mapping of the area with airborne LiDAR (Light Detection and Ranging) data acquisition and GIS based analysis aimed at addressing the challenges of flooding. In addition to these efforts, the Nigerian government and international community have been active with measures to address the challenges of flooding at various locations within the country including the Lagos area (Olorunfemi, 2011; NIHSA, 2013). Besides engineering works such as dams, bridges and sustainable urban drainage systems, there has also been financial assistance to victims of flooding and these appear to be a common practice. These are undertaken by the National Emergency Management Agency (NEMA), Nigeria Hydrological Services Agency (NIHSA), Nigerian Meteorological Agency (NIMET), the National Environmental Standards and Regulations Enforcement Agency (NESREA) which by 2009 Nigerian Acts supersedes the Federal Environmental Protection Agency (FEPA). It is not intended to discuss the structure, specific roles and the unique position of these agencies with regards to flood management in Lagos. These aspects have been comprehensively discussed by Obeta (2014). However, it is important to mention that the activities of these institutions with regards to disaster management are generally coordinated by NEMA.

Although detailed data are not available, the historical perspective of disaster management in Nigeria provides clarity to the temporal evolution of flood awareness in Lagos. Primarily, the institutional framework in Nigeria goes back more than four decades. The federal government of Nigeria has since the First, Second and Third National Development Plans of 1962-68, 1970-74 and 1975-80 respectively initiated plans for management of all disasters including flooding. This was through the federal and state ministries of works. On the basis of flooding and associated hazards, the primary aim of these initiatives was to create awareness among the citizenry and to develop sound response strategies. This development has evolved to the present time in what is now known as institutional approaches to managing disaster. Lately, the institutional framework has incorporated operations such as flood warning through the NISHA, improving general flood awareness through the National Orientation Agency (NOA) and integration of local, state and federal disaster emergency management agencies. Efforts are being made to facilitate evacuation and provide flood victims with urgent humanitarian needs.

Despite the recent initiatives, these developments have been criticised as weak while the roles of the institutions are not clearly defined (Adeaga *et al.,* 2005; Oshodi, 2013; Soneye, 2014; Nkwunonwo *et al.,* 2014; Adelekan, 2015). Critically, current measures undertaken by these agencies appear to control flood rather than mitigate its impacts on ecological systems, and as a result there is still an increasing number of people being affected by flooding yearly. Environmental sustainability and policy, social responses, physical intervention and environmental management are also critical issues requiring attention (Aderogba *et al.,* 2012; Olajuyigbe *et al.,* 2012; Aderogba, 2012b; Adeaga, 2008; Ilesanmi, 2010). Whilst it is unreasonable to claim that the weakness of these flood mitigation measures probably leads to more frequent flooding in the area, in can be argued that that such measures have improved the experience of the general population with regards to flooding.

3.5.2.8 Recent research efforts

From the literature, researchers have suggested several options in relation to possible flood hazard mitigation and adaption responses in Lagos. Adedeji *et al.* (2012) highlighted the importance of building the capacity for flood preparedness through spatial planning and land management. Ogunsote *et al.* (2011) suggested combating environmental degradation through sustainable landscaping. The need for sustainable management of solid waste which was emphasized in section 2.5.1.3 was recommended by Folorunsho & Awosika (2001). Komolafe *et al.* (2014) argued for the adoption of proactive measures to risk management and adaptation whilst constant geophysical and hydrological evaluation was emphasised by Oyedele *et al.* (2009). Adelekan (2013) reiterated the UNISDR recommendation which calls for the participation private sectors in risk management through investment decision in building and construction. Other factors besides flood prevention are also important to reduce the potential impacts of flood events. The humanitarian relief supply chain for victims of flooding in the Lagos area was investigated by Soneye (2014). This study identified the need for more empirical investigation into such crucial components of flood risk management in Lagos. In relation to the planning framework, sustainable housing development and functionality of planning laws and regulations as well as the role of governance in flood management in Lagos area and indeed in Nigeria have been examined by a number of authors including Aluko (2011) and Oshodi (2013).

Other research focuses on integral components of flood risk such as probability of flooding, exposure and vulnerability to flooding. Despite these studies, insufficient knowledge of the vulnerabilities to flooding of local communities, urban residents and the general public constrains effective flood risk management in Lagos. More scientific approaches such as flood modelling and flood vulnerability assessment which drive recent approaches to flood risk management in more developed countries are generally lacking. Little action has been undertaken to raise public awareness of flood risk or to address gendered vulnerability, as highlighted by Odunuga *et al.* (2012), Ajibade *et al.* (2013) and Adelekan (2010). Although as an unprecedented measure, Lagos state government has made significant efforts at providing high resolution airborne LiDAR data and topographic maps which promote research towards flood risk in the area. However, since many of these datasets are produced and sold commercially, the limited access of researchers to them arguably undermines their usefulness.

A possible solution to such a limited access to LiDAR data is to apply global datasets such as ASTERGDEM (Advanced Space-borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) and STRM (Shuttle Radar Topographic Mission). However, the resolution of spatial data is a crucial factor in flood modelling and flood risk assessment. Elmoustafa *et al.* (2015) examined the effects of elevation data resolution on Lagos storm drainage schemes. The study compared a 15m horizontal resolution DEM produced from Russian Stereo Satellite images (RSS) with the Lagos LiDAR DEM resampled to 5m horizontal resolution, using a drainage stream watershed modeling tool. The study revealed that RSS DEM produced misleading and false drainage direction unlike the higher resolution Lagos LiDAR DEM. This result underscore the importance of LiDAR DEM for hydrological purposes such as flood modelling in Lagos. It also shows that the geomorphology of urban features significantly influence hydrodynamics so that global datasets often do not provide realistic results when used to model hydrological features such as flood hazard in urban areas (van de Sande *et al.*, 2012). Flood modelling research is still looking into possible ways of simulating accurate flood variables on the basis of low scale global datasets, and this is the issue for the present research.

3.5.3 Flood risk assessment in Lagos

There has been a great deal of research about the assessment of flood risk in Lagos in general. However it can be argued that these studies did not adequately discuss issues relating to the three key components being applied in flood risk estimation. Studies by Carmo (2000), Huq & Aslam (2003), Samuels *et al.* (2006), Lumbroso *et al.* (2008) and Di Baldassarre *et al. (*2010) indicate that several other data poor communities such as Bangladesh, Mozambique and India seem often overwhelmed by the task of urban flood risk management, due to the lack of standard flood risk assessment techniques. The apparent tendency to address flood risk management by controlling flooding rather than mitigate its impacts prevails, and this undermines a realistic flood risk assessment in those areas including Lagos, Nigeria (Nkwunonwo *et al.,* 2016). Flood hazard research has shown that flood risk assessment, an important aspect of flood risk management, is being undertaken at various administrative scales in United Kingdom and elsewhere in Europe, the United States and Australia (Samuels *et al.,* 2006; Merz *et al.,* 2007; Kundzewicz *et al.,* 2010; Jongman *et al.,* 2012). The review of flood risk assessment presented in Nkwunonwo *et al.* (2016) shows that such a procedure is 'unidentifiable' within the context of Lagos. Although only few publications presented explicit critical discussions about the assessment of flood risk in Lagos, none of them explicitly assessed the level of exposure to flooding of social and environmental systems. Studies relating to the vulnerabilities of social and environmental systems to urban flooding are largely limited in scope (Ajibade *et al.,* 2013). Flood hazard estimation is collapsed into the general framework of climate change analyses (see for example: Aderogba, 2012a).

3.5.3.1 Hazard estimation

For the Lagos area, no study known to the author considered flood hazard estimation although Odjugo (2006) and Adelekan (2010) investigated rainfall pattern over spatial and temporal scales. Odjugo (2006) investigated changing rainfall pattern in Lagos over three decades. Adelekan (2010) on the bases of qualitative survey and secondary data analyses attributed increasing flood risks in Lagos Island to mainly changes in the frequency and intensity of rainstorms between 1971 and 2005. Other studies that estimate flood hazard were embodied within the general framework of climate change research (see for example, Aderogba 2012a). The lack of an explicit study on flood hazard estimation for the whole city makes it difficult to appreciate how the probability of flood hazard occurrence is being determined in Lagos. Moreover, a clear understanding of the evolutionary trend of the hazard is denied. A consensus idea is that the hazard has been increasing since the last five decades (Odunuga 2008, Adelekan 2015). It is expected that future research should be directed towards this crucial aspect of flood risk assessment.

3.5.3.2 Exposure analysis

Existing studies on FRA for Lagos were not clear on the subject of exposure to flooding of social and environmental systems. However, this aspect of flood risk assessment can be derived from studies that consider land use (LU) and land cover (LC) change analyses, population expansion and urbanisation (see table 3-6). These studies indicate that the level of human and economic resources exposed to urban flooding in Lagos is undoubtedly high. Some of the major conclusions emerging from these studies which indicate a rapid urban growth with a corresponding increasing pressure on arable lands, and depletion of wetlands, mangroves and swamps are issues of research importance within the context of vulnerability and future adaptation to urban flooding in Lagos (Akpomrere & Nyorere, 2012; Obiefuna *et al.,* 2013). Such migration of people into Lagos city from other rural communities and states in Nigeria which escalates residential needs and challenges (highlighted in section 3.3) presents a structural adjustment and development issue that can be addressed within the context of urban FRM in Lagos.

3.5.3.3 Vulnerability assessment

From the literature, it is clear that vulnerability to flooding is being assessed under varying contexts and objectives. There are numerous studies that have considered the vulnerabilities of social and environmental systems to flooding within the Lagos context (for example, Action aid, 2006; Douglas *et al.,* 2008; Adelekan, 2010; Olajuyigbe *et al.,* 2012; Ajibade *et al.,* 2013; 2014; Nkwunonwo *et al.,* 2015b; Nsorfon, 2015; Olokesusi *et al.,* 2015). Action aid (2006) investigated vulnerability but tied Lagos with other four African cities. The study was carried out on the basis of key management criteria including local people's perceptions of the causes of flooding, adaptation and the community's social coping capacity. Some of the limitations in the study were addressed by Douglas *et al.* (2008), which considered the vulnerability on the bases of climate change and adaptation strategies for the urban poor in Africa.

Table 3-6: Some studies that indicated exposure to urban flooding in Lagos area of Nigeria

S/No.	Author(s)	Study	Context	Major findings
1.	Nwafor (1986)	Physical environment, decision-making and land use development in Metropolitan Lagos	Urban growth	Rapid changes in land use classes were detected. Major upward trend in urban growth since 1960. Urban renewal and highway development radiating from the inner-city to the hinterland were the major catalysts.
2.	Abiodun (1997)	The challenges of growth and development in metropolitan Lagos.	Urban growth	Extensive and persistent urban growth. Key growth factors are the city's economic vitality and pivotal position in Nigeria's economy. Major growth challenges are survival of urban residents and city's sustainable development.
3.	Barredo & Demicheli (2003)	Urban sustainability in developing countries' megacities: modelling and predicting future urban growth in Lagos.	Urban growth	By 2020, Lagos will experience astronomical spatial growth as a direct consequence of population expansion. Up to 27 million people will inhabit Lagos by 2020.
4.	Adepoju *et al.* (2006)	Land use/land cover change detection in metropolitan Lagos (Nigeria):	LU & LC change detection	Lagos urban growth is phenomenal. Between 1984 and 2002, about 35% increase in n urban areas was recorded
5.	Sunday & Ajewole (2006)	Spatial determinants of urban land use change in Lagos, Nigeria.	LU & LC change detection	Changing pattern of land use (LU) land cover (LC) in Lagos is characterised by significant socio-economic and environmental implications. Flooding and other implications are expected to worsen in the future given this present trend.
6.	Braimoh & Onishi (2007)	Implications of the changing pattern of land cover of the Lagos coastal area of Nigeria.	LU & LC change detection	Remote Sensing was used to investigate land use changes, while binary logistic regression was used to model the probability of observing urban development as a function of spatially explicit independent variables
7.	Odunuga (2008)	Urban land use change and the flooding patterns in Ashimowu Watershed, Lagos, Nigeria	LU scenario and flooding (Alimosho)	A progressive increase in built- up area at the rate of 28 ha/yr. between 1965 and 2003.
8.	Olaleye *et al.* (2009)	Land use change detection and analysis using remotely sensed data in Lekki Peninsula area of Lagos, Nigeria.	LU & LC change detection	Between 1964 and 2003 built up areas grew from 40.93 *ha* to 7271.19 *ha.* Evolution in new classes of land use was observed. Which include industrial, commercial and recreational land use class
9.	Nwokoro & Dekolo (2012)	Land use change and environmental sustainability: the case of Lagos Metropolis.	LU change and environmental sustainability	Between 1990 and 2006, built-up areas increased by approximately 17%.There was an obvious loss of forest resources and agricultural land to urban development.
10.	Akpomrere & Nyorere (2012)	Land use patterns and economic development of Ikeja in Lagos State, Nigeria: the GIS approach.	LU patterns and economic development	From 1962 to 1994, built up area in Lagos rose from 6.55% to 63.90% and from 63.90% to 67.99% between 1994 and 2004. Decreases in vegetation cover and undeveloped areas were recorded.
11.	Adebayo (2009)	Impact of urban land use changes on property values in Metropolitan Lagos.	Urban land use changes and property	Significant changes in land use pattern from residential to commercial. Significant implication in property values in the area. These created social and environmental problems such as traffic congestion, and noise pollution. Need for adequate land use planning identified.
12.	Nkwunonwo (2013)	Land use/Land cover mapping of the Lagos Metropolis of Nigeria using 2012 SLC-off Landsat ETM+ Satellite Images	Land use and land cover mapping	By 2012, four major LU/LC themes were identified in Lagos, and they include; water body, vegetation, residential, and industrial areas. Urban areas, that is, residential and industrial areas, account for more than 54% of the whole Lagos metropolis.
13.	Obiefuna *et al.* (2013)	Spatial changes in the wetlands of Lagos/Lekki Lagoons of Lagos, Nigeria.	Wetlands changes	Mangrove wetlands decreased from 88.51km^2 to 19.95km^2 between 1984 and 2006 at -3.12km^2 /yr. Swamps decreased from 344.75km^2 to 165.37km^2 between 1984 and 2006.at - 8.15km^2 /yr. Built-up areas increased from 48.97 km^2 to 282.78 km^2 at 10.61 km^2/yr. Water body decreased from 685.58 km^2 to 654.98 km^2 at −0.16 km2/yr. Bare land increased from 24.32 km^2 to 72.73 km^2 at 2.2 km^2/yr. Vegetation decreased marginally from 1369.15 km^2 to 1361.08 km^2 at −0.37 km^2/yr. Most of the increase in built-up area occurred in the Eti-osa Local Government Area (LGA) and then in the Kosofe LGA. The key implication is flood risk on affected areas.

Studies by Adelekan (2010) and Olajuyigbe *et al.* (2012) were localized to small urban communities and individual LGAs. The studies lack the element of “wider application” required for social and political links necessary to take advantage of resources that would accelerate recovery for populations socially vulnerable to flooding. Adelekan (2010) investigated the vulnerability of coastal communities in Lagos and responses to changing climatic conditions. The patterns of flood vulnerability and resilience amongst women were investigated in Ajibade *et al.* (2013). Throughout the study, the question: "Is vulnerability gendered?" was addressed. Whereas it can be recognized that gender is a key consideration in matters relating to social vulnerability, dealing with it in isolation lacks the substance to reveal the pattern of vulnerability in an area. On the basis of political ecology, Ajibade *et al.* (2014) argued that the two crucial factors responsible for vulnerabilities of social systems in Lagos are limited access to housing and weak housing rights. The sources of social vulnerability to floods in informal settlements of Lagos was investigated in Nsorfon (2015) while Nkwunonwo *et al.* (2015b) highlighted the relevance of assessing such vulnerability for the whole of Lagos. Olokesusi *et al.* (2015) investigated the influence of awareness of and responses to flood warnings on physical vulnerabilities of the affected communities in Lagos.

Although these studies are major contributions to knowledge which provide some evidence to suggest that vulnerability is an important aspect of flood risk in Lagos, significant gaps still exist in the literature with regards to accurate assessment of vulnerability in the area. The lingering susceptibilities and the lack of coping capacity to flood hazard in the area suggest the need to carry out more vulnerability research, especially towards social vulnerabilities. The problem of data limitation was raised but not discussed. The means to obtain and utilize freely available data to assess vulnerability indices remains both a promising and a challenging issue. The data available must be good enough to give a measure of reliability in flood risks mitigation. Attempting to address this situation, Ajibade *et al.,* (2013) utilized demographic data, in addition to primary survey to adapt proven methodologies to local situations.

Most of these studies were based on a limited random sample of data which is insufficient to make accurate generalisation. Critical issues of vulnerability analyses such as choice and measurement of vulnerability indices were not addressed. This contradicts a widely accepted philosophy that accurate assessment of vulnerability is related to these critical issues (Adger, 2006). Classical analyses of vulnerability should be able to consider every available factor that undermines the chances of resistance available to social and environmental systems. With regards to achieving a more substantial goal of mitigating the risk of urban flooding, a specific objective of this research is to critically evaluate vulnerability and to construct an index of social vulnerability. This index can inform the development of more realistic FRM policies, and thus will address the issue of increasing susceptibility as well contribute towards building a society more resilient against urban flooding.

3.5.3.4 Flood modelling in Lagos

Flood modelling is used to promote flood risk reduction in the US, the Netherlands and United Kingdom, but in Nigeria it is arguably too often ignored. This has continued to raise the question of how actionable flood risk assessment can be achieved. Flood modelling has been largely ignored in Lagos for reasons such as data requirement and availability, lack of specialist technology, funding and the applied skills required. Academic research seems to be the most likely option in terms of the responsibility to develop flood models. Besides

The present research has been unable to refer to any other specific contributions of academic research towards flood modelling in Lagos aside Mosuro (2012) which used LiDAR DEM to model indicators of property exposure to flooding in Lagos. Although the study was all-encompassing, and utilised high resolution datasets, it did not sufficiently address the flood risk assessment challenges in Lagos and other data poor urban communities. The lack of bespoke or generalised flood models and its poor application in the flood risk management in the area seem to suggest that flood modelling procedures considered by academic curricula in Lagos are mainly theoretically and on the periphery. As NIHSA (2013) pointed out, it appears such an intensive research should be promoted and funded by the government and other interested bodies. To date, the author is not aware of any such development. Moreover, the uncertainties associated with flood modelling can discourage investment of resources into it. To the best of the author's knowledge, no public agency in Lagos undertakes the procedure as a specific role.

It can be argued that relatively few studies have highlighted the relevance of flood modelling and its implications with the paucity of relevant datasets (Nkwunonwo *et al.*, 2014, van de Sande *et al.,* 2012), although Adeaga (2008) implemented a flood hazard mapping and risk management in north eastern part of Lagos. Although flood modelling was mentioned in these studies, solutions to the problems raised remain largely unanswered. The present research considers the development of a new flood model and construction of indices of social vulnerability as potential solutions to the challenges of flood risk assessment in Lagos and other data poor urban areas. The new flood model which combines the capabilities of SIFDS and CA to overcome the limitations in existing flood modelling methodologies can be used to simulate pluvial flooding on the basis of available LiDAR DEM and 'daily amount' rainfall data. Combined with indices generated from an assessment of vulnerability, this model can provided the basis for flood risk mapping and the development of policy for effective management of Lagos urban flooding.

3.6 Summary

The Lagos metropolis is the hotspot of major economic activities in Nigeria, but widespread urban flooding is a major issue which undermines the relevance of the city. Flooding in Lagos is arguably an annual event, which affects considerable number of human population and development assets. Whilst climate change with severe pluvial events, poor urban planning and anthropogenic activities are the main drivers of these floods, rapid population growth and urbanisation escalate the level of human and economic impacts. Present efforts to tackle flooding are limited, and are lacking in the fundamental elements of flood risk assessment. Critically, such efforts appear to be influenced by the economic, political and cultural philosophy of the area, and thus appear to control flooding rather than mitigate its impacts on human populations and urban infrastructure.

To achieve the goal of flood risk management in the Lagos area, current efforts must be underpinned by provision of accurate and quality flood data and other relevant datasets. These datasets are often unavailable, and the use of existing flood models in Lagos is being constrained by a number of research issues including lack of funds and technical limitation. Therefore, the development of a new and bespoke urban flood modelling tool is crucial, and this is a major objective of the present research. This tool will be used to reconstruct flood hazard scenarios, which will combine with flood damage data and used in depth damage functions, to provide an assessment of flood risk to be used for actionable flood risk management policies.

Intuitively, management of urban flood risk also demonstrates that the need for vulnerability analysis within the framework of flood risk assessment is of critical importance. This will arguably require a clearer understanding of the susceptibilities of human populations and their lack of capacity to cope with urban flooding. To this end, the next chapter considers social vulnerability to urban flooding and how to construct its possible indices for Lagos using freely available datasets.

4 Critical Evaluation of Vulnerability to Urban Flooding, and Construction of Social Vulnerability Indices (SocVI) for the Lagos Area

Flood risk in the present research is considered as a function of hazard probability and its consequences, drawn from Crichton (1999) risk model. Within this framework knowledge of vulnerability, social vulnerability, in the case of the present research is of crucial importance as it can help to explain why mostly human populations are unable to cope with urban flooding in Lagos. Therefore, this chapter presents a review of the general concept of vulnerability, aimed to galvanize discussions towards improving on flood risk management in Lagos. The chapter also presents discussions on social vulnerability to urban flooding in Lagos, highlighting the relevance of assessment of such vulnerability context to flood risk management (FRM) in the area. Within this context and in relation to the idea of building a resilient city, indices of social vulnerability (SocVI) for the sixteen local Government Areas (LGAs) in the Lagos area are constructed, to identify areas, on the basis of social factors, within the conurbation which are highly vulnerable to urban flooding in Lagos.

4.1 Vulnerability and its relevance to the present research

Considering vulnerability in relation to urban flood risk, there are two key issues, which reflect the significance of the present research. Firstly, the varied understanding of risk, the choice of vulnerability indices and how to measure them, are debatable issues within vulnerability research (Füssel, 2007; Hufschmidt, 2011; Paul, 2014). Secondly, although vulnerability assessment is often critical to various issues arising from global initiatives on disaster risk reduction, little effort has been made towards the actualisation of such initiatives across-the-board, to reflect significant progresses in flood risk management (Schipper & Pelling, 2006).

The 'safer world' idea of Yokohama strategy, 1994, 'resilience of nations and communities' of Hyogo Framework for Action (Godschalk, 2003; Klein *et al.,* 2003; UNISDR, 2007; Manyena, 2006; Cutter *et al.,* 2008; Matsuoka & Shaw, 2011; Pelling, 2012) and the most recent Sendai Framework for Disaster Risk Reduction (Kelman, 2015), which recommends private and public sector investment commitment into disaster mitigation, are yet to be fully actualized within the context of urban flood risk management. Significant progress has been reported in localities including Philippines, Indonesia, Vietnam and majority of the developed countries (Matsuoka & Shaw, 2012; Djalante *et al.,* 2012; Trujillo & Baas, 2014). However, in the majority of the cities within DCs, such as Lagos, Nigeria, where flood risk management policies are yet to be fully integrated into development plans and programmes, these initiatives are still far from reality (Pelling & Wisner, 2012; van Niekerk & Coetzee, 2012).

Various concepts (including resilience, adaptation and adaptive capacity) are being used to conceptualise and complement vulnerability (example Smit & Wandel, 2006). However, such concepts in addition to critical issues such as: cultural theory, environmental justice and resettlement, appear not to have been fully understood within the context of vulnerability assessment, climate change analysis, and flood risk management in the Lagos area in particular and in the DCs in general (Turner *et al.,* 2003; Clark & Dickson, 2003; Cutter & Emrich, 2006; Maantay & Maroko, 2009; Cutter, 2012; Lopez-Carr & Marter-Kenyon, 2015). Despite the abundant human and economic resources in the DCs (some of which are mentioned in chapter 3) in addition to the present global opportunities in flood risk assessment methodologies, flood risk management practice remains underdeveloped. Situations like this are often attributed to weaknesses in governance although in the present context, uncertainty and unpredictability of flood hazard which subject the DCs to a high level of threat are generally underlined (Burrel *et al.,* 2007; Baan & Klijn, 2004; Merz *et al.,* 2010; Olorunfemi, 2011). As well as finding solutions to the lack of flood data and other relevant data, research is needed in the direction of corresponding flood risk management with the vast opportunities, resources and potentials available in the DCs. This drives the present research in relation to vulnerability analysis, in which indices of social vulnerability have been constructed for the Lagos area on the basis of a low-cost method, which uses easily accessible demographic and topographic datasets.

4.1.1 The general concept of vulnerability

Using Crichton's (1999) risk framework, vulnerability forms a major component of risk assessment, and which becomes more crucial given the importance of knowledge regarding the propensity or predisposition of social and environmental systems to be adversely affected by hazards (Adger, 2006). The concept has been extensively discussed within regional and global environmental change, climate change adaptation, sustainability science, human ecology as well as hazard and risk research (Turner *et al.,* 2003; Birkmann 2007; Füssel, 2007; Kok *et al.,* 2016). The multidisciplinary disposition of vulnerability research and the need to address issues within well-defined social, ecological and institutional framework drive diversities in the interpretations and applications of vulnerability (refer to: Svensson, 2000; Adger, 2006; Cannon & Müller-Mahn, 2010; Hufschmidt, 2011; Blaikie *et al.,* 2014). This is important to the present research which integrates various vulnerability views to explain the differences in the degree, at various spatial scales, to which systems, often referred to as 'elements at risk' (people, assets, critical infrastructure and economic activities), are likely to be affected by urban flooding in Lagos.

From a seminal work on the subject of risk, Varnes (1984) identified vulnerability as one of the three components essential to risk analysis and cartography. In the author's view, vulnerability is the degree of loss that an 'element at risk' of any hazard is expected to suffer. Chambers & Conway (1992) and Bohle *et al.* (1994) in defining vulnerability identified two key components: exposure and coping capacity. From the human ecological point of view, which mostly applies to the present research and in relation to Lagos urban flooding, vulnerability refers to the degree to which an individual, a property, or community is likely to be predisposed to harm or damage (White *et al.,* 2001). Within climate change research, vulnerability is defined in terms of exposure, sensitivity and adaptive capacity (McCarthy *et al.,* 2001; Turner *et al.,* 2003; Adger 2006). A more critical understanding of vulnerability especially in damage assessment suggests the potential for loss which varies with time and space (Cutter *et al.,* 2008). Within the United Nations framework, vulnerability is being acknowledged as the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of social, ecological and economic systems to the impact of hazards (UNISDR, 2004). This framework underlines the importance of addressing the poor knowledge of vulnerability concept in the Lagos area, given the vast human population, a myriad of economic activities and the topography, which is mainly consisted of water bodies.

These interpretations and shades of meaning underscore the significance of a study in relation to assessment and modelling of vulnerability in risk conceptualisation and management. Assessment of vulnerability is generally a procedure to identify and rank vulnerabilities across a given group (Wisner *et al.,* 2004; Adger 2006, Fedeski & Gwilliam, 2007; Patnaik & Narayanan, 2009; Pataki *et al.,* 2012). It promotes a broader perspective of a potential hazards and assists to capture the range of characteristics that interact directly with social and environmental systems to shape their susceptibilities to hazardous events (Eakin *et al.,* 2010; Jeffers, 2013). The final document of the World Conference on Disaster Reduction: the Hyogo Framework for Action, 2005-2015, shows that such a procedure is fundamental to investigating the impacts of disasters on social, economic and environmental conditions (UNISDR, 2007). In view of Lagos urban flooding, vulnerability assessment will uncover the fundamental drivers of large scale impacts of flooding among human populations and development assets (Tapsell *et al.,* 2010; Ludy & Kondolf, 2012).

Much theoretical perspectives that exist in the vulnerability literature can be a source of confusion and uncertainty in the outcome of vulnerability modelling at a local scale. In a recent comparative study aimed to galvanize interest for more sensitive discussion on vulnerability, Hufschmidt (2011) used six vulnerability models to show the similarities and dissimilarities that exist between various contextual frameworks of vulnerability. The study argued that despite promoting a better understanding of vulnerability especially within the context of social systems, diversity seems to cause obvious confusions. The Tyndall Centre for climate change research promotes applications in a wide range of contexts, systems and hazards through a 'tentative' concept of vulnerability, which draws on several existing vulnerability perspectives (Brooks, 2003). This paper only attempts to diffuse the confusion in the various concepts of vulnerability that exist in the literature. This issue of a tentative vulnerability can be useful in data poor situations such as which relates to the present research. With respect to urban flooding, a major issue which should inform such a tentative vulnerability is the specificity of an urban area based on available data. In view of this, the present research considers social vulnerability concept and argues that using simple but standardised methods to conceptualise and analyse such vulnerability within Lagos context, leads to the development of a more effective FRM policy for the area (Changnon, 2005; Tapsell *et al.,* 2010).

Emerging issues from various contextual studies on vulnerability suggest that the concepts of exposure, sensitivity, resilience, coping capacity, adaptation and adaptive capacity are fundamental to a proper interpretation of vulnerability and adoption of a suitable framework for a new case study (Adger, 2006; Hinkel, 2011). The figure 4-1 below represents Birkmann (2013) representation of these components within the scales and complexities of vulnerability concept. It is argued that understanding these concepts and representing them by means of available data within the context of vulnerability analyses remain a significant source of gaps in vulnerability research (Brooks, 2003; Aven, 2011). For a place such as Lagos where the apparent multidimensionality of vulnerability relating to the spatial and temporal dimensions of risk is a major limiting factor, this is more problematic (Turvey, 2007). Moreover, disaster management in such places often gives more attention to recovery and reconstruction than impact mitigation by building the coping capacities of elements at risk (Mirza, 2003).

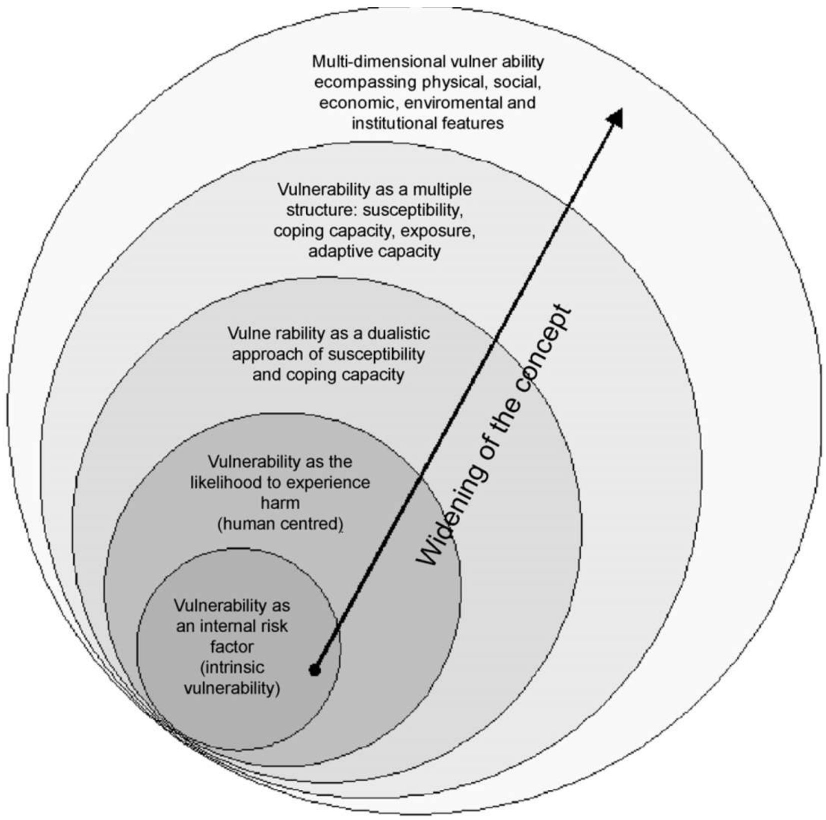


Figure 4-1: Representation of the components of vulnerability within scales and complexities of vulnerability concept.
Source: Birkmann (2013).

The specific objective of the present critique is not to contest the theoretical perspectives and extensive ontologies that exist in a large body of literature relating to these all-important concepts. However, fundamental and widely accepted notions are adopted and discussed within the contexts of vulnerability to urban flooding and FRM in Lagos. This will make it easier to understand and model vulnerability to urban flooding within Lagos context, given that significant advancements in problem-solving strategies are related to the development of location-specific and disciplinespecific science (Perrings, 2007). Although this research is first attempt to construct a vulnerability model for Lagos, one of the raison d'êtres is to investigate the applicability and limitations of local demographic data and its use in social vulnerability modelling. However, recommendations would be made of the type of data that would be needed for future vulnerability modelling based on the theoretical framework presented within this section.

4.1.2 Exposure and sensitivity

Among the emerging issues from vulnerability research, exposure and sensitivity are critical in the context of urban flooding, due to the human and economic implications of urbanisation. The concept of exposure gives an impression of the precondition for potential damage, perceived in terms of spatial and temporal distribution of elements at risk in relation to a danger zone (Cutter *et al.,* 2000; Hollenstein, 2005; Tate & Cutter, 2010; Li *et al.,* 2010). The sensitivity of the system is a measure of the degree to which it can be altered by perturbations (Adger, 2006; Gallopín, 2006). Exposure and sensitivity are important components in the definition of risk and vulnerabilities within natural hazard (Douglas, 2007; Smith, 2013). It is not enough to conclude that risk is real simply because some elements are being exposed to the source of a hazard. This is because an element can be exposed to a hazard, yet remains insensitive or unaltered by the hazard. This argument is supported by the idea of 'human adjustment', suggesting various behavioural patterns exhibited by people, as a strategy to improve their ability to cope with hazards (Hufschmidt, 2011).

In chapter 3, it was argued that Lagos urban flooding, to a large extent, is being influenced by extensive human and development activities, both which increase the level of exposure and sensitivity of social and economic elements. Various studies have examined human adaptation to urban flooding in Lagos and most cities in the DCs (Douglas *et al.,* 2008; Adelekan 2010; Ajibade *et al.,* 2013). However, knowledge regarding how exposure and sensitivity interact to produce the actual flood risk which is important for improvement in FRM in the urban areas, considering the concept of vulnerability, is limited (Nkwunonwo *et al.,* 2016).

4.1.3 Adaptation, adaptive capacity and resilience

Throughout vulnerability and disaster risk research, the concepts of adaptation, adaptive capacity and resilience suggest a state in which the vulnerabilities of elements at risk are relatively minimal (Paton *et al.,* 2000; Smit & Pilifosova, 2003; Gallopín, 2006; Zakour & Gillespie, 2013). Key findings from the literature suggest that the main objective of these concepts within vulnerability research is to explain why people are vulnerable and the reasons these vulnerabilities vary from one person to another. However, these concepts still suffer from contextual diversity despite extensive research. According to the study by Smit & Wandel (2006) which on the basis of global ecological change perspective argued that adaptation is a dynamic process in which a system is enabled to adjust to any kind of condition. Such ability to adjust implies that a system has adaptive capacity which reflects its robustness and resilience (Maguire & Hagan, 2007). In fact, resilience according to Holling (1973, pg. 14) is a '*measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables'*.

Holling's definition only provides a basic framework to conceptualise vulnerability and construct plausible metrics for analyses. More important discussions relating to resilience and the other complementary concepts are contained in Grothmann & Patt (2005), Smit & Wandel (2006), Pike e*t al.* (2010), Hufschmidt (2011) and Engle (2011). However, newer ideas and critical issues emerging from resilience research form the ethos of flood risk management strategies and policies across national, regional and global scales, for examples: the UNISDR HFA and the EU flood directive (UNISDR, 2007; Schmidt *et al.,* 2011; Surminski *et al.,* 2014). For the purpose of the present research, these vulnerability components and critical issues emerging from the literature are used to frame vulnerability in the context of Lagos urban flooding, to identify research direction and to foster dialogue towards improving FRM in the area.

From the behavioural context of vulnerability, the notion of *'false human adaptation'* can lead to increased threats of natural hazards (Hufschmidt, 2011, pg.624). Various studies relating to climate change and natural hazard in Lagos underscore the lack of adaptation or presence of 'false human adaptation' measures (Douglas *et al.,* 2008; Adelekan, 2010; Adeoti *et al.,* 2010; , 2011; Ajibade *et al.,* 2013; Ajibade & McBean, 2014). Komolafe *et al.* (2014) claimed that Nigeria as a whole has adopted reactive measures to adaptation and resilience, and these have not been helpful within the context of reducing vulnerabilities and risk on people and the communities. Oladipo (2010) identified policies and strategies within Nigerian political framework, although the question of how the citizens will respond to climate change and its effects remains largely unanswered. In a study to appraise the adaptation strategies in three selected cities, Dhaka, Lagos and Hamburg, Breitmeier *et al.* (2009) identified two significant gaps in knowledge with regards to resilience and adaptation strategies in Lagos. Firstly, the lack of a warning system and poor awareness of climate-related events including flooding prevail. Secondly, current urban governance does not include adaptation measures, while existing livelihood support systems, such as quality drinking water, are weak.

These gaps highlight the importance of considering vulnerability analysis within the present research. Through the analysis of vulnerability, the present research can contribute knowledge towards addressing the susceptibilities and lack of coping capacities of people and assets to urban flooding in Lagos. Although such knowledge largely improves the general awareness of urban flood risk, it will strengthen the method of communication of flood warnings, as well as people's responses to them. It will also make room for city planners to adopt a more pre-emptive approach to developing urban flooding adaptation measures, as well as strengthen existing livelihood support systems.

4.2 Social vulnerability

Such conceptual diversity in vulnerability studies arguably results in the myriad of methodologies that exist in the current literature relating to the assessment of vulnerabilities (see for example; Cutter *et al.,* 2003; Birkmann 2006; Ippolito *et al.,* 2010; Jeffers 2013). Due to uncertainties caused mainly by the uniqueness of case studies and the inaptness for calibration in places plagued by lack of quality data, these methodologies have been limited in scope and application (Cutter *et al.,* 2008; Romieu *et al.,* 2010). Many aspects are based on economic, physical and environmental factors (for example, O'Brien *et al.,* 2004; Birkmann, 2008; Li *et al.,* 2010; Cinner *et al.,* 2012). Social vulnerability assessment is arguably not adequately discussed. This is a major issue for the present research, given that economic, environmental and physical assessment of vulnerability lacks the capacity to reveal all sources of vulnerability of social systems (Cutter *et al.,* 2003). With regards to urban flooding, in which reducing human impact is a critical objective, assessment of vulnerability not based on social features is arguably insufficient to hazard mitigation. Considerable attention is given to urbanisation, climate change and land use scenarios at the expense of social factors.

Assessment of social vulnerability contributes essential knowledge to the solution of vulnerabilities of human population, and this arguably is fundamental to FRM policies. Best practices in FRM and lessons learned from flood risk reduction throughout Europe and the US give the impression that protection of human populations is central in any risk management procedure (EC, 2004; Messner & Meyer, 2006; Merz *et al.,* 2010a; Balbi *et al.,* 2012). For the Lagos area, whilst in theory a methodology that focuses attention on assessment of social vulnerability to flooding and not underscoring the relevance of other components of vulnerability will be ideal given all other 'elements at risk', in reality, developing it, considering the limitations due to the paucity of good quality data, is unrealistic. However, those concerns that were raised in chapter 3 with regards to urban flooding and management in Lagos (refer to section 3.5) seem to suggest that even an estimate of social vulnerability assessment can serve, at least, a preliminary purpose in Lagos FRM, towards reducing human vulnerabilities to urban flooding.

Knowledge about the theories and perspectives that underlie social vulnerability is fundamental to its assessment and application especially towards improving social capacity (Tapsell *et al.,* 2010; Kuhicke *et al.,* 2011). Within vulnerability research, social vulnerability creates an empirical link between social factors such as poverty, gender variation and socio-economic status, and human population at risk (Cutter *et al.,* 2003). Social factors often do not receive attention during post-disaster estimation of losses and, as a result, social vulnerability is not well discussed in the literature (Dunning, 2009). Whilst social sources of vulnerability are being described as a product of place and social inequalities, there are other claims that it originates from the day to day routine activities that subject human populations to highly susceptible places, and go on to influence both their sensitivities and their capacities to respond to and adapt (Cutter & Emrich, 2006; Birkmann, 2007; Yamal, 2007).

Some of the recent studies on social vulnerability indicate that such an approach to vulnerability is widely applicable in the management of urban flooding (Tapsell *et al.,* 2010; Lee, 2014; Akukwe & Ogbodo, 2015). This is because of the human dimension of the risk involved, often perceived as 'socially constructed' (Dake, 1992; Slovic, 1999; Parker *et al.,* 2007). Within this context, Kaźmierczak & Cavan (2011) analysed social vulnerability in addition to hazard and exposure estimation to propose apposite response measures to urban flooding in Greater Manchester, UK. The study provided evidence of social vulnerability among communities described as culturally diverse and deprived of basic necessities within the study area. Overall high risk of flooding among the vulnerable group was found to depend on the interaction between social vulnerability, spatial extent of the hazard, land use and types of housing units present in the area. Lee (2014) proposed a social vulnerability framework to be used to delineate spatial development in Chiayi, Taiwan. Armaș & Gavriș (2013) used a combined model of social vulnerability index and the spatial multi-criteria social vulnerability index to show that social vulnerability in the postcommunist Bucharest is an urban process which raises the concern that the population at risk lacks the capacity to cope with disasters.

Social vulnerability is not well discussed In the Lagos area, due partly to lack quality data to represent social factors. The only known scientific study was undertaken by Ajibade *et al.* (2013) who used primary sources of data to assess the vulnerability of women to flooding in Lagos. Drawing from the work of Cutter *et al.* (2003), Birkmann (2006), Fekete (2010) and Tapsell *et al.* (2010), Nkwunonwo *et al.* (2015) showed that analysing social vulnerability can be useful towards delineating where the greatest social needs of a wider population are and setting priorities for meeting them.

The relative responses of different places and people to shocks and stresses emerging from hazards with flooding in perspective, is often measured on the basis of a 'social vulnerability index' (abbreviated as SocVI in the present research) (Rygel *et al.,* 2006; Flanagan *et al.,* 2011; Oulahen *et al.,* 2015). Fekete (2009) described how SocVI was used as a tool to develop and validate social vulnerability map defining population characteristics to fluvial sources of flooding covering all counties in Germany. Although there are uncertainties, which seem to limit the application of SocVI, how the collection of variables respond to the sensitivities of the conceptual underpinning of SocVI construct, and specific geographic contexts have been investigated (Schmidtlein *et al.,* 2008; Tate, 2012).

Although, SocVI is typically a number that reveals many things about social groups within a spatial framework, the issue of how it is computed remains an important issues within social vulnerability research (Tapsell *et al.,* 2003; Zahran *et al.,* 2008). Major issues like choice of indicators, method of aggregation, and assignment of weights to them, are yet to be resolved. The current literature acknowledges the flurry of methodologies for constructing this index as long as the key factors of vulnerability (exposure, sensitivity, lack of coping capacity and lack of resilience) are captured and the indicator selected sufficiently fulfills the research demands (Turner *et al.,* 2003).

Regardless of epistemic position (qualitative or quantitative), a significant challenge facing the task of constructing a social vulnerability index is choice of/selection of indicators, and this is an issue which the present research attempts to overcome (Tapsell *et al.*, 2010; Yoon, 2012). In Cutter *et al.* (2003) and Abson *et al.* (2012) among other authors, the United States Census Bureau data have been explored to compute social vulnerability indices. These studies define social vulnerabilities on the basis of indicators such as poverty, age, gender, race, ethnicity, disability which are now globally acknowledged (Rygel *et al.,* 2006; Ajibade *et al.,* 2013). However, choosing data in lieu of such indicators requires that issues such as multicollinearity and singularity existing within chosen variables must be resolved as the tendencies for variables to correlate too highly and to measure essentially the same thing undermine the results of social vulnerability constructions (Alwang *et al.,* 2001).

The absence of a standard for the choice of data collection for constructing a social vulnerability leaves the researcher with an option of finding a way to either reduce the sample size of the acquired data or aggregate them. In Clark *et al.* (1998), a practical approach to this challenge was proposed by implementing a factor analysis (FA) to reduce a large sample of a dataset to a more manageable number, whilst still retaining their central themes. This approach has been widely used in many recent studies including Holand *et al.* (2011). In Cutter *et al.* (2003), the authors applied the principal component analysis (PCA) to achieve the purpose of dataset reduction. Both approaches of FA or PCA, adopted by the authors above seem to share a similar aim of reducing the size of a large sample of data, identifying and extracting factors that explained most of the variations in the acquired datasets. Under sensitivity analyses, SocVI obtained using these approaches seem to work (Schmidtlein *et al.,* 2008).

Besides the lack of a sound methodology for measuring social factors, aggregating and assignment of weights to proxies of such factors pose significant constraints to the assessment of social vulnerabilities (Cutter *et al.,* 2003; Birkmann, 2006). To overcome such limitations, Adger *et al.* (2004) and Alwang *et al.* (2001) outlined a number of approaches. One of the approaches involved constructing a social vulnerability index by means of aggregating the relevant proxies. Although this was straightforward and reasonable in situations where available data are insufficient to run a more complex model, such methodologies do not necessarily reveal the structure and causes of the vulnerability and could also lessen the importance of a single vulnerability factor (Adger *et al.*, 2004). In contrast, the second option which involves combining components scores to compute the index by means of a simple weighted average mentioned in Wu *et al.* (2002) is acceptable if all variables contributed equally to the overall vulnerability index. Otherwise, a subjective decision has to be made to create a weighting scheme. It is against such a background that applying PCA/FA becomes relevant to aggregation of proxies.

In Cutter *et al.* (2003), the authors aggregated proxies by means of the result of PCA, whereby independent factors that accounted for much of the variances in the modelled data – factor loadings – were put in an additive model and used to compute the overall social vulnerability index for the area. Although applying PCA/FA to the computation of social vulnerability index seems the best approach, it requires a number of stringent considerations. First, the sample size must be reasonable enough, say at least 10-15 participants per variable, as shown in Field (2006). This makes the application of PCA/FA to analysis involving an area of few districts, says sixteen LGAs, over very large numbers of variables difficult. A number of opinions have been expressed with regards to sample size for PCA/FA. For example, Nunnally (1978) recommended having ten times as many participants as variables. Kass & Tinsley (1979) argued and recommended having between 5 and 10 participants per variable up to a total of 300. So, there are varying rules of the thumb concerning the sample size to variable ratio. However, there is a minimum, and according to McCallum *et al.,* (1999), should also depend on other aspects of the design of the study like communalities, in which two or more variables suggest a similar vulnerability component. Nevertheless, irrespective of the study, a sample should be more than fifty, preferably about one hundred and the ratio of the variables to the cases must be at least one fifth.

Although PCA/FA does always give an idea of the major thing and the communalities that a cluster of variables is measuring, running the model requires knowledge of the mathematics of orthogonal projection and eigenvalues and eigenvector simplifications (a case that resides within engineering and most earth sciences). It is equally important to have a basic knowledge of statistics to be able to run such PCA/FA models. The authors in Rygel *et al.* (2006), analysed variables for social vulnerability assessment by means of PCA and later treated them with Pareto Rankings, which suppress the pressure of assigning weights to variables, and ranks them based on the levels of their statistical significance to the overall vulnerability modelling, and not based on any raison d'être of the researcher. Assigning weights to variables can be the best option where the vulnerabilities of the area are well understood. However, it is impractical to do so especially to highly complex, socio-economic landscapes such as exemplified in many urban areas of DCs. Pareto Rankings technique has only been applied to cities in data rich areas. No research has investigated the outcome of such an approach in data poor areas. Moreover, Rygel *et al.* (2006) argued that data poor areas will find this technique quite complicated since it requires some relevant datasets which are difficult to access in such areas.

4.3 Construction and mapping of social vulnerability indices for Lagos

The preceding parts of this chapter have addressed the conceptual issues of vulnerability. This part focuses on the construction of SocVI. As the realisation of such a goal is often hampered by the lack of quality datasets, a more realistic approach based on the data available is conceived and implemented in the present research, for assessment of social vulnerability to urban flooding. The extent to which data can be collected and analysed for social characteristics such as age, gender variations, socio-economic status, etc., and their influence on vulnerability to urban flooding is examined. SocVI is calculated for the Lagos area by means of demographic data and easily accessible elevation model, which covers the whole of Lagos city.

The method described in this chapter is based on specific issues relating to social vulnerability to Lagos urban flooding. Such issues as family structure, peculiar gender variations, and settlement pattern have been utilised in the present research, to construct the Lagos SocVI. Moreover, as reviewed in the section 4.2 above, limitation in the data available for the present research makes PCA or FA unsuitable for the present SocVI construct. Key features of this method are: (1) Simple modifications based on location-specific issues, (2) modularity, in which specific vulnerabilities are computed based on individual social variables, and (3) sparse-data sensitivity. In addition, this method is adapted from well-known approaches for example Cutter *et al.* (2003); UNDP/HDI (2006); Rygel *et al.* (2006); IPCC (2007) and Akukwe & Ogbodo (2015). These approaches use social characteristics as indicators to represent various components underlying the framework of social vulnerability being adopted. Although these approaches are being standardised, the paucity of good quality dataset to represent these indicators, especially in places without national database of social variables, is a major limitation.

Lagos is one of the places that do not have good quality datasets to represent indicators of social vulnerability. Although the 2006 national demographic dataset and data from the Lagos state digest of statistics are available, but they are not detailed. Whilst social vulnerability constructs are often based on data at ward levels, the data for Lagos area are available at LGA and Local Council Development Authority (LCDA) levels and at these levels, information on social variables is generalised. However, the focus and working theory of the present research is to construct a realistic SocVI despite the scale of available datasets.

To utilise demographic datasets in the present research, two modifications, which are consistent with current issues in the literature and are also suitable based on the study area, have been made. The first modification relates to the indicators, when compared to previous studies, is the inclusion of information describing family structure. This information include: the percentage number of houses owned by head of family, the percentage number of houses owned by any other member of the family, the percentage number of people with relationship with the head of family. Such inclusions are based on location-specific indicators, such as settlement pattern, which vary from place to place, and according to local evidence, a significant amount of the causes of vulnerability to flooding in Lagos, are due to the way the people live. It is argued that co-habitation tends to be an advantage in such areas, since the capacity to cope and recover quickly from losses after the hazard is often developed by a mutual co-existence. However, co-habitation, in situations in which the source of livelihood for an entire household is limited, can undermine quick recovery from losses after a sudden flood event.

To make the vulnerability assessment exclusive to flood hazard, the next modification was the inclusion of topographic information to the variables for SocVI construct. Due to the spatial extent of the LGAs being considered, the average elevation for each of the constituting LGAs was extrapolated, supposing that vulnerability to flooding relates to relative differences in elevation since flooding in the study area is also aided by flat topography. This is particularly important for handling uncertainty due to the absence of a flood hazard map and the lack of information to describe large scale topographic features such as drainage systems.

4.3.1 Data used for SocVI for the Lagos metropolis of Nigeria

The present research utilises demographic data (obtained from 2006 Nigerian national census, Lagos state digest of statistics and Abstracts of Lagos state local government statistics) to rank the sixteen LGAs of the Lagos metropolis of Nigeria with respect to susceptibility and lack of coping capacity to flood hazards due to pluvial events. Other relevant datasets are 30m horizontal resolution, 20m vertical accuracy ASTER GDEM and political boundary of the Lagos metropolis of Nigeria in vector format. These data were selected based on their availability and relevance with respect to the study area. For appropriate selection and grouping of the datasets, the general view of vulnerability, proposed by Adger (2006) and IPCC (2007) in which vulnerability is defined on the basis of exposure, susceptibility and lack of coping capacity was adopted in the present research.

Nigerian demographic data is the result of the latest housing population census conducted in the country in 2006. The dataset consists of variables at the LGAs levels, and representing social vulnerability indicators (Cutter *et al.*, 2000; Wu *et al.,* 2002). These data include: population figures, gender and age distribution, housing conditions, family structure, marital status, disability figures and socio-economic variables. The datasets were selected in such a way to reflect the concept of vulnerability based on super themes, which are exposure, susceptibility and lack of coping capacity to urban flooding in Lagos. Although both dataset lack the key details of social variables, the data from Lagos state digests of statistics and Abstracts of Lagos state local government statistics data are more refined, given that information at LCDA level covers less spatial extent than the 2006 census report which covers mainly larger LGAs. Therefore, careful integration of the two datasets was carried out. Table 4-1 gives a summary of the data classed as indicators (in addition to topography, which rounds them up to a total of nine indicators) and variables for computing social vulnerability indices for the conurbation.

Table 4-1: Summary of the data classed as indicators and variables

S/NO.	INDICATORS	VARIABLES
1.	Poverty	% Below SSCE & None education % Houses with access to more efficient cooking fuel % Houses without access to more efficient cooking fuel % Houses with access to more efficient lightning fuel % Houses without access to more efficient lightning fuel % Houses with more convenient solid waste disposal % Houses without more convenient solid waste disposal % Has no access to telephone % Has no access to TV % Houses with access to good drinking water % Houses with no access to good drinking water % Houses with no healthy sanitation facility % Houses not owned by occupiers
2.	Age	% TP (15-69) Years % TP (70-85+) Years % age 0-14 years
3.	Gender	% Male % female gender
4.	Marital status	% Persons without marriage partner
5.	Housing condition	% House on separate stand / Yard % House made of traditional materials % Flat in blocks of flats % Semi-detached houses % Rooms / Let in houses % Informal & Others % Earth / and Wood material for floor % Earth / and Wood material for wall % Thatched, Earth / and Wood material for Roof
6.	Family structure	% Without Regular homes % More than four persons in a room % House owned by head of family % House owned by wife % Renters % Immediate relations to head of household % Non-immediate relations to head of household % Absence of Regular Sleeping Room
7.	Socio-economic status	% Number of development projects % Professionals % Average Tenement % Number of Primary Health Care % Number of births % 2007 Annual Revenues % Literacy
8.	Disability	% Disability
9.	Topography	Average elevation value for each LGA

4.3.2 Data Arrangement and Screening

The collected data were tabulated in MS-EXCEL 2010 spreadsheet in the form of a regular matrix, with the columns representing the indicators, and the rows representing names of the 16 LGAs of the Lagos metropolis (see figure 4-1). Excel 2010 spreadsheet was chosen for this present research because of the availability of mathematical functions and the flexibility to create newer ones to run the vulnerability model.

S/No	LGAs	Land Area (Sqkm)	Population (Male)	Population (Female)	Total Population (TP)	Population Density (PD)	% TP	% PD	% Male	% Female	TP (70-80+) Years	TP (0-14) Yreas	TP (15-69) Years	% TP (70-80+) Years	% TP (0-14) Years	% TP (15-69) Years	Development Project
1	AGEGE	11.263	238456	223287	461743	40996.45	5.74	13.74	2.96	2.77	7274	154066	300403	0.09	1.91	3.73	3
2	AJEROMI-IF	12.395	352273	335043	687316	55451.07	8.54	18.59	4.38	4.16	9816	231985	445515	0.12	2.88	5.54	1
3	ALIMOSHO	186.195	665750	653821	1319571	7087.04	16.40	2.38	8.27	8.12	16124	472723	830724	0.20	5.87	10.32	5
4	AMUWO-OI	135.240	173742	155233	328975	2432.53	4.09	0.82	2.16	1.93	4307	94089	230579	0.05	1.17	2.86	1
5	APAPA	26.798	123163	99823	222986	8320.99	2.77	2.79	1.53	1.24	3005	67102	152879	0.04	0.83	1.90	17
6	ETI-OSA	193.460	158858	124933	283791	1466.92	3.53	0.49	1.97	1.55	3114	74151	206526	0.04	0.92	2.57	2
7	IFAKO-IJAY	26.769	219109	208628	427737	15978.82	5.31	5.36	2.72	2.59	5072	141576	281089	0.06	1.76	3.49	0
8	IKEJA	46.427	171782	145832	317614	6841.15	3.95	2.29	2.13	1.81	3857	83771	229986	0.05	1.04	2.86	35
9	KOSOFE	81.889	358935	323837	682772	8337.77	8.48	2.80	4.46	4.02	8645	209231	464896	0.11	2.60	5.78	16
10	LOGOS-ISL/	8.707	110042	102658	212700	24428.62	2.64	8.19	1.37	1.28	5658	57057	149985	0.07	0.71	1.86	7
11	LAGOS-MAI	19.572	170568	156132	326700	16692.21	4.06	5.60	2.12	1.94	6538	97826	222336	0.08	1.22	2.76	9
12	MUSHIN	17.576	326873	304984	631857	35949.99	7.85	12.05	4.06	3.79	12596	188483	430778	0.16	2.34	5.35	1
13	OJO	158.884	315401	293772	609173	3834.07	7.57	1.29	3.92	3.65	5267	221385	382521	0.07	2.75	4.75	2
14	OSHODI-ISO	44.999	325207	303854	629061	13979.44	7.82	4.69	4.04	3.78	8659	197304	423098	0.11	2.45	5.26	5
15	SHOMOLU	11.615	207519	196050	403569	34745.50	5.01	11.65	2.58	2.44	7618	121549	274402	0.09	1.51	3.41	2
16	SURULERE	23.122	260509	242356	502865	21748.33	6.25	7.29	3.24	3.01	9676	147274	345915	0.12	1.83	4.30	4

Figure 4-2: Excel clip of social vulnerability data

4.3.3 Data Normalization

To ensure uniformity in scales and units, and that the averages of sample will be about zero, and sample standard deviations, unity, the present research adopted part of the methodology used in UNDP's Human Development Index (HDI) (UNDP, 2006) to normalize the datasets of various units and scales. HDI presupposes that a functional relationship of the contributing variables with vulnerability should be known. Using previous studies such as Cutter *et al.* (2003), this is determined by how each variable within the indicator category contribute to social vulnerability, either positively or negatively. The negative contribution decreases vulnerability and is indicated with a downward arrow. Conversely, a positive contribution increases vulnerability, and is shown as an upward arrow. By using the HDI methodology for normalization, it is possible to suppress the bias of weights assignment based on expert knowledge of the study area. Table 4-2 gives a summary of the functional relationship of the indicators and the main assumptions to obtain the functional relationships. An important uniqueness of the HDI methodology is that functional relationships are determined before the normalization of the datasets.

Table 4-2: Functional relationships based on UN HDI methodology adopted for normalizing the variables

S/No.	Indicators	Functional Relationships	Main Assumptions
1.	Poverty	↑	Poor people are generally vulnerable
2a.	Age (0 – 14 Years)	↑	Children are generally vulnerable.
2b.	Age (15 – 69 Years)	↓	Greater ratio of males to females, the age category contributes to the socio-economic status
2c.	Age (70 – 85+ Years)	↑	Older people are generally vulnerable
3a.	Gender (Female)	↑	Women are generally vulnerable
3b.	Gender (Male)	↓	Men are less vulnerable
4.	Disability	↑	Generally vulnerable
5.	Housing conditions	↑	More houses are either dilapidated or built with less flood-proof materials.
6.	Socio-economic	↑ ↓	General assumption is that it can both create and reduce vulnerability.
7.	Marital Status	↑	People without a marriage partner are often vulnerable
8.	Family Structure	↑	The arrangement of families in terms of size and relationship to the owner of the house / family head contributes to vulnerability.
9.	Topography	↑	Places with lower elevation are more vulnerable

Equations 4-1 and 4-2 below are two models for data normalisation by HDI methodology, and are appropriate for positive and negative functional relationships respectively.

$$x_{ij} = \frac{x_{ij-Min(j)}}{Max\ (j) - Min\ (j)}$$

Equation 4-1: Positive functional Relationship

$$x_{ij} = \frac{Max(j) - x_{ij}}{Max\ (j) - Min\ (j)}$$

Equation 4-2: Negative functional Relationship

x_{ij} is the value of *i*th row and *j*th column of the variable table, ***Max (j)***, and ***Min (j)*** are the maximum and minimum values in the *j*th column.

4.3.4 Aggregating and ranking the variables

The method of aggregating in Patnaik & Narayanan (2009) (which applies simple averaging) was adopted for aggregating and ranking the standardised variables for each indicator of vulnerability. Patnaik and Narayanan method proposed equation 4-3 below for use in aggregating the group variables and ranking the resulting vulnerability scores. In using this method, the standardised variables that made up each indicator were aggregated by simple averaging to obtain a discrete vulnerability for each indicator ***(AI)***. For those indicators such as marital status, disability and topography having a single variable, their normalized values were taken as the discrete indicator of vulnerability. The outcome of this operation is shown in table 4-3.

$$VI = \frac{\left[\sum_{i=1}^{n}(AI)^{\alpha}\right]^{\frac{1}{\alpha}}}{n}$$

Equation 4-3: Variables aggregation model

VI is the vulnerability index, ***AI*** is vulnerability for each indicator component, ***n*** represents the number of sources of vulnerability, and α is equal to ***n***.

Table 4-3: Vulnerability of various components that contribute to the overall Social vulnerability in the Lagos metropolis of Nigeria. Emphases are on peaks for each indicator.

S/No	**LGAs**	**Gender Vulnerability**	**Age Vulnerability**	**Marital status Vulnerability**	**Disability Vulnerability**	**Housing condition Vulnerability**	**Family structure Vulnerability**	**Socio-economic condition Vulnerability**	**Poverty Vulnerability**	**Topography Vulnerability**
1	Agege	0.50	0.48	*1.90*	0.22	0.48	0.38	*0.75*	0.41	0.10
2	Ajeromi-Ifeledun	0.49	0.55	0.43	0.43	0.69	0.58	0.50	0.49	0.61
3	Alimosho	0.50	*0.75*	1.00	*1.01*	0.39	*0.71*	0.35	0.52	0.42
4	Amuwo-Odofin	0.49	0.38	0.10	0.10	0.42	0.31	0.62	0.58	0.90
5	Apapa	0.49	0.35	0.01	0.00	0.50	0.29	0.52	0.50	0.92
6	Eti-osa	0.48	0.35	0.06	0.05	0.63	0.32	0.36	0.60	0.97
7	Ifako-Ijaiye	0.50	0.42	0.19	0.19	0.31	0.36	0.48	0.44	0.00
8	Ikeja	0.49	0.37	0.09	0.08	0.27	0.33	0.73	0.43	0.35
9	Kosofe	0.48	0.50	0.42	0.42	0.61	0.56	0.60	0.49	0.96
10	Logos-island	0.50	0.44	0.00	0.00	0.40	0.29	0.48	0.47	0.90
11	Lagos-mainland	0.50	0.42	0.10	0.09	*0.79*	0.35	0.66	0.51	0.54
12	Mushin	0.49	0.60	0.38	0.37	0.53	0.52	0.47	0.40	0.35
13	Ojo	0.49	0.44	0.36	0.35	0.37	0.45	0.61	*0.67*	0.85
14	Oshodi-Isolo	0.49	0.50	0.38	0.37	0.49	0.50	0.62	0.43	0.95
15	Shomolu	0.50	0.47	0.17	0.16	0.48	0.38	0.60	0.44	0.51
16	Surulere	0.49	0.52	0.26	0.25	0.47	0.43	0.74	0.42	*1.00*

* The method used in the present research computed vulnerability indices (representing the 16 LGAs in Lagos city) for each of the nine indicators which were presented in table 4-1 has produced

Similarly the overall SocVI based on the discrete vulnerabilities of the indicators is obtained by putting the discrete vulnerabilities into an additive model and dividing the outcome by the number of indicators considered – in this case nine. The number of indicators does not affect the outcome of the SocVI as long as the functional relationships of the variables were accurately determined and applied at the normalization stage. This operation is repeated for all the constituting LGAs with the outcome tabulated as shown in table 4-4, which delineates the overall SocVI for the sixteen LGAs of the Lagos metropolis of Nigeria.

A significant advantage of applying the Patnaik & Narayanan (2009) in the present research methodology is the possibility of knowing how each indicator contributes to the overall social vulnerability, and this is simply an average of independent indicator scores. It is most suitable for the study due to the complexity in using other models, limited sample size, lack of data, and the possible issues of subjectively assigning weights which will significantly undermine the outcome of the present SocVI model.

For the final mapping and visualization of the indices of social vulnerability, ESRI ArcGIS 10.2 software was applied. While linking the attribute table containing the indices of social vulnerability of the Lagos metropolis of Nigeria and the spatial database – vector shapefiles – of the study area (generated by means onscreen digitizing of its hardcopy political map), a vector map delineating the indices of social vulnerability was derived. To enable further presentation and visualization, the resulting map was symbolized using graduated colour scheme to create five classes, ranging from less vulnerable classes to highly vulnerable or classes of extreme social vulnerabilities. The use of graduated colour schemes as against graded colours (low to high) was necessary in order to differentiate between the LGAs in respect of their social vulnerabilities which is important consideration of this study.

4.4 The constructed SocVI of the Lagos metropolis

The result of the SocVI construct reveals three LGAs in the Lagos area classed as very highly vulnerable to flood hazard and four LGAs as highly vulnerable to flood hazard. The remaining LGAs are classed as follows: four LGAs are relatively vulnerable to the hazard, three are moderately vulnerable and the remaining two are less vulnerable. Alimosho, Agege, Kosofe, Ojo, Surulere, Ajeromi-Ifeledun and Oshodi-Isolo LGAs are the highly vulnerable areas while Ifako-Ijaiye and Ikeja LGAs are the less vulnerable ones. Apapa, Lagos Island and Shomolu LGAs are vulnerable, but Eti-osa, Lagos mainland, Mushin and Amuwo-Odofin LGAs are moderately vulnerable (see table 4-4 and figure 4-3).

Table 4-4: Overall social vulnerability (SocVI) indices for the Lagos metropolis of Nigeria.

S/No.	LGAs	Overall Social vulnerability indices
1	Agege	0.65
2	Ajeromi-Ifeledun	0.60
3	Alimosho	0.71
4	Amuwo-Odofin	0.49
5	Apapa	0.45
6	Eti-osa	0.48
7	Ifako-Ijaiye	0.36
8	Ikeja	0.39
9	Kosofe	0.63
10	Logos-island	0.44
11	Lagos-mainland	0.50
12	Mushin	0.51
13	Ojo	0.57
14	Oshodi-Isolo	0.59
15	Shomolu	0.46
16	Surulere	0.57

Additionally, the vulnerability of each social variable is shown (figures 4-4 to 4-13). The results show that Alimosho along with Agege, Ifako-Ijaiye, Lagos-Island, Lagos-mainland, and Shomolu LGAs may be ranked as highly vulnerable as to gender variations. Alimosho LGA is most highly ranked in terms of age differences, marital status, disability and family structure. Lagos mainland Surulere and OJo LGAs are ranked highly vulnerable in terms of housing condition, socio-economic status and poverty respectively. The likelihood to be socially vulnerable to flooding in terms of elevation is highest in Surulere. These results are discussed further in Chapter 8.

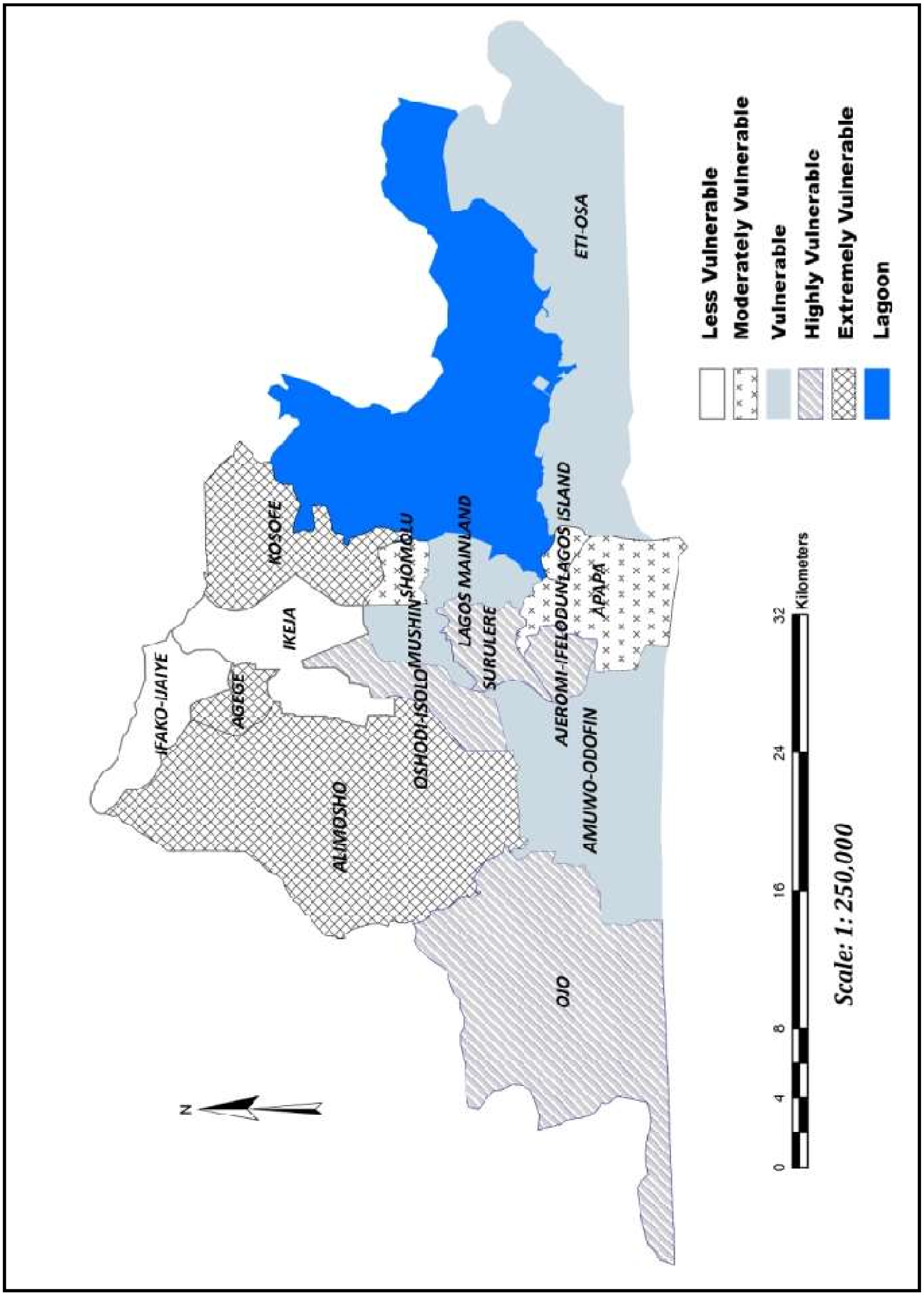


Figure 4-3: Overall SocVI

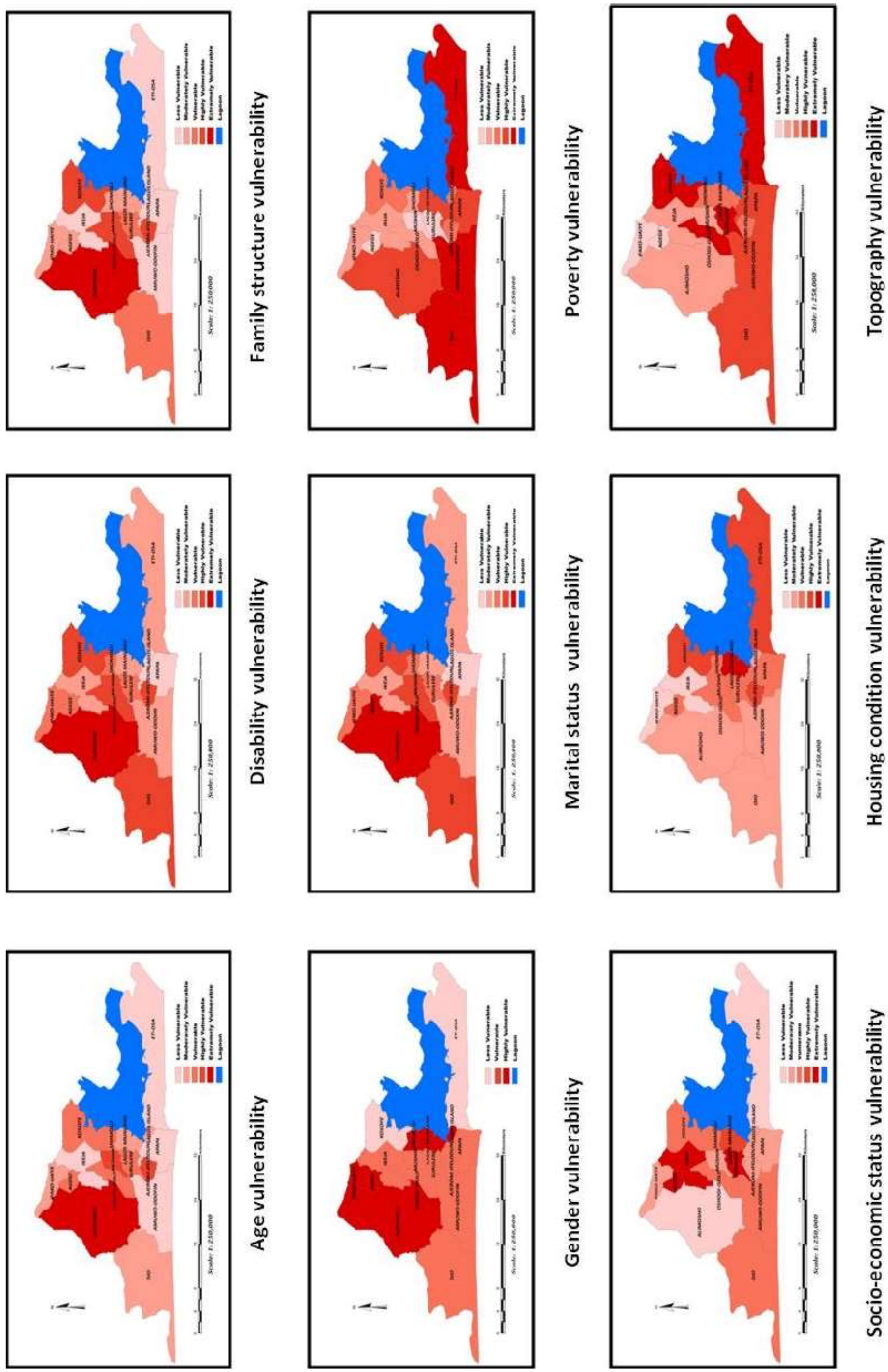


Figure 4-4: Map of the sixteen LGAs of Lagos area of Nigeria, based on each individual component of social vulnerability.

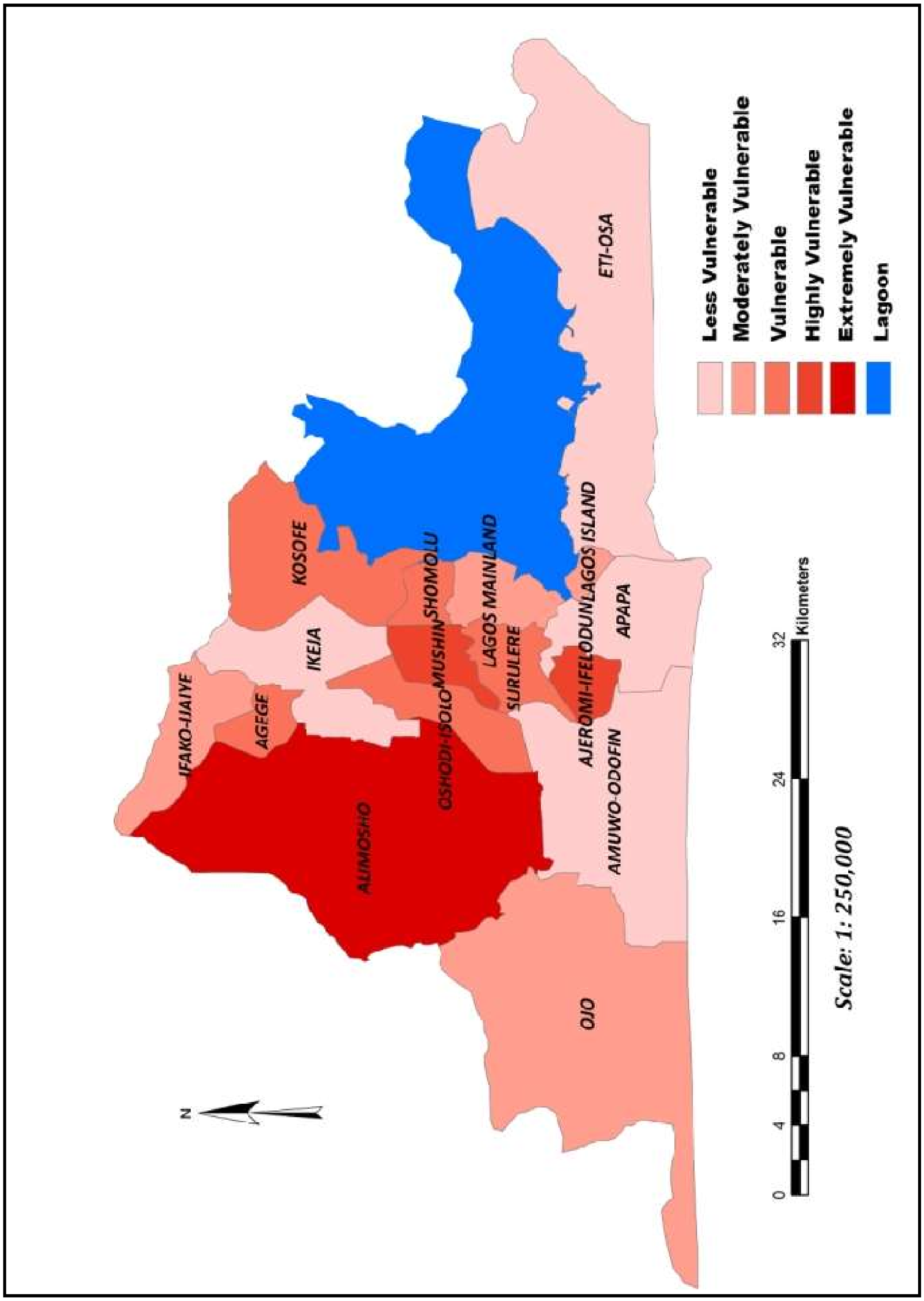


Figure 4-5: Vulnerability due to age differences

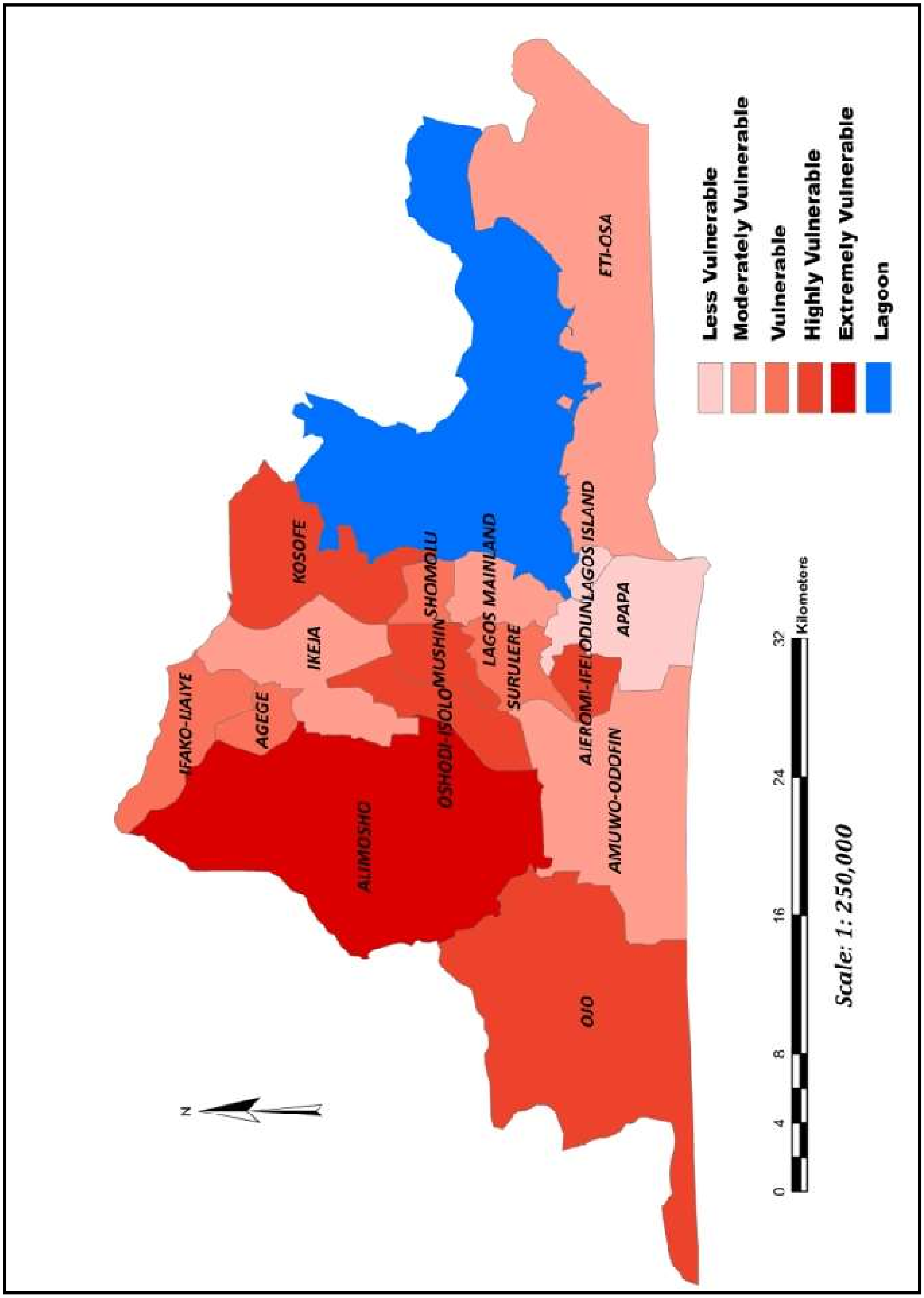


Figure 4-6: Vulnerability due to Disability

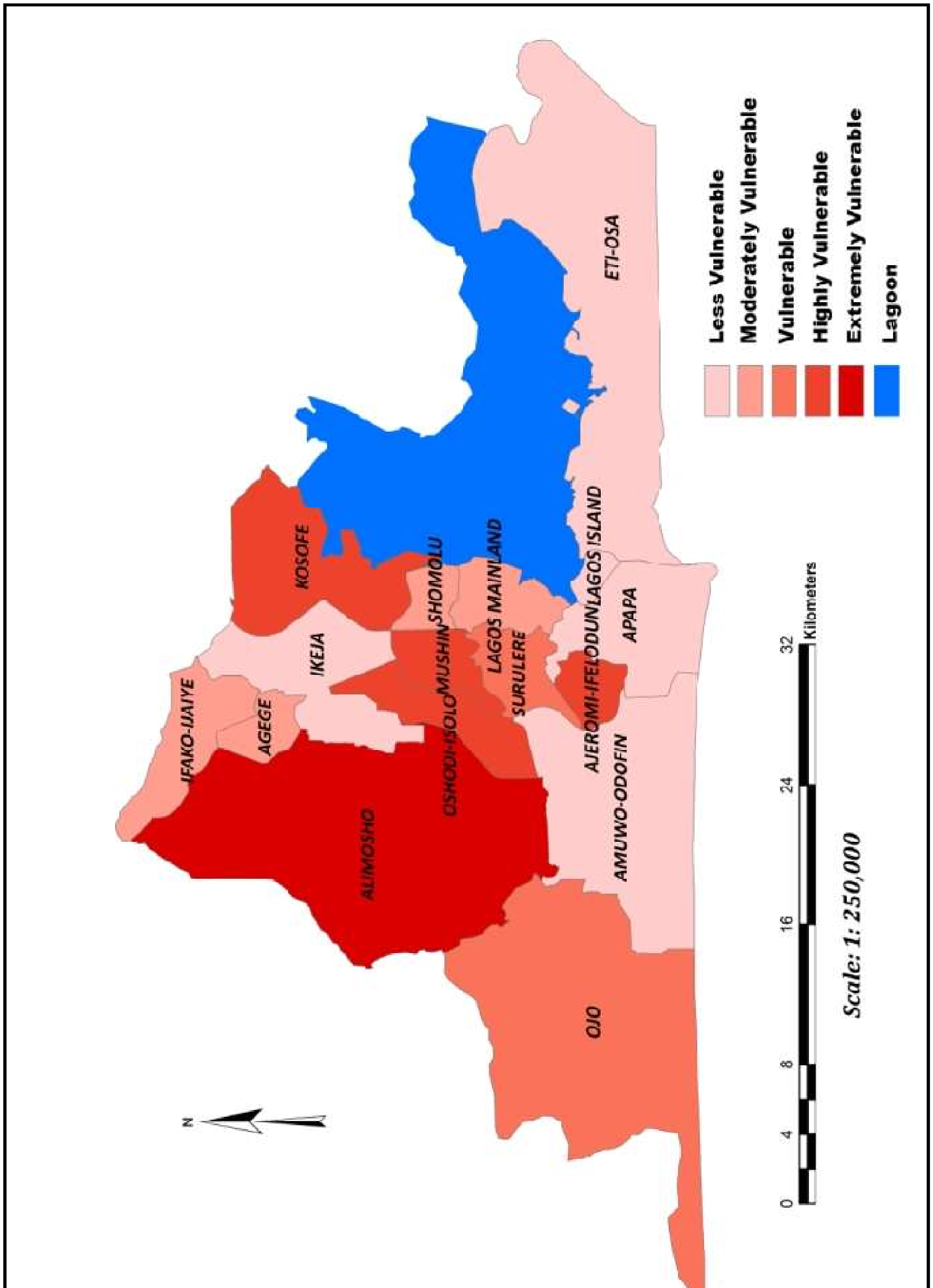


Figure 4-7: Vulnerability to Family Structure

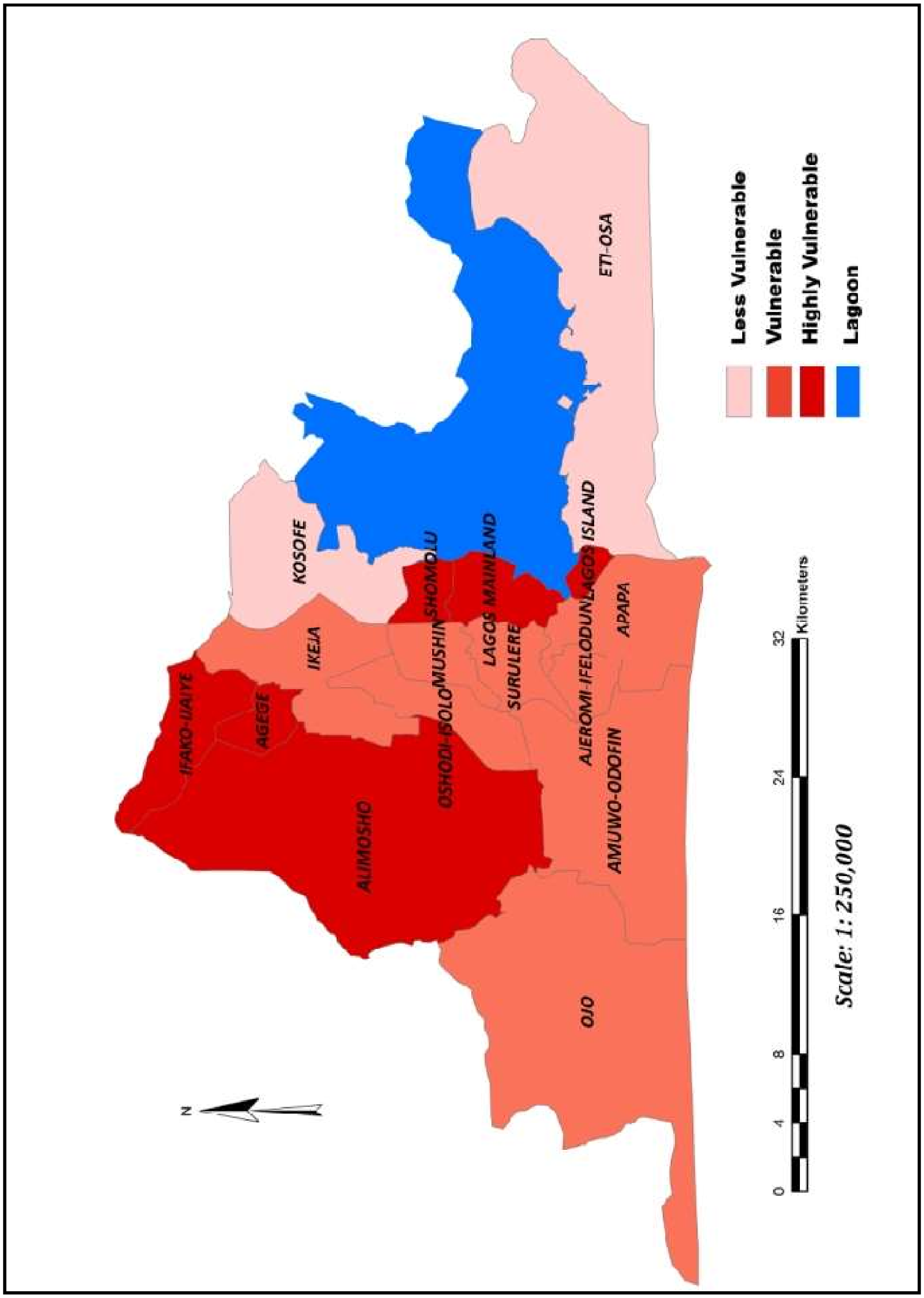


Figure 4-8: Vulnerability due to Gender Differences

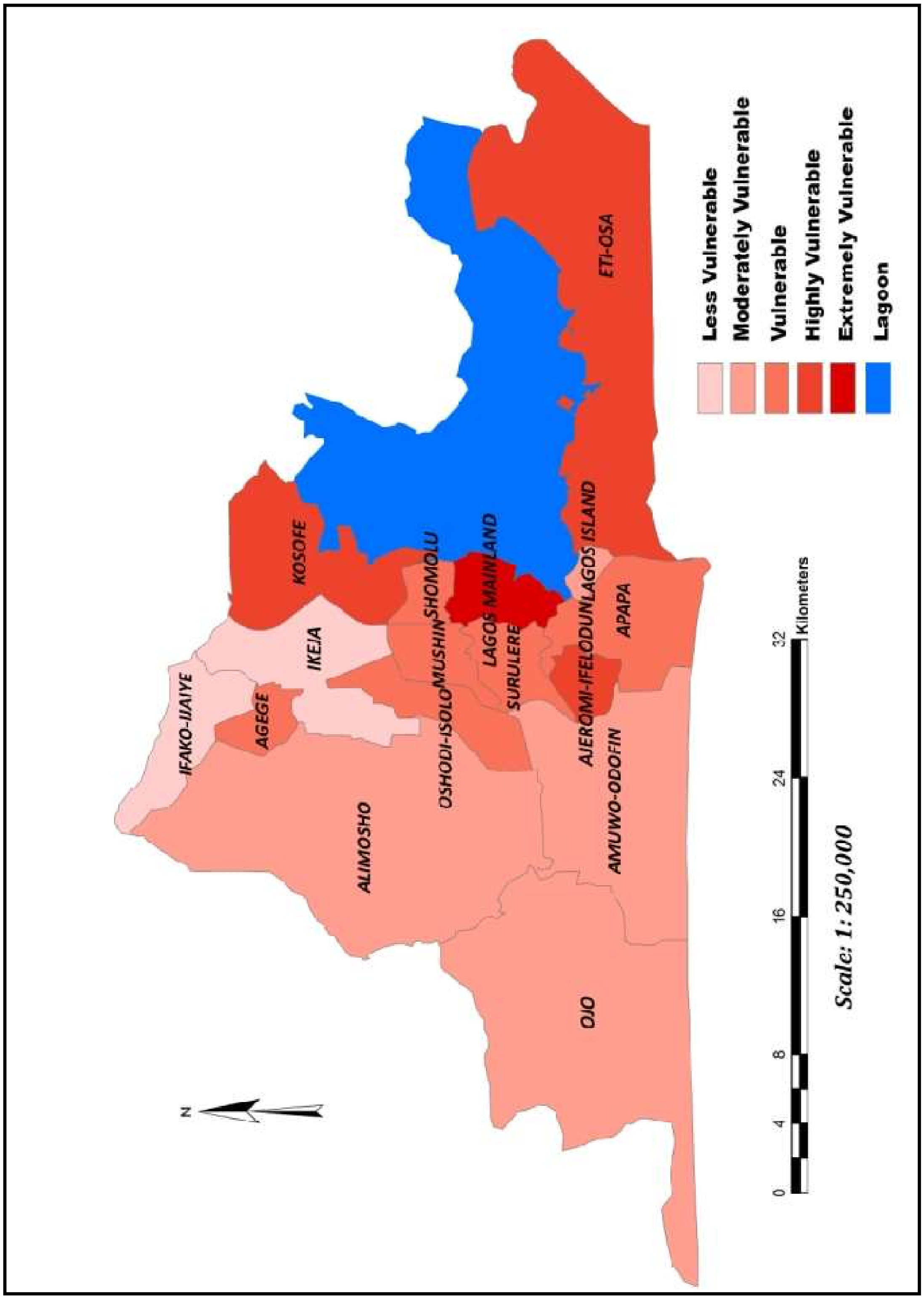


Figure 4-9: Vulnerability due Housing Condition

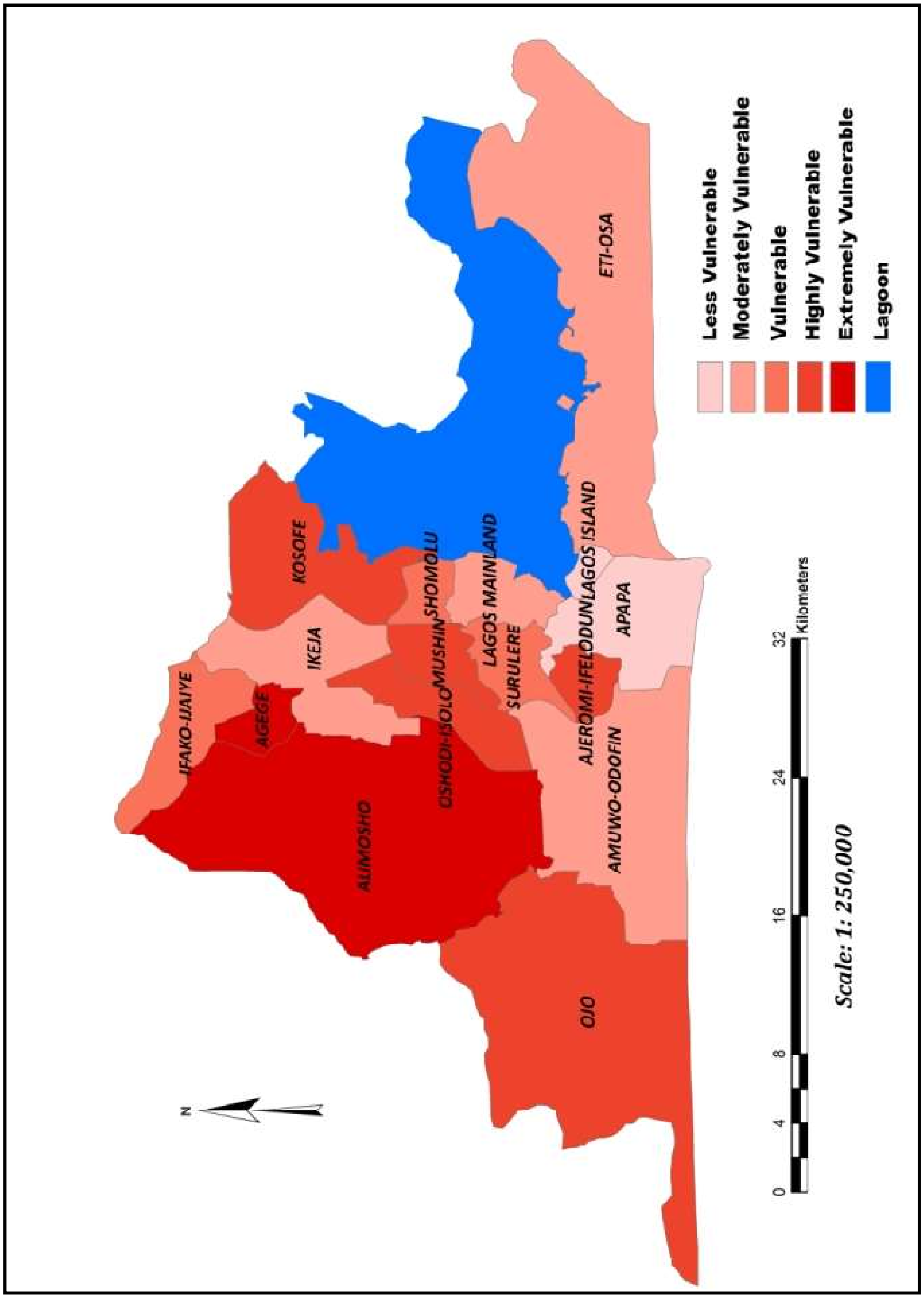


Figure 4-10: Vulnerability due to Marital Status

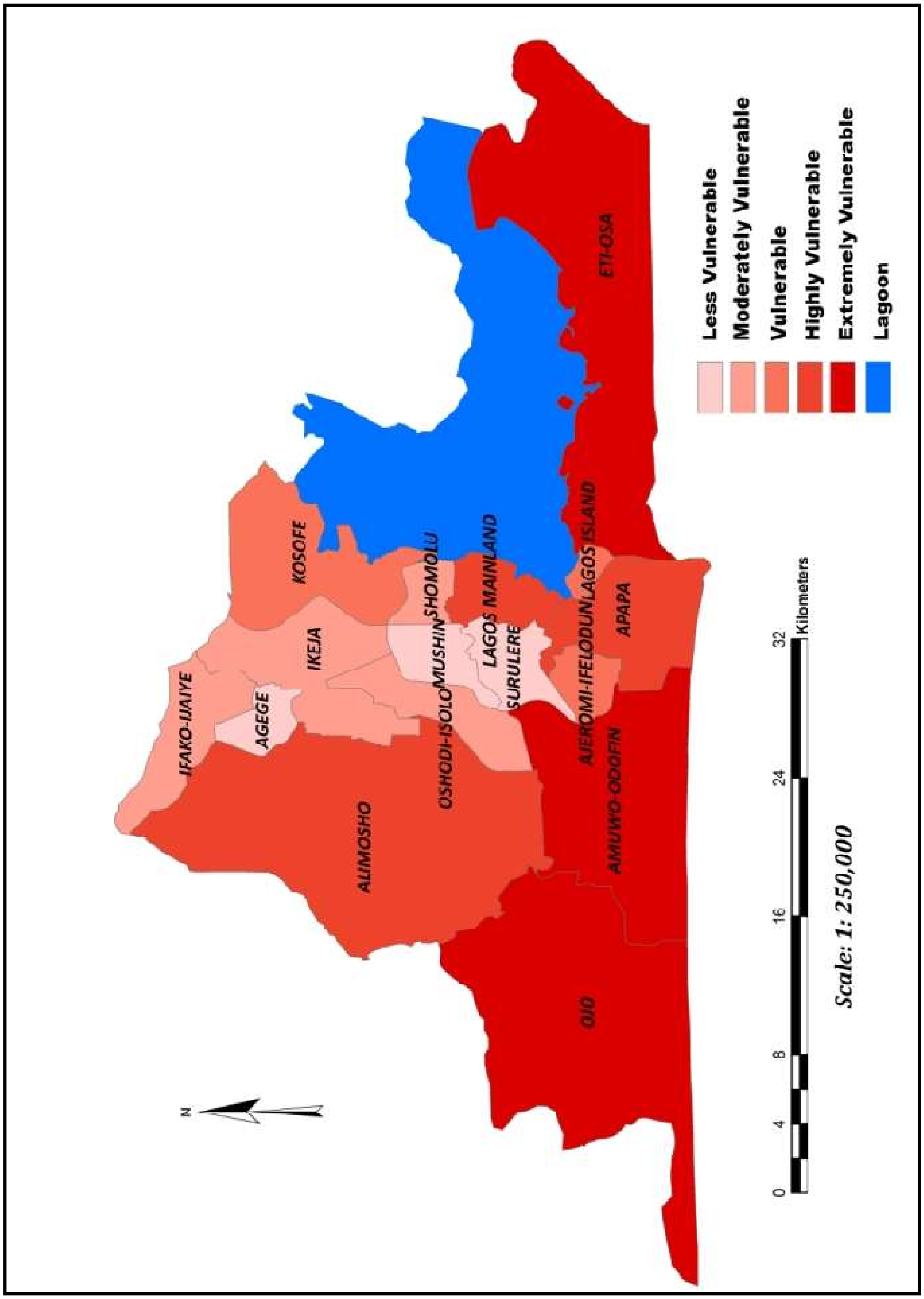


Figure 4-11: vulnerability due to Poverty

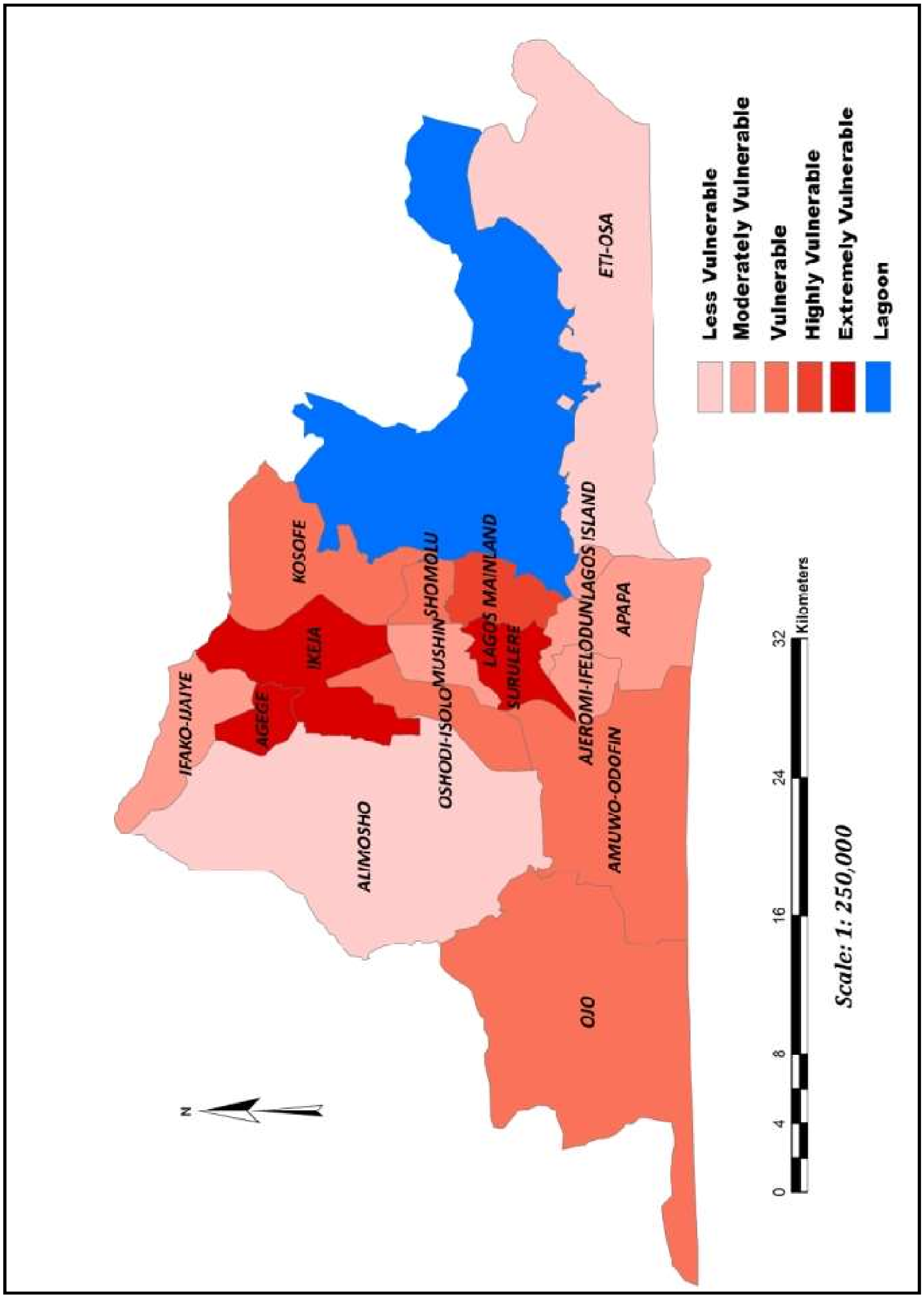


Figure 4-12: Vulnerability due to Socio-economic Status

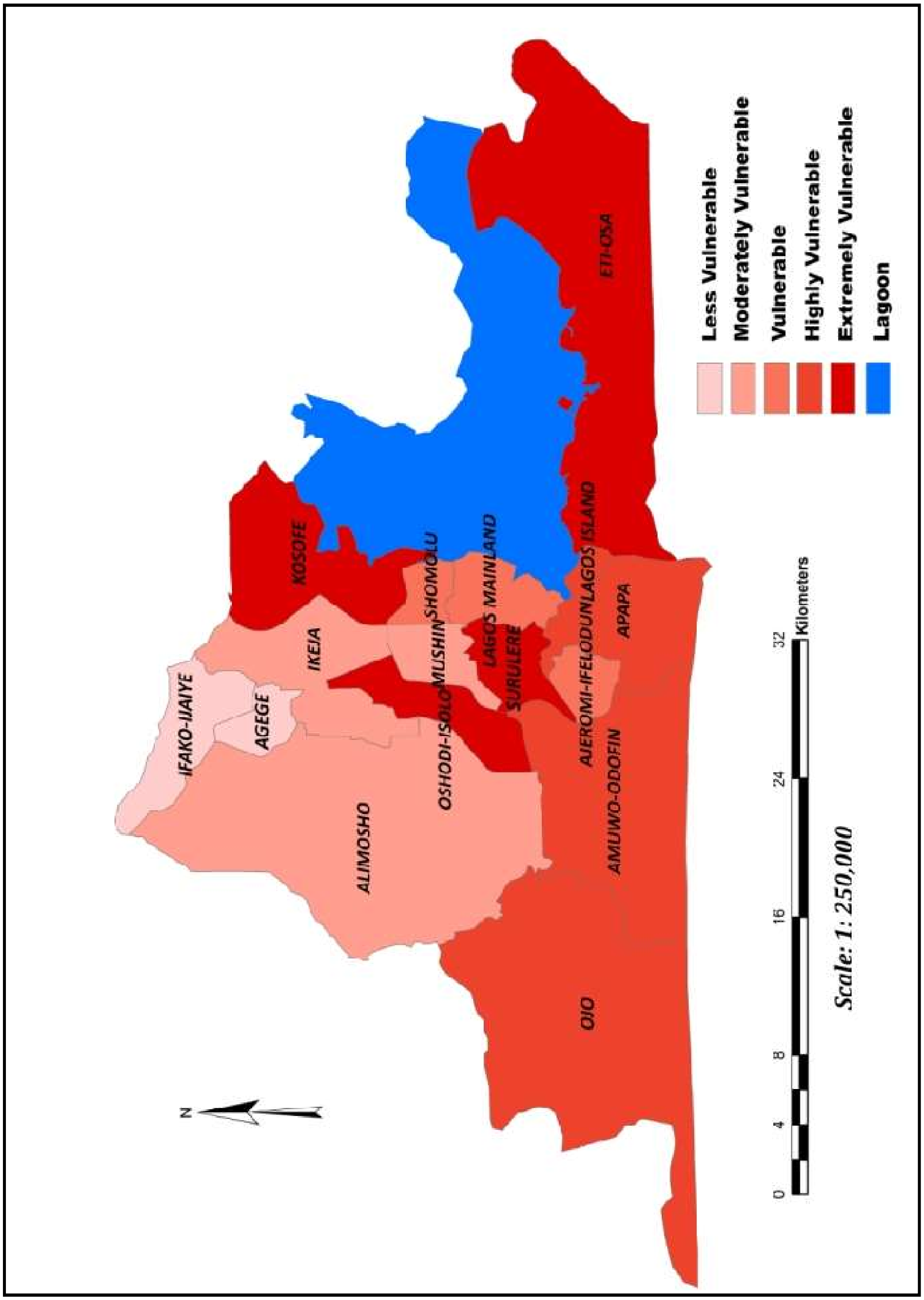


Figure 4-13: Vulnerability due to Topography (height differences)

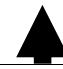
In the SocVI construct, the highly vulnerable LGAs (Alimosho, Agege and Kosofe LGAs) which appeared as the predominantly lower elevation areas underscored the relevance of topography being used as proxy to flood hazard in the study area. From table 4-3, the high vulnerability scores shown by these areas may be attributed to the dominant indicators, whilst overall vulnerability is treated as disaggregated components including age distribution, marital status, disability, family structure and socio-economic condition. Within Lagos context, these indices suggest susceptibility and a lack of coping capacity to flood hazard (Nkwunonwo *et al.,* 2015).

A regression test may be used to understand the relative power of the variables in the resulting SocVI calculation. Therefore, from the coefficient values in table 4-5 ‘gender’, ‘socio-economic condition’ and ‘poverty’ appeared to have contributed more significantly to the overall SocVI, while ‘family structure' and ‘Age’ only contributed minimally. To clearly delineate the strength of these indicators’ contributions, table 4-6 shows a diagrammatic representation of the indicators in arrows according to their strengths to the overall SocVI. How these dominant indicators influence social vulnerability to flooding in the Lagos area is discussed in chapter 8.

Table 4-5: Regression Result showing the strength of indicators to SocVI.

Regression Statistics	
Multiple R	0.962
R Square	0.925
Adjusted R Square	0.838
Standard Error	0.039
Observations	16
INDICATORS	COEFFICIENTS
Gender (Female)	0.8996
Age (0-14), (70-85+)	0.2096
Marital status	0.4729
Disability	0.4491
Housing Condition	0.4326
Family structure	0.2682
Socio-economic	0.5144
Poverty	0.4784

Table 4-6: Contributions of indicators to SocVI, represented with varying thickness and sizes of arrows

S/No.	Indicators	Functional Relationships
1.	Gender (Female)	
2.	Age (0 – 14 Years) and (70 – 85+ Years)	
3.	Marital status	
4.	Disability	
5.	Housing conditions	
6.	Family Structure	
7.	Socio-economic	
8.	Poverty	

Any decision for urban development can be based on these outcomes (tables 4-5 and 4-6), which suggests the need to direct attention towards addressing those social factors that contribute mostly to the overall social vulnerability among the human populations in each of the LGAs within the Lagos area. These include age, marital status, and gender differences.

4.5 Summary

A critical understanding of social vulnerability is crucial for the proper management of Lagos urban flooding. However, such understanding has been constrained by the diversity of vulnerability views, and a lack of data and sound methodology for vulnerability assessment. Oddly, social vulnerability to urban flooding in Lagos is not well discussed, although two important studies provide literature evidence of social vulnerability analyses in the area. These include the study that used primary datasets to examine the vulnerabilities of female gender and another which conceived the relevance of assessing social vulnerability to urban flooding. To address the gap in knowledge of social vulnerability to urban flooding in the Lagos context, a new index of social vulnerability (SocVI) for Lagos has been constructed, using a part of the Human Development Index (HDI) methodology to aggregate the variables and the Patnaik and Narayana (2009) methodology to rank the resulting factors.

The method described in this chapter uses freely available datasets to construct indices that explain the susceptibilities and lack of coping capacities among human populations to urban flooding across the sixteen LGAs in the Lagos area. This method is realistic for places where quality datasets are not easily available, and provides a useful alternative to the standardised methodologies which often involve Principal Component Analysis (PCA), Factors Analysis (FA), and assignment of weights.

The constructed SocVI includes important social factors that must be addressed in order to positively tackle human vulnerabilities to urban flooding in Lagos. These factors including age distribution, marital status, disability, etc., are discussed in chapter 8. Some social science concepts, which might be useful to consider in order to facilitate the actualisation of flood risk management in Lagos within the context of UNISDR idea of living with floods are also discussed. This SocVI only one of the two essential keys to improve the knowledge of urban flooding and its management in the Lagos area. The second key is flood modelling, which is presented in the next three chapters, starting with a review of existing methodologies.

5 Flood modelling methodologies

Assessment of urban flood hazard is underpinned by an understanding of the physics of flood propagation, and an appropriate representation of the underlying hazard components within a simple mathematical framework (Bedient et al., 2008). As an important foundation of the present research, the aim of this chapter is to discuss the hydrological processes that relate to urban flooding, and to review flood modelling procedures. This is an attempt to understand the critical foundation of urban flood modelling, and to further justify the development of a novel flood model, and its application in Lagos which both form the key objectives of the present research. Whilst discussions in this chapter are not exhaustive, more in-depth considerations of the subjects can be found in Chow et al. (1988), Ward & Robinson (2000), Pender & Faulkner (2010) and Sampson et al. (2013).

5.1 Precipitation and runoff: hydrology in urban environment

Precipitation, which mainly occurs as rainfall or snowfall on land areas, vegetation and water bodies, is the major source of water into the hydrologic cycle, whilst runoff is the outcome of heavy amounts of precipitation which exceeds the capacity of the soil to infiltrate, and overwhelms the efficiency of urban drainage systems (Bedient *et al.,* 2008; Birkel *et al.,* 2010; Houston *et al.,* 2011). These duo components of the hydrologic cycle are considered to be the major catalyst of urban flooding (pluvial and groundwater sources inclusive) and this has excited much research (refer to Bedient *et al.,* 2008). Over the years, the means to address the threats of urban flooding within the context of hydrological science have remained issues of global significance especially, in view of the changing precipitation pattern due to climate variations, and increased runoff caused by rapid urbanisation (Milly *et al.,* 2005; Oki & Kanae, 2006; Jian, 2009; Hanjra & Qureshi, 2010; Merz *et al.,* 2010a).

In relation to urban environment, of all the factors influencing runoff, urbanisation is considered the most critical in the current literature (Kjeldsen, 2009; Barron *et al.,* 2011). Urbanisation decreases infiltration capacity and the time of peak and increases the rate of runoff and the peak discharge (see figure 5-2 and figure 5-3), and this condition has largely been associated with urban flooding (Li & Wang, 2009; Barron *et al.,* 2011). Urban flooding in the Lagos, considered in chapter 2, is an exemplar of the picture, with considerable part of the land surfaces covered by impervious surfaces (Action aid, 2006). The process of runoff and its impacts on environmental systems have been adequately discussed in the literature (see for examples, Descheemaekera *et al.,* 2006; Zhu *et al.,* 2011; Sayama *et al.,* 2011). However, within the context of Lagos urban flooding, this phenomenon has not been well researched (Odunuga, 2008; Adelekan, 2010).

5.1.1 Hydrology and flood modelling

A better understanding and modelling of the relationship between precipitation, runoff, urbanisation, climate change and urban flooding is therefore important in tackling urban flood risks and other water-related problems (Beven, 2012). In theory, the continuity relationship that exists between precipitation input, output and storage is rudimentary to hydrology, and underpins the development of physically based conceptual flood models (Chow *et al.,* 1988; Singh & Woolhiser, 2002; Dutta *et al.,* 2003). Most flood modelling methodologies in the flood hazard literature are based on rainfall-runoff relationship, which often includes urban storm drainage systems and soil infiltration capacity (Pappenberger *et al.,* 2005; Brocca *et al.,* 2008; Brocca *et al.,* 2011) Such modelling approaches require considerable data reflecting the spatial and temporal dimensions of key hydrological components (Hunter *et al.,* 2007; Patro *et al.,* 2009). The lack of such datasets in the Lagos areas has been well stated as a fundamental rationale for the present research, which hypothesises that a reliable urban FRM for data sparse locations can be achieved on the basis of a flood model which can be implemented using easily accessible input data. This is the principle that underlies the development of a new flood model in the present research.

5.2 Shallow Water Equations (SWE)

The shallow water equations (SWEs) or the *Saint Venant equations (SVEs),* form the underlying mathematical framework for flood modelling. These equations are often difficult to solve, and appropriate understanding of how they are derived is crucial in formulating and developing algorithms for urban flood models in the case of Lagos. SWEs are mainly non-linear hyperbolic partial differential equations (PDEs) for which closed-form solutions are almost impractical. Only approximate solutions exist which are provided by means of suitable numerical schemes solved over a mesh of grids of varying characteristics (de St. Venant, 1871; Chow, 1964).

SWEs take their roots from the *Reynold's transport theorem* (RTT), which explains the time-dependent variations in the mass and volume of a fluid, due to external forcing parameters, and uses physical laws to account for the fluid flowing continuously through a control system (Chow *et al.,* 1988). Cunge *et al.* (1980) argued that differential forms of the SWEs can be obtained from the integral forms if one assumes that the dependent variables are continuous differential functions. Following this assumption, the continuity and momentum equation of the SWEs may be written as equations *5-1* and *5-2*, as well as equations *5-3* and *5-4* all of which represent conservative and non-conservative forms of continuity and momentum equations respectively.

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + q = 0$$

Equation 5-1: SWE – Continuity Conservative

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g\left(S_o - S_f\right) = 0$$

Equation 5-2: SWE – Momentum Conservative

$$V\frac{\partial y}{\partial x} + y\frac{\partial V}{\partial x} + \frac{\partial y}{\partial t} = 0$$

Equation 5-3: SWE – Continuity Non-conservative

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g\left(S_o - S_f\right) = 0$$

Equation 5-4: SWE – Momentum Non-conservative

V (L^3) is the volume vector of the fluid, Q (L^3T^{-1}) is the discharge, q (L^2T^{-1}) is the discharge per unit width, g (LT^{-2}) is the force of gravity, A (L^2) is the cross-sectional area, t (T) is the time, x and y (L) are spatial dimensions, S_o and S_f are bed sloped and friction slope (-) respectively.

From the momentum equation 5-2, five terms can be identified, and these include local acceleration ($\frac{1}{A}\frac{\partial Q}{\partial t}$), convective acceleration ($\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)$), pressure term ($g\frac{\partial y}{\partial x}$), slope term (gS_o) and friction term (gS_f). The 'local acceleration' term describes the change in momentum due to change in velocity over time. The 'convective acceleration' term describes the change in momentum due to change in velocity along the channel. The 'pressure force' term describes the force proportional to the change in water depth along the channel. The 'gravity' term describe the force proportional to the bed slope, whilst the 'friction' term describes the force proportional to the friction slope. These terms are fundamental in the formulation of simplified flood models which will be discussed later in section 5.3.6.

In deriving the SWEs from the Navier-Stoke theorem, de St. Venant (1871) made a number of assumptions, which can be summarized as follows:

1. Flow is considered one-dimensional, and cross-sectional velocity is uniform, so that water level across the section can be represented with a horizontal line.
2. The streamline curvature is small, and vertical oscillations are negligible, and the pressure acting on the surface can be assumed as hydrostatic.
3. The average bed slope is small so that the cosine of the angle it makes with the horizontal can be represented as unity.
4. The effects of boundary friction and turbulence can be accounted for by resistance laws which are analogous to those in steady-state flows.
5. The variation of channel width along *x* is small compared to the water depth, making it shallow a water phenomenon.

These assumptions, and a critical understanding of the SWEs are crucial in the conceptualisation of urban flood modelling, and classification of flood modelling methodologies and tools, and this is discussed in the next section. Moreover, within the framework of the present research, these discussions in relation to the SWEs formed the bedrock of the SIFDS, which was combined with CA, to develop a new flood model. The physical parameters that were represented in the new model (that is friction, slope and gravity) were combined together within the basic framework of the SWEs.

5.3 Urban flood modelling

Flood modelling generally involves developing algorithms to simulate flood propagation in order to address the threats of flooding on human populations, economic activities and critical infrastructure (Bates & De Roo, 2000; Bates *et al.,* 2005; Ne'elz & Pender, 2009). The procedure is an essential prerequisite for flood risk and flood hazard assessment and mapping (Merz *et al.,* 2007; De Moel *et al.,* 2009; Sayers *et al.,* 2013). It has in fact been sufficiently demonstrated that with long term rainfall record, flood modelling can be used to reconstruct particular historical flooding events (such as 1 in 50, 1 in 100, 1 in 200, 1 in 500 and 1 in 1000 flood return periods) in terms of inundation depth, extent and water flow velocity (Apel *et al.,* 2006 (Hunter *et al.,* 2007; de Moel *et al.,* 2009; Gall *et al.,* 2009; Fernandez & Lutz, 2010; Sampson *et al.,* 2013; Yan *et al.,* 2015). Despite these merits, only few research has considered modelling urban flooding from pluvial events (Chow, 1964; Mujumdar, 2001Chen *et al.,* 2009; Ghimire *et al.,* 2013; Glenis *et al.,* 2013; Meesuk *et al.,* 2015). More attention has been given to modelling flooding from fluvial and coastal flooding events, as well as those resulting from dam break (Hénonin *et al.,* 2010; Di Baldassarre & Uhlenbrook, 2012; Yan *et al.,* 2015; Ward *et al.,* 2015). These are important limitations within flood risk assessment research, and which motivate the present research towards urban flood modelling and FRM in data poor countries.

Urban flood modelling is often problematic since flood risk in such places is largely driven by a complex combination of physical and geomorphological processes (Jha *et al.,* 2012). Flood models that accurately represent such phenomena as hydraulic jumps, and supercritical flow condition which are induced by the nature of an urban area, are limited. Thus, existing models lack extensive external calibration which leads to lack sufficient flexibility for application to external case studies (Hunter *et al.,* 2007; Hunter *et al.,* 2008). In the flood modelling literature, there are some limitations in flood modelling procedure which underline the significance the present research with respect to urban flood modelling. As mentioned in chapter one, the lack of large scale calibration datasets, high computation cost and copyright restrictions are major issues with existing flood models (Wheater, 2002; Mark *et al.,* 2004; Maksimović *et al.,* 2009). In addition, the majority of these models are often totally unstable or conditionally stable on the basis of a CFL (Courant-Freidrichs-Lewy) condition, which prescribes small time steps, leading to high computation burden (Bates & De Roo, 2000, Bates *et al.,* 2005; Van Der Knijff *et al.,* 2010).

Lagos in particular which has only 'daily total amounts' rainfall data coupled with the lack of political will to acquire proprietary model licenses cannot benefit from these existing models. Chapter one of this thesis highlights the development of new flood models as one of the key strategies to addressing the limitation with existing flood models. However, there are discussions in the flood modelling literature relating to modifying existing models to address these limitations (Bates & De Roo, 2000; Yu & Lane, 2006a; Almeida *et al.,* 2012). In modifying existing flood models, many complex techniques that are found in the literature include: simplification of the mathematical formulations or reduction in the complexity of the underlying framework of the flood models, adaptation of numerical solution, parallelisation of models, and sub-gridding of spatial computation domains (Mignot *et al.,* 2006; Yu & Lane, 2006b; McMillan & Brasington, 2007; Yu, 2010).

Irrespective of the flooding type, these potential limitations in flood modelling can be identified by reviewing methodologies that exist in the flood modelling literature. Arguably, there have been much diversity in the classification of flood modelling methods, due partly to lack of a standard scheme. For the purpose of this research, classification has been based on spatial extent, dimensionality and mathematical complexity (see figure 5-1). This classification approach is intended to shed some light into the existing methodologies and the main assumptions involved in developing flood models. More detailed discussion of the classification criteria for flood models can be found in Knapp *et al.* (1991), Troutman (1985) and Todini (1988). Based on this classification, table 5-1 provides a list of some known flood modelling tools, applicable to flood risk assessment. The table shows that there is no perfect flood model. As well as being able to simulate flood hazard, these models have limitations, which undermine their applications in different places, especially urban environments, and this is the main rationale for focusing on the development of a new flood model in the present research.

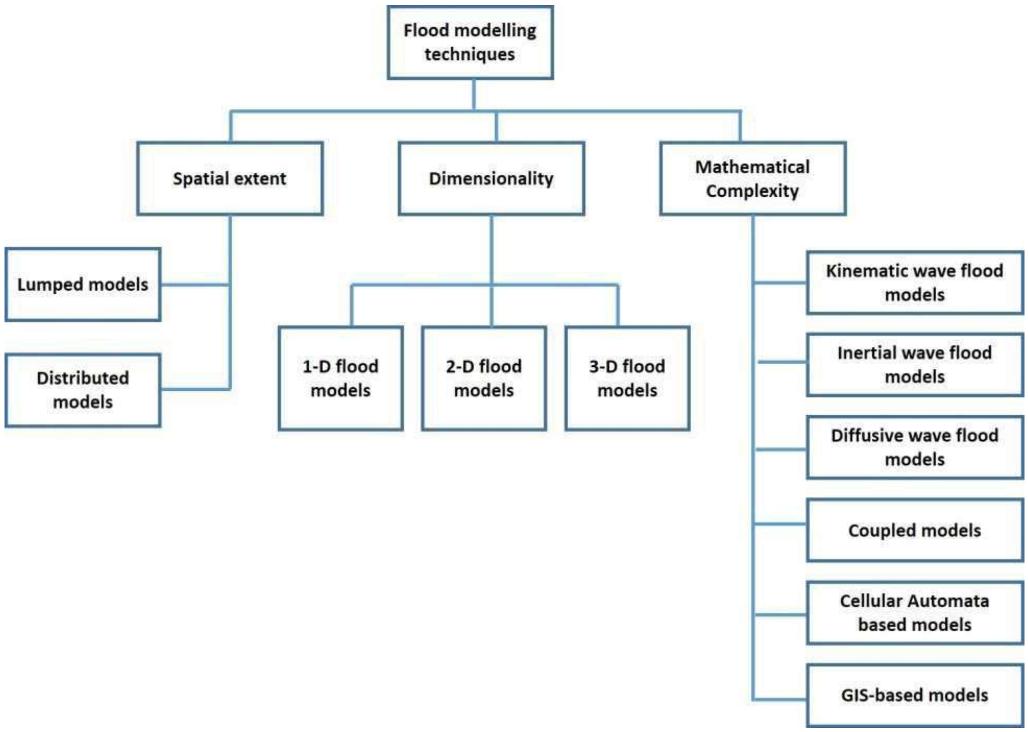


Figure 5-1: Classification of flood modelling methodologies.

5.3.1 Lumped flood modelling

Lumped flood modelling, also referred to as hydrologic flood routing, is a procedure to predict flood inundation as a function of time at a particular location within the catchment (Bedient *et al.,* 2008). Flood models resulting from such techniques are simple to develop, and they apply the hydrologic principle of continuity relation that links inflow, outflow and change in storage (Samani & Shamsipour, 2004). They also utilize mathematical and statistical concepts to represent and solve hydrological problems and a number of flood models are based on this technique. However, their applications in water flow problems, such as urban flooding, have been limited (Ludwig *et al.,* 2003).

Table 5-1: Summary of flood modelling tools available in the literature.

S/no.	Author(s) (Date)	Model name	Model Type & Dimensionality	Main Assumption	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
1.	Army Corps Of Engineers (ACOE) (1995)	HEC-RAS	1-D Hydraulic	Basically, the model solves the one dimensional energy equation for steady flow. However, it can solve the full 1D shallow water equation for unsteady flows.	One-dimensional energy equation to solve for friction and contraction	Implicit finite difference solution	Open source. However, user assistance is limited to ACOE users.	Extensive documentation, suitable for a wide-range of data quality, easily adaptable and easy to set up.	Model instability and limitation in environments that require multi-dimensional modelling.
2.	Army Corps Of Engineers (ACOE) (1992)	HEC-HMS	Hydrologic	Primarily designed to simulate the precipitation run-off process of dendritic drainage basins. Also capable of solving a range of hydrologic problems	Different statistical and mathematical concepts describing physical processes are used in modelling.	Analytical solutions of underlying mathematical representation of hydrologic processes.	Open source. However, user assistance is limited to ACOE users.	Extensive documentation, suitable for a wide-range of hydrologic applications and amenable for integration with other software.	Would generally fail under dynamic flood simulation conditions.
3.	Halcrow, (now CH2M HILL) (2009)	ISIS-2D	2-D Hydraulic	Designed to work either standalone or within the ISIS suite	Full two-dimensional shallow water equations	Alternating Direction Implicit (ADI) , FAST and Total Variation Diminishing (TVD)	Commercial	Wide range of clientele. Suitable for hydrodynamic flood simulation.	Slow simulation speed and requires a high resolution topographic data.
4.	Halcrow (now CH2M HILL) (2008)	ISIS-1D	1-D Hydraulic	Designed primarily for modelling water flows and levels in open channels and estuaries.	Full one-dimensional shallow water equation	Muskingum-Cunge scheme for steady state and 4-point Preissmann scheme for unsteady state.	Commercial	Suitable for steady, unsteady, subcritical, supercritical and transitional flows	Assumes velocity normal to cross section and not suitable for dynamic flood simulation
5.	Halcrow (now CH2M HILL) (2009)	ISIS - FREE	Coupled 1-D/2-D Hydraulic	Provides an advanced one-dimensional (1D) and two-dimensional (2D) simulation engine, analysis and visualisation tools.	One-dimensional and two-dimensional shallow water equations.	Alternating Direction Implicit (ADI) , FAST and Total Variation Diminishing (TVD)	Open source	Suitable for wide range of applications including urban areas, coastal and river channels.	Limited to 250 1D nodes and 2500 2D cells.
6.	Halcrow (now CH2M HILL) (2011)	ISIS-FAST	Simplified 1-D / Simplified 2-D	Quick simulation of flooding using simplified hydraulics	Simplified shallow water equations	FAST solvers	Commercial	Simulation speeds are up to 1,000 times quicker when compared to traditional 2-D flood models	Requires high resolution data and is commercial software.
7.	Bates and De Roo, (2000)	LISFLOOD-FP	Simplified 2-D	A raster-based hydraulic model that is assumed to possess the simplest hydrologic process representation.	One-dimensional Kinematic and two-dimensional diffusive wave equations.	Explicit finite difference solution.	Research	Extensive documentation, easily adaptable and simple to set up	Requires a high resolution topographic data for simulation.
8.	De Roo, A.P.J., Wesseling, C.G. and Van Deursen,	LISFLOOD	GIS-based distributed hydrologic model	LISFLOOD is a GIS-based hydrological rainfall-runoff-routing model.	One-dimensional Kinematic wave equation	4-point implicit finite difference solution and analytical solutions of other hydrological	Research	Wide range of applications including simulation of interception of rainfall by vegetation, evaporation of intercepted	Not a stand-alone code. It requires a base platform of PCRaster modelling environment.

	W.P.A. (2000)					components.		water and Leaf drainage.	
9.	DHI (1997)	Newer MIKE 11	1-D Hydraulic	Developed to simulate flow and water level, water quality and sediment transport in rivers, flood plains, irrigation canals, reservoirs and other inland water bodies	Full one-dimensional Saint Venant equations, diffusive and kinematic wave approximation	Muskingum method and Muskingum-Cunge method for simplified channel routing	Commercial	complemented by a wide range of additional modules and extensions covering almost all conceivable aspects of river modelling	Limited to rivers and fluvial-related flood events. Model can be unstable under two-dimensional flood conditions.
10.	DHI	MIKE 21	2-D	Developed to simulate flows, waves, sediments and ecology in rivers, lakes, estuaries, bays, coastal areas and seas in two dimensions	Full 2-dimensional shallow water equations	Implicit finite difference techniques with the variables defined on a space-staggered rectangular grid.	Commercial	Suitable for hydrodynamic flood simulation. Simulates bulk flow characteristics, flow velocity in various directions of flow.	Simulations time steps and model stability are affected by C-F-L condition. Needs to be calibrated.
11.	DHI (2007)	MIKE-FLOOD	Coupled 1-D/2-D Hydraulic	Developed to enhance the independent functionalities of MIKE 11 and MIKE 21	One-dimensional and two-dimensional shallow water equations.	Coupled solution of 1-D/2-D shallow water equations.	Commercial	Satisfactory real-time simulation of flood inundation in river, coastal and urban areas.	Not well adapted in terms of application to many places. Models requires calibration
12.	BMT-WBM (1990)	TUFLOW – 1D	1-D	Simulation of complex hydrodynamics of flood using full 1-D St. Venant equations.	Full one-dimensional shallow water equation	Second order Runge-Kutta finite-difference solution	Commercial	Dynamic linking capability between domains. Fast from computational point of view.	There are uncertainties in solution and are poor at process representation.
13.	BMT-WBM (1997)	TUFLOW – 2D	2-D	Simulation of complex hydrodynamics of flood using full 2-D free surface shallow water equations.	Full two-dimensional free surface shallow water equations	Stelling Finite Difference and ADI	Commercial	Dynamic linking capability between domains. Satisfactory representation of process.	Slow, but dynamically captures bulk flow characteristics.
14.	JBA Consulting (1998)	JFLOW	Simplified 2-D	Designed to address the challenge of process representation. It is basically a simplified physics flood model.	Diffusion wave equation	Explicit finite difference scheme	Commercial	More accurate flood simulation and simple to set up and useful at coarse resolution.	Conditional stability through the C-F-L condition. Unable to account effects of small scale features during flood simulation.
15.	Cardiff University R. Falconer	DIVAST(depth-integrated velocities and solute transport)	2-D	Solution that includes the effects of: local and advective accelerations, the earth's rotation, free surface pressure gradients, wind action, bed resistance and a simple mixing length turbulence model.	Full 2-dimensional shallow water equations	Implicit finite difference technique and the ADI formulation.	Commercial	Unconditionally stable. Constant time steps	Lacks the ability to capture shock resulting from simulation.
16.	Cardiff University	DIVAST-TVD	2-D	To address some limitations inherent in the original DIVAST model.	Full 2-dimensional shallow water equations	TVD-McCormack explicit finite difference scheme	Commercial	Ability to capture shock	Conditional stability

17.	Deltares	SOBEK	2-D	Specially designed for Overland Flow	Two-dimensional Saint-Venant equations	Finite difference Scheme. By means of a rectangular grid	Commercial	The model is capable of handling wetting and drying, spatially varying surface, roughness and wind friction.	Conditional stability
18.	Deltares / Delft Hydraulics	SOBEK	1- D	Specially designed for Rural, Urban and River flows.	One-dimensional Saint-Venant equations	Finite difference Scheme.	Commercial	Breaches can be modelled by means of a complex "river weir" with time dependent properties.	Conditional stability
19.	Électricité de France. (EDF) (2010)	TELEMAC	2-D	Designed to address the challenges of process representation and limitations in channel and floodplain flood modelling	solves the full two-dimensional shallow water equations	finite-element or finite-volume method and a computation mesh of triangular elements	Commercial	It can perform simulations in transient and permanent conditions	Conditional stability
20.	Électricité de France. (EDF) (2010)	TELEMAC	3-D	To address some limitations inherent in the 2-D version of the model	Navier-Stokes equations, whether in hydrostatic or non-hydrostatic	finite-element or finite-volume method and a computation mesh of triangular elements	Commercial	Ability to capture 3-D hydrodynamic features of an area. Suitable for all flood sources	Conditional stability
21.	Nottingham Uni.	TRENT	Full 2-D	A flood model that is able to capture full hydrodynamic properties.	Shallow water equations	Explicit Finite difference scheme	Commercial	Shock capturing ability	Stable at CFL condition, using adaptive time stepping.
22.	Martin & Gorelick, 2005	MOD_freeSURF 2D	2-D	To obtain a more efficient flood simulation through a more robust numerical scheme.	Unsteady state Shallow water equations	Semi-implicit, semi Lagrangian numerical scheme.	Open source	Modularity, computational efficiency and minimum data requirement	Lacks extensive validation.
23.	Ghimire *et al.,* (2013)	CADDIES	2-D	A model that performs optimally at simulating flooding in urban areas.	Rules that govern movement of water in-between cells	Cellular automata	Open source	Fast simulation of flooding	Lacks extensive validation.
24.	Jimmy S. O'Brien	FLO-2D v. 2007.06 and 2009.06	Simple 2-D	Hydrodynamic model for the solution of the fully dynamic equations of motion for one-dimensional flow in open channels and two-dimensional flow in the floodplain.	Full 1-D and 2-D shallow water equations.	Finite difference solutions	Commercial	A combined hydrologic and hydraulic modelling for urban and river flooding.	Bridge or culvert computations must be accomplished external to FLO-2D using methodologies or models accepted for NFIP usage.
25.	Chen et al., (2009)	GUFIN (2009)	Simplified model	A model that simplifies the use of distributed models for urban environment	GIS- based	GIS and infiltration functions	Research	Integrates GIS and quite suitable for urban flooding. Results compares well with numerical codes.	Lacks extensive validation.
26.	DHI Water and Environment	MIKE URBAN 2010	Coupled 1D and 2D	Has the capability to analyse storm sewer networks. Flow conditions associated with weirs, orifices, manholes, detention basins, pumps, and flow regulators can be reflected.	1-D unsteady flow		Commercial	Suitable for flow in urban areas. Integrates GIS capabilities.	Lacks the ability to capture some hydrodynamic phenomenon such as shock and supercritical flows.

5.3.2 Distributed flood modelling

Distributed flood modelling, also referred to as hydraulic flood routing, is more complex, but arguably gives a better result of flood modelling than the hydrologic counterpart. This is because of the many physical parameters such as slope, gravity, friction, etc., which the resulting models attempt to represent, and to simulate flooding, this routing technique solves both the continuity and momentum equations, especially those arising from the SWEs (refer to pages 125-126). In this distributed flood routing technique, flow rate and water level are assumed to vary with space and time within the hydrologic system. This technique has since been the basis for many flood inundation models and has established presence in the literature over many years (Bates & De Roo 2000; DHI 2003). Unlike the hydrologic flood simulation models, hydraulic flood models are more efficient at handling critical concerns – which includes unsteady flow, backwater effects, shocks, supercritical and subcritical flows, gradually varied flows and low friction effects – which often arise when simulating flood in complex urban terrains (Mark *et al.,* 2004; Mignot *et al.,* 2006). Major limitations and critical concerns for the distributed flood modelling are distributed topographic dataset requirements, model instability, and intensive model runtime, and these highlight the importance of the present research (Aronica *et al.,* 2002; Hall *et al.,* 2005; Hunter *et al.,* 2007; Quiroga *et al.,* 2013).

5.3.3 One-dimensional flood models

One-dimensional (1-D) flood models such as ISIS, MIKE 11 and HECRAS represent the channel and floodplain as a series of cross-sections perpendicular to the flow direction and solve either the full or some approximation of the 1-D SWEs. (Samuels, 1990; Ervine & MacLeod, 1999; Haider *et al.,* 2003; Bates *et al.,* 2005). They are the simplest of all flood models, and are characterised by severe limitation in their representation of hydrological processes (Samuels, 1990). They are computationally efficient and lend themselves easily to parameterization using traditional field surveying, without necessarily requiring distributed topographic and friction data (Bates & De Roo, 2000). However, the simplicity of the 1-D flood models is a result of significant neglect of important aspects of flood hydraulics, which often characterize flooding in urban areas (Horritt & Bates, 2001; 2002; Haider *et al.,* 2003).

The predictive capabilities of the 1-D flood models are often enhanced when coupled with two-dimensional models, or other applications such as GIS, although researchers who attempted the idea have recorded some limitations, which is a major issue in relation to urban flooding. Mark *et al. (*2004) used a 1-D flood model coupled with GIS to simulate urban flood inundation for cost-effective planning and management of urban drainage system. Despite the potential within the proposed model, the treatment of a large scale topographic feature such as street channels was clearly the greatest source of inaccuracy. Seyoum *et al.* (2011) used storm sewer model SWMM5, coupled with a newly-developed two-dimensional, zero-inertial overland-flow model to simulate the interaction between the sewer system and the urban floodplain. Results from two case studies demonstrate that such a coupled model can be capable of simulating a realistic flood inundation. However, considerable knowledge of geospatial mapping techniques was essential for the model to be applied in a way that can generate optimum results. These issues prompt researchers towards the use of two-dimensional and three-dimensional flood models.

5.3.4 Two-dimensional flood models

The two-dimensional (2-D) flood models such as TUTFLOW, SOBEK and MIKE 21 solve the 2-D SWEs by means of appropriate numerical schemes (Mignot *et al.,* 2006; Soares-Frazão *et al.,* 2008; Abderrezzak *et al.,* 2009; Dottori & Todini, 2013). Such models have been increasingly applied in the prediction flood of all sources and so far accounts for the optimal performance achieved in flood modelling, although they have been subject to a higher computational cost which often leads to a compromise in grid resolution (Bates *et al.,* 2005). Advances in remote sensing technology (especially through high resolution and high accuracy input data such as airborne LiDAR (Light Detection and Ranging) and Synthetic Aperture Radar (SAR) data) and improved computing capacity seem both to have increased the popularity of two-dimensional models (Hunter *et al.,* 2008). To simulate urban flooding, a major advantage of the 2-D flood models is the comprehensive representation of flow hydrodynamics along with small scale topographic features which seem to have significant contributions to flooding (Yu & Lane, 2006). However, the paucity of this high resolution input datasets in many DCs is a major limitation to the use of 2-D flood models.

5.3.5 Three-dimensional flood models

The three-dimensional (3-D) flood models solve the full *Navier-Stoke equation*s and consider flow of flood water as completely 3-D (Casulli & Walters, 2000; Chen *et al.,* 2003). Indeed, to be able to dynamically represent the physics of water flow, especially in the urban areas, it is worthwhile to apply the 3-D models (Bates *et al.,* 2005). Nevertheless, some authors have argued that such a model would be unnecessarily complex if some assumptions can lead to simpler models that would offer realistic solution (Horritt & Bates, 2001; Hunter *et al.,* 2008). However, input data and high computation cost and other measurable practical challenges seem undermine the practical actualisation and wider application of the 3-D flood models (Ne'elz & Pender, 2009).

5.3.6 Reduced complexity flood models

These reduced complexity flood models (RCMs) or the simplified two-dimensional flood models are an attempt to circumvent the severe limitation on the computation requirement for the physically based models that solve the full SWEs (Rinaldi *et al.,* 2007; Du *et al.*, 2012; Cai *et al.,* 2014; Douvinet *et al.,* 2015). Reduced complexity models (RCMs) are those that generally solve the simpler kinematic, diffusive and inertial formulations or combine two or more simpler equations rather than solve the highly complex full shallow water equations, to simulate flood inundation (Bates & De Roo, 2000; Yu & Lane, 2006b; Hunter *et al.,* 2007; Bates *et al.,* 2010; Vacondio *et al.,* 2015). This class of flood models has been shown to be very useful in making realistic and experimental predictions under appropriately prescribed initial and boundary conditions, and they form the bases of recent progresses in urban flood modelling (Bates & De Roo, 2000; McMillan & Brasington, 2007; Neal *et al.,* 2012).

They are built upon the hypothesis that *'an ideal model should be simple and able to provide the required information whilst reasonably fitting available data'* (Hunter *et al.,* 2007 pg. 210). Thus, RCMs such as LISFLOOD-FP, JFLOW, ISIS-FAST, etc., have been based on simple mathematical complexity, and the means to represent physical components of flooding within a simple mathematical framework has been a major debate within flood modelling research (Bates & De Roo, 2000; Yu & Lane, 2006).

Simple hydraulic process representation is the driving principle of the RCMs. This group of models attempt to overcome those limitations inherent in the one-dimensional, full two-dimensional and three-dimensional flood models. The RCMs present less of a computational burden, and often require data at various resolution (Hunter *et al.,* 2007). However, debates are still on-going regarding the degree of reduction in the shallow water equations to make a RCMs potentially viable for accurate flood risk assessment (Moussa & Bocquillon, 2000; Neal *et al.,* 2012). The question of how to represent hydraulic variables such as acceleration, friction, slope, gravity, mass and momentum in an optimal and dynamic fashion, considering the required model accuracy and availability of input data remains debatable and so far unrealistic (Horritt & Bates, 2001; Hunter *et al.,* 2006; Moussa & Bocquillon, 2009). Whilst there are clear justifications for model simplifications, the limitation placed by the uncertainty in the representation of these variables constrains the applications of RCMs for simulating flood inundation in complex urban environments (Hunter *et al.,* 2007; Fewtrell *et al.,* 2011). However, on the basis of cost-benefit analysis, it can be argued that focusing on immediate needs in the DCs for flood data, which address economic limitations and the lack of coping capacity of the vulnerable population, should outweigh considerations for reducing model uncertainty. Therefore, more investigations towards developing bespoke flood models which explore the potentials within freely available datasets for flood risk assessment, arguably need to be emphasised.

The momentum equation 5-4 (refer to page 126) which expresses the relationship between velocity and mass of a fluid in motion is fundamental in the development of RCMs, in which a simplified versions of the SWEs is solved. To obtain a RCM, term(s), which the modeller considered negligible for a particular flood simulations procedure are excluded from the momentum equation. Indeed these simplifications reduce model complexities, but they are also based on assumptions which appear to increase epistemic uncertainties which correspondingly increase the limitations in flood model (Pechlivanidis *et al.,* 2011). However, the level of simplicity within a model, considering practical significance and accuracy remains largely unknown (Hunter *et al.,* 2007). This creates much gap in the current literature, in relation to the development of an ideal model (Ward *et al.,* 2015). In spite of this limitation the contributions of the RCMs, using kinematic, diffusive, and inertial equations, over the years towards mapping and assessment of flood risk have been significant (De Moel *et al.,* 2009). This is despite the lack of quality data in many environs which limits model calibration, the complexity of many urban environments and the accuracy requirements of flood modelling, all of which constrain model applications to external locations (Fewtrell *et al.,* 2011).

5.3.6.1 Kinematic wave equation

Kinematic wave equations (KWEs) or kinematic wave approximation is an equation within the RCM framework that represent the simplest form of SWEs most widely applied to flooding and other water flow phenomena (Pappenberger *et al.,* 2005, 1981; Bates & De Roo, 2000; Liu *et al.,* 2004; Bradford & Sanders, 2002; Bates *et al.,* 2005; Patro *et al.,* 2009). LISFLOOD-FP is a well-known flood model based on the KWEs. Such approximation assumes that inertial and pressure terms in the momentum equation of the full SWEs are negligible so that the equation refers to the study of fluid motion exclusive of the influence of mass and force. For the KWEs, friction is equal to slope (see equation 5-5 below), representing a steady state uniform flow. Solutions to the momentum equation are easily derived by substituting equation 5-5 with an equation describing uniform flow, such as the well-known Manning's formula (equation 5-6 below). Thus flood models based on KWEs are described using the continuity equation and a momentum equation substituted with equation 5-8. In terms of wave speed, the wave representation of the model can be compared to a monoclinal wave in which the dimensionless Froude number (*Fr*) is less than 2 (Bedient *et al.,* 2008).

$$S_o = S_f$$

Equation 5-5: Kinematic model

$$S_f = \frac{V^2 n^2}{R^{\frac{4}{3}}}$$

Equation 5-6: Manning's formula

Since the publication by Lighthill & Whitham (1955), which first named and described the KWEs, a plethora of work has been done in solving the equations, and applying the principle to flood simulation generally (Miller & Cunge, 1975; Bates & De Roo, 2000; Looper & Vieux, 2012). In overland flow, simulation of flood inundation benefits from kinematic simplifications, given the continuous addition of lateral flow (Horritt & Bates, 2001). For channel routing applications, such simplification appears to predict a steeper wave with less dispersion and attenuation than actually occurs. The effect of the accumulation of errors in such models show that such simplification is not generally justified for most channel routing applications (Bedient *et al.,* 2008, pg. 275-277). The suitability of models based on KWEs for simulating flooding in urban areas is not well investigated. The presence of backwater effects along with other dynamic flow characteristics (which are not well-accounted for in kinematic wave theory), can undermine the applications of models based on such simplification for flood inundation predictions in urban areas.

5.3.6.2 Diffusive wave equation

The diffusive wave equation (DWEs) or diffusive wave approximation is considered a good trade-off for computation efficiency between the complexity of the full SWEs and the simplified kinematic wave model (Moussa & Bocquillon, 2009). With a well-established assumption for solving unsteady and full dynamic flows, the DWEs exclude inertia and mass from the momentum equation and retains pressure, slope and friction terms (See equation 5-7) (Hunter *et al.,* 2008).

$$\frac{\partial y}{\partial x} - \left(S_o - S_f\right) = 0$$

Equation 5-7: Diffusive model

Similar to the kinetic models, flood models based on DWE consists of the continuity equation and a new equation formed by substituting a uniform flow equation into equation 5-7. Such models are vital when it is required to simulate water flow driven mainly by gravitational forces and dominated by shear stress, that is, under uniform and fully developed turbulent flow conditions especially in the presence of overbank flow. They are also applicable to flood wave propagation in stream channels and for modelling gradually varied flow models (Alonso *et al.,* 2008; Moussa *et al.,* 2007). Yu & lane (2006a) proposed a diffusive wave flood model that simulates fluvial flooding in an urban area. The model performed optimally when tested on River Ouse Yorkshire, UK, despite the high resolution data requirement. To apply such models in urban catchments, given the tendency for topography effects to modify water flow characteristics, more enhancements are needed to capture supercritical effects, and this is a major limitation (Bates *et al.,* 2010).

5.3.6.3 Simple inertial equations

Simple inertial equation (SIEs) recently began to receive attention since it was first proposed more than three decades ago (Cunge *et al.,* 1980). The equation is driven by the need for a flood model which is able to capture supercritical effects, thus enhancing model suitability for urban areas (Bates *et al.,* 2010). In principle, simple inertial equation approximates the SWEs by neglecting the advective acceleration term in the momentum equation (See equation 5-8).

$$\frac{\partial Q}{\partial t} + gA\frac{\partial y}{\partial x} - gA\left(S_o - S_f\right) = 0$$

Equation 5-8: Simple inertial model

From equation 5-8, y can be made equal to the sum of water flow depth (h) and elevation (z) and the third term ($gA(S_o - S_f)$) can be substituted with equation 5-9 (Manning's uniform flow formula: refer to page 139) to account for friction slope, and approximating hydraulic radius *R* to water flow depth. Thus equation 5-9 is derived which forms the basis of flood models driven by simple inertial assumption (Refer to Almeida *et al.,* 2012; 2013 for details of how this equation was derived).

$$\frac{\partial Q}{\partial t} + gA\frac{\partial(h+z)}{\partial x} + \frac{gn^2|Q|Q}{h^{\frac{4}{3}}A}$$

Equation 5-9: Simple inertial model 2

Analogous to all other approximations of the SWEs, simple inertial equations retain the continuity equation and equation 5-9. Unfortunately, there have been limited investigation into these equations, and this appears to undermine a nuanced understanding of the performance of inertial equation across various terrains including urban areas. However, with the results obtained from studies by Bates *et al.* (2010) and Fewtrell *et al.* (2010), there are significant prospects and potentials associated with the application of such equation for modelling flooding in urban areas.

Collectively, these groups of RCMs models have so far provided realistic applications in the areas of urban flood modelling (Bates *et al.,* 2010; Liu *et al.,* 2015). Simple process representation is the main aim in adopting this class of flood models, whilst they seem to present less of a computational burden at different resolution, and attempt to overcome those limitations inherent in the one-dimensional, full two-dimensional and three-dimensional flood models. However, in view of urban flood modelling, there are still debates within flood modelling research regarding the criteria for approximating the SWEs, modelling of wetting and drying, treatment of source terms, and formulation of optimal numerical solutions (Moussa & Bocquillon, 2000; Tsai 2003; Bates *et al.,* 2010; Neal *et al.,* 2012; Medeiros &Hagen, 2013).

Various investigations have been carried out to establish the criteria for simplifying or approximating the SWEs (Vieira, 1983, Moussa & Bocquillon, 2000; Tsai 2003; Hunter *et al.,* 2007). Theoretical considerations such as computational efficiency and stability have been debated as fundamental for simplifying SWEs (Hunter *et al.*, 2007). Vieira (1983) compared various solutions of the full SWEs with those of the simplified versions for a range of non-dimensional Froude and wave numbers. Results show that for any boundary condition, zones defined within the Froude numbers appear to be the basis for simplifying the SWEs. Moussa & Bocquillon (2000) used 'linear perturbation theory' to analyse the different terms in the SWEs, and expressed flood waves as functions of three non-dimensional variables, including the ratio between inundation extent and the width of the main channel. Finally, different inundation extents were analysed and compared. Results show that increasing inundation extents restrict the rationale for simplifying SWEs. This situation is a research problem which presents the opportunity to test novel ideas in flood modelling, and this is what the present research entails.

5.4 Numerical solutions to shallow water equations

Numerical solutions to SWEs and their simplifications form important aspects of flood modelling procedure (Cunge *et al.,* 1980). Over the years various numerical schemes have been formulated to solve various hydrodynamic problems especially in the computational mathematics and flood modelling literature (LeVeque 1997; Casulli 1990; Bates *et al.,* 2010). Some of the widely applied numerical schemes include the characteristics schemes, explicit and implicit finite difference schemes, semi-implicit finite difference schemes, finite element, and finite volume numerical schemes (LeVeque, 1997; Bradford & Sanders, 2002; Quaterronin & Valli, 2008; Abderrezzak *et al.,* 2009; Johnson, 2012; Casulli 2014; Dumbser *et al.,* 2015). The growing ideology that underlies these developments is the provision of an unconditionally stable hydrodynamic solution within a relatively convenient computation cost (Casulli 2014). Recently, effort has been made to improve the computational integrity of TELEMAC-3D numerical model by the inclusion of 'culvert functionality' (Teles *et al.,* 2015). Despite these progresses, the solution to model instability and computation cheapness remains a lingering debate.

The method of characteristics is one of the early numerical schemes designed to make the SWEs tractable. The scheme is adapted to modelling flood flows using uniform mesh of grids, although its performance has been relatively poor in relation to conservation of mass and momentum and capturing shocks and discontinuities (Freeze, 1972; Duchesne *et al.,* 2001). Finite volume and finite element schemes are more complex schemes, but are well adapted to all characteristics of grids (Cockburn et *al.,* 1989; Bassi & Rebay, 1997; Wang, 2002; Jenny *et al.,* 2003; Johnson, 2012). Explicit and implicit finite difference schemes (FDS) earned their popularity in flood modelling due to their suitability to structured grids (Bates & De Roo, 2000; Horritt & Bates, 2001). When computation of water levels and velocity are made using already known components of the SWEs equation, the computation is known as explicit. However, when such computations are without recourse to any previously obtained values, the method is implicit.

Flood models based on explicit schemes are computationally inexpensive, however they are unstable. For their stability, such models tend to apply the Courant-Freidrichs-Lewy (CFL) condition which prescribes small time steps for model implementation, and this is a critical limitation which the present research has attempted to overcome. Flood models based on implicit schemes are unconditionally stable, but require extensive computer time to run. Within flood modelling research, concerns for computational intensiveness and stability of models have remained an on-going debate because of the significant attention which numerical flood modelling has received in the literature (Wu, 2004; George, 2011).

The semi-implicit finite difference scheme (SIFDS) emerged as a compromise between computational intensiveness and conditional stability of models is one of the potential workarounds (Casulli, 1990). The scheme was meant to couple the computation cheapness of the explicit scheme and the unconditional stability of implicit scheme in a single model for simulating floods. Various investigations carried out on the scheme indicate its robustness and suitability for various water flow dynamical settings (Casulli & Stelling, 2011; Dumbser & Casulli, 2013; Wong *et al.,* 2013). However, their applications to full or simplified versions of the SWEs have not been adequately studied, although Almeida *et al. (*2012) used the scheme to improve the predictive ability of an inertial flood model in low friction. Applications in urban flood modelling are little researched (Casulli & Stelling, 2011). Moreover adapting the scheme to a new mathematical philosophy such as cellular automata has not been attempted. Thus, the flood model developed in the present research is an attempt to advance the knowledge of SIFDS.

5.5 Additional techniques for simulating water flow dynamics

Due to the inherent difficulty in solving the SWEs to obtain distributed or lumped flood models, flood modellers are now proposing methodologies which utilize mathematical rules and data analyses techniques. Although there are a couple of techniques within this category that exist in the literature (refer to: Cunnane, 1988; Wheater, 2002; Wheater *et al.,* 2005), GIS-based flood modelling and Cellular Automata (CA) based modelling techniques are two techniques that are being used extensively.

5.5.1 GIS-based flood models

Within environmental and flood modelling literature, the application of GIS for flood hazard assessment and mapping are well researched (Boonya-aroonnet *et al.,* 2007; Merwade *et al.,* 2008; Dawod *et al.,* 2011; Sarker & Sivertun, 2011; Paquette & Lowry, 2013) Many hydrologic and hydraulic flood models incorporate GIS capabilities, and are often applicable to flood hazard assessment and mapping operations, data synthesis and analyses, as well as output visualization (Chen *et al.,* 2009; ISIS: Halcrow, 2009). Chen *et al.* (2009) proposed a GIS-based urban flood inundation model, GUFIM, which comprised of two components (storm runoff and inundation models). Results obtained from University of Memphis, Tennessee case study suggest that GUFIM can be a potential alternative to highly complex physically based models.

Despite these efforts, a significant factor that often constrains the use of GIS as a tool in flood modelling is the acquisition cost of GIS software, copyright restrictions and technical difficulties (Steiniger & Hunter, 2013). A number of widely versatile GIS software are capital intensive, whilst many open source versions do not incorporate flood simulation tools. Diversity of standards for input data also constrains the applicability of GIS for flood modelling. For example most LiDAR data are compressed in file extensions (for example *.las* format) that are unrecognised by most GIS. Although these limitations are being overcome, many end-users who undertake routine black box flood modelling operations especially in the DCs have yet to access the full potential of GIS.

5.5.2 Cellular Automata (CA) based flood models

CA basically consists of a set of mathematical procedures that solve complex physical problems using cellular systems in which time is discrete and a set of universal laws apply. The idea was first proposed by Von Newman and Stanislav Ulam in the 1940s (von Neumann, 1951). Several applications in physical systems, especially in biological and physical sciences spans many decades of research (Ermentrout & Edlestein-Keshet, 1993; Ilachinski, 2001). Recently, a number of water flow applications, linked to flooding have been reported, and these offer suitable solutions to complex hydrological systems (Rinaldi *et al.*, 2007; Parsons & Fonstad, 2007; Dottori & Todidni, 2010; Cai *et al.,* 2014). It is claimed that hydrodynamics simulated with CA compare well with those of traditional hydraulic and hydrologic techniques (Ghimire *et al.,* 2013). Thus, CA is being considered in recent times as a potential alternative to the often intractable numerical solutions of the shallow water equations (Cai *et al.,* 2014).

Research into the applications of CA to modelling flooding is still emerging. New directions of research have included the optimisation of time step and boundary conditions, analysis of neighbourhood relationship, to improve the accuracy of flood simulation, uncertainty analyses and synergistic application of CA principles with numerical flood modelling techniques (Parson & Fonstad, 2007; Cirbus & Podhoranyi, 2013). Dottori & Todini (2011) incorporated the local adaptive time step algorithm proposed by Zhang *et al.* (1994) and the inertial formulation adapted to Bates *et al.* (2010) LISFLOOD-FP into a CA-based flood model developed in Dottori & Todini (2010). The idea of adaptive time stepping was applied in Ghimire *et al.* (2013), to develop a fast 2- dimensional urban simulation model based in CA. Li *et al.* (2013) combined a hydrologic flood model with a CA-based model to analyse a multiple sets of geographic layers, in order to develop a mechanism that can be conveniently integrated into a digital earth system for real-time simulation and analyses of dam-break flood risks.

Results of several real and hypothetical test cases emerging from these synergistic applications show that the functionality of CAs is significantly enhanced by integrating numerical procedures, and this is often without a corresponding loss of accuracy in the results. Dottori & Todini (2011) reported that the use of inertial formulation and local time step algorithm in the modified model increased the simulation speed by up to a multiple of four, reducing the model run time by approximately 97%. The computation time for the CA developed in Ghimire *et al.* (2013) was found to be much less than it is for an urban inundation model (UIM) developed by Chen *et al.* (2009). It was shown that whilst the CA required about three minutes of processing time on a small desktop computer (Intel Pentium-D CPU with 3 GHz processor, and 1 GB RAM), the UIM required nearly ninety-eight minutes.

However, there were some limitations, given that the CA model performed poorly in reproducing two-dimensional flow dynamics as in one-dimensional cases. These were found to be comparable with the uncertainties related to available data for actual flood events (Dottori & Todini, 2011). When we consider that paucity of data is a major cause of limitation in flood modelling, the need for more work towards optimising the functionality of CAs, to enable their applications in a wide range of case studies, becomes a growing research concern. In this regards, the possibility that there remains much to be known about how to tackle this challenge is a key hypothesis that should drive more research into the development CA-based flood simulation models. New directions of research should also include how to improve the accuracy of flood simulation, uncertainty analyses and integration of CA principles with numerical flood modelling techniques (Parsons & Fonstad, 2007; Cirbus & Podhoranyi, 2013).

5.6 Calibration of flood models

Uncertainties are unknown possibilities that accompany models which need to be found in order to assess the level of model's reliability and integrity (Horritt & Bates, 2002; Pappenberger *et al.,* 2005; Liu, 2009). They sometimes account for the variations between model predictions and observed or real world data (Fewtrell *et al.,* 2011). The ubiquitous nature of uncertainty in flood hazard prediction and flood risk assessment and the need for its estimation and communication to other professionals and decision makers is now widely acknowledged (Krzysztofowicz 2001; Todini 2007; Faulkner *et al.,* 2007; Hall *et al.* 2011; Pappenberger *et al.,* 2008). In flood modelling, estimation of uncertainties is a crucial stage of work to understand these variations (Bates *et al.,* 2006). Whilst the sources of uncertainties in flood modelling principally include the design of the model itself, parameters that are considered and the input data (Merwade *et al.,* 2008), the communication of their estimates assures confidence when using the models in decision making and promotes proactive strategies and measures towards flood risk management (Hall *et al.*, 2011; Jung & Merwade, 2011).

Calibration is somewhat a procedure to address the challenges of uncertainties. It seeks to find appropriate values, which will ensure that model yields realistic predictions irrespective of geographical locations (Hunter *et al.,* 2005; Pappenberger *et al.,* 2007). The significance here is to know to what extent a model can be applied to other geographical location within the context of scale and availability of input data (Wiechel *et al.,* 2007). In the calibration procedure, the model parameters are adjusted within the boundaries of uncertainty to reach a goodness-of-fit in model prediction of reality (Mason *et al.,* 2009). Within the context of flood modelling, a wider application of existing flood inundation models for assessing human, environmental and economic impacts of flood inundations is being undermined by limited external calibration (Hunter *et al.,* 2005). However, since the last two decades, several attempts to calibrate flood inundation models have been extensively discussed in the flood modelling literature (Beven & Kirkby, 1979; Horritt 2000; Mason *et al.,* 2009; Di Baldassarre *et al.,* 2009; Leandro *et al.,* 2011), although it is still argued that existing flood models have not reached the acceptable calibration limit (Hunter *et al.,* 2007; Fewtrell *et al.,* 2011). This is due to the lack of appropriate calibration data, which has a critical concern in flood modelling and flood risk assessment research (Bates & Horritt, 2002; Bates *et al.,* 2010; Beven & Hall, 2014; Sun *et al.,* 2014).

At present, progress in remote sensing technology is increasing the availability of appropriate data for model calibration (Bates *et al.,* 2005). However, within the poor localities such as in the DCs in which Lagos is an example, the cost of acquiring these data and other technical considerations remain major challenges to full utilisation of remote sensing technology in order to harness the potentials of model calibration. However, studies are still underway towards the means of addressing this present limitation, which seems to inform goals of many flood modelling exercises (Chen *et al.,* 2009; Bates *et al.,* 2010; Almeida *et al.,* 2012; Samson *et al.,* 2013). No study to the author's best knowledge has provided the means of addressing these limitation and gaps within Lagos context, to enable application of ensemble, research and open source flood models. Although calibration was not carried out in the present research, it is still an important discussion towards a critical understanding of the causes and implications of limited applications of flood modelling in Lagos case study which is the basis of the present research. Consequently, given the urgent need to improve flood risk management in the area, a logical alterative is the development of a bespoke flood model that will take advantage of easily accessible datasets, and this is what the present research does.

In addition to calibration of flood models to reduce uncertainty, researchers also suggest sensitivity analysis to assess how robust a scheme is to varying assumptions (Beven & Binley, 1992; Aronica *et al.,* 1998; Beven & Hall, 2014). While uncertainty analysis is typically a direct problem, that is can applied in situations where quantities in a system under analysis are precisely unknown or need to be determined, however, sensitivity analysis can be thought of as addressing the inverse of a problem and in revealing the effects of model input variables on the overall variation in the model prediction (Hall *et al.,* 2005). It identifies the factors that demonstrate the most significant influence on model output, those that show null contributions and those that may need further investigation to improve on their contribution is fundamental (Hall *et al.,* 2009; Hall *et al.* 2011). Uncertainty analysis involves estimation of uncertainties in model inputs and apportioning them to model predictions (Hall & Solomatine, 2008). Sensitivity analysis assists with the understanding of the performance of a flood model to various parameters, for example topography and Manning's friction coefficient (Saltelli *et al.,* 2004; Bates *et al.,* 2006). It generally examines how the variation in model prediction can be apportioned to different sources of variation (Campolongo *et al.,* 2007).

Uncertainty and sensitivity analyses are now routine procedures that provide a general basis for evaluation of model behaviours and performance (Romanowicz *et al.,* 1994; Aronica *et al.,* 2002, Pappenberger *et al.,* 2005). Within this context, a major concern is the lack of uncertainty and sensitivity analyses procedures that possess the robustness and complexity which can match with existing flood inundation models (Hall *et al.,* 2009; de Moel *et al.,* 2014). Over the past the two decades a number of methodologies for sensitivity and uncertainty analyses have been reported in hydrological engineering and flood modelling literature (Hall *et al.,* 2005; Pappenberger *et al.,* 2008). These approaches (for example, Bayesian uncertainty estimation, Generalized Likelihood Uncertainty Estimation (GLUE), Monte Carlo Simulations (MCS) and Linear regression analysis) are based on complex statistical analyses and rigorous mathematical modelling (Aronica *et al.,* 2002; Oakley and O'Hagan 2004; Yu *et al.,* 2015). Whilst there are special considerations for using a particular methodology, Hall *et al.* (2009) reviewed a range of existing methodologies for sensitivity analysis and indicated that there are potentials and limitations associated with various existing methodologies. These limitations can often lead to misleading conclusions, in which sensitivity analysis fails to replicate the actual model behaviour. However, the choice of methodology can be based on empirical and economic factors (Hall *et al.,* 2009).

5.7 Summary

Flood modelling is a procedure to characterise flooding in terms of water depth, extent and flow velocity. The continuity relationship between key hydrological components underlies the formulation of mathematical frameworks for a realistic flood modelling methodology. Irrespective of the type of flooding, there are a number of potential limitations in the current flood modelling methodologies, and these necessitate the need for research. Existing flood models, classified in terms of spatial extent, dimensionality and the complexity of the shallow water equations, which form the governing mathematical framework, are either overly simple or downright complex to be applicable in many urban environment, where lack of appropriate data and technology to run these models are major limitations.

The plethora of flood models, especially those developed on the basis of reduced mathematical complexity, including those based on GIS and Cellular Automata (CA) frameworks seem to provide a solution to the limitations in flood modelling. However, the prevailing lack of model calibration in external locations and limited funds to acquire existing models hamper a wider application of such models particularly in the urban locations within the DCs such as Lagos considering the limitations posed by lack of data. For the Lagos area, this issues, among others that confront a realistic management of urban flood risk, has necessitated the need to develop a new flood model in the present research. The development and technical framework of this new flood model are discussed in the next chapter, while its application, which is expected to stimulate new scientific discussions that will advance the philosophy of urban flood risk management in Lagos and other places within the DCs, further highlights the potential impacts of the present research.

6 *GFSP-1*: The Development and Technical Framework

The main aim of this chapter is to describe the technical framework, and the development procedure of the new flood model, GFSP-1 (Geoinformation Flood Simulation Program - 1), which combines the capabilities of a cellular automata (CA) framework and a semi-implicit finite difference scheme (SIFDS) formulation. The development of this new flood model, a key objective of the present research, is an attempt to provide a flood model useful for Lagos urban flooding. The new model achieve unconditional stability, computation simplicity and minimum data requirement, with regards to characterising urban flood hazard, especially in the Lagos urban area of Nigeria. The innovation in this research is the combination of CA and SIFDS within a flood model framework, and whilst this synergistic arrangement is novel within the context of flood modelling, it advances the current knowledge in flood modelling for urban flood risk assessment.

6.1 CA and its sub-components

Figure 6-1 illustrates the concept of CA showing the properties of a set of three square boxes within a circular cellular space are transformed into two different states 'b' and 'c' from the original state 'a'. This transformation is driven by transition rule, determined by the type of physical property to be transformed. CA is a time explicit technique, which determines the state of a dynamic system during time *t+1* on the basis of the state of the same system and its neighbours at time *t*.

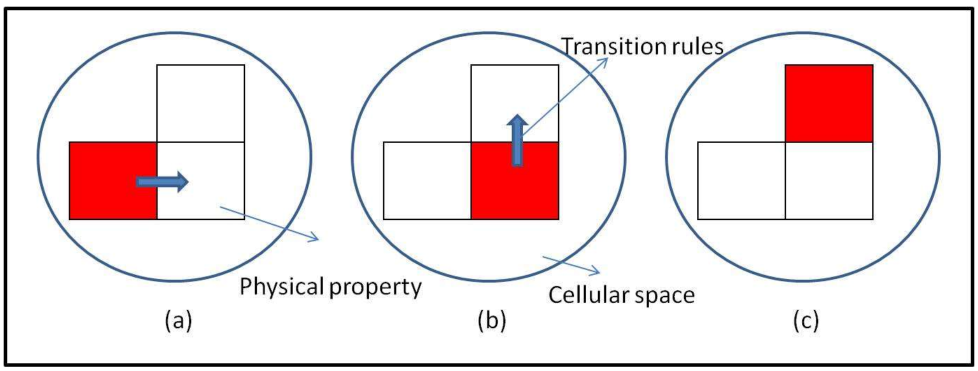


Figure 6-1: Idealisation of a CA showing three square boxes within a circular cellular space transformed into two different states 'b' and 'c' from the original state 'a'.

The CA framework proposed in this research encompasses the four essential features of an ideal CA formulation. These include (1) the mesh of cellular space, which provides the simulation domain; (2) the neighbourhood; (3) a set of transition rule(s); and (4) the boundary condition. This is similar to the idea in other studies such as Parsons & Fonstad (2007), although system state and time step are also important components in CA formulation (Ghimire *et al.*, 2013). Time step and system states are important factors not only for CA formulation, to determine the pace at which the model operations progress, but also in the simulation of dynamic systems elsewhere.

6.1.1 Mesh of cellular space

Mesh of cellular space is simply a framework of grids, which can be defined as a discrete representation of the geometry involved in the physical phenomenon consisting of multiple variables of which only one variables is independent. These grids subdivide the computational geometry into a finite number of triangular or rectangular shaped cells over which the mathematical model expressing multiple variables can be approximated. They can be structured or unstructured depending on the topological relationship and node connectivity (see figure 6-2). Structured grids tend to have fixed nodes connectivity which is not possible with the unstructured, although the latter are generally more flexible and adapts easily to any computational situation. Meshes store the geospatial metadata (longitude, latitude and elevation) of topographic features, and as a result are used extensively in flood modelling and other practical situations (Sanders, 2007).

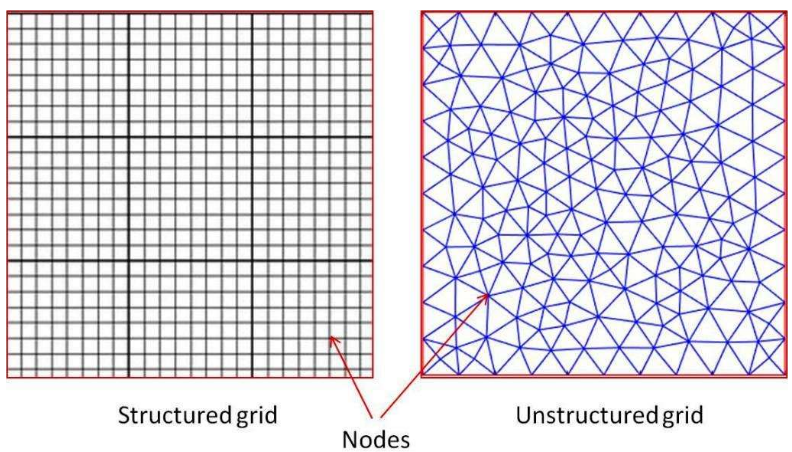


Figure 6-2: Different types of mesh structures that one encounters in practical situations. These are dependent on node connectivity and topological relationship

Mesh structure and resolution for flood modelling are dependent on a number of factors including possible CPU runtime, model stability condition, and the required solution accuracy, and therefore the present research has considered the need for an appropriate neighbourhood system for CA formulation, and enhanced computation speed for the new flood model. These are major issues in flood modelling research which highlight the significance of a topographic model as the basis of a mesh of a cellular space for flood modelling (Horritt & Bates, 2001; Cook &

Merwade, 2009). In this context, researchers (see for examples Sanders, 2007; Erpicum *et al.,* 2010; Tarekegn *et al.,* 2010; Fewtrell *et al.,* 2011) have shown that of all the current topographic models, including 1-*km* GTopo, *90-m* SRTM and *30-m* ASTERGDEM, etc., airborne LiDAR topographic model, for all intents and purposes, is best suited for urban flood modelling, and thus the present research has considered it. This is due to accuracy in its representation of the complex urban geomorphology (Horritt & Bates, 2001; Fewtrell *et al.,* 2011).

6.1.1.1 Airborne LiDAR dataset

Airborne LiDAR is a remote sensing data acquisition technique that uses a laser scanner, an inertial measurement unit (IMU), and a specialized GPS receiver to measure variable distances of earth's features (see figure 6-3). LiDAR creates a three-dimensional point cloud model of the earth and its surface features, and currently represents the most detailed and accurate method of creating DEMs. It is not the intention of the author to discuss further the LiDAR technology in terms of its operational framework, and the wide range of applications. Such discussions can be found in Goodwin *et al.* (2009), Höfle & Rutzinger (2011) and Ussyshkin & Theriault (2011). However, airborne LiDAR technique is capital intensive, and this is an issue of research significance within the context of large scale impacts of urban flooding in the DCs, and how to effectively manage them.

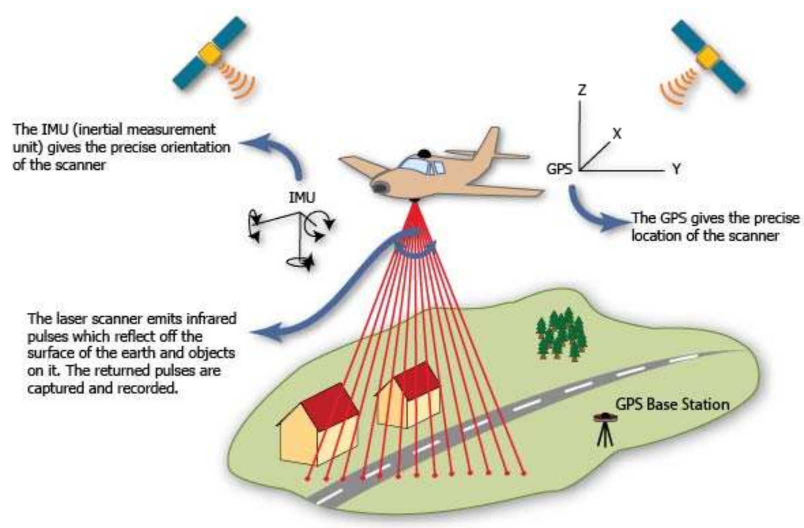


Figure 6-3: Schematics showing the basic components and working principle of LiDAR technology. Source: http://www.qpeak.com/scientific-enterprises

One major advantage LiDAR has in comparison with other topographic models is the ability to filter out reflections from the point cloud model to create a bare earth digital terrain model (DTM), and a digital surface model (DSM), which represents ground surface features such as water bodies, roads, etc., This is a crucial factor, and relevant to flood modelling. However, to be appropriately utilised in flood modelling, LiDAR DEMs requires extensive post-processing, and this is a major issue, which the present research has addressed in relation to the Lagos airborne LiDAR DEM. The datasets were converted from the primitive *'.las'* image compression to the more versatile *'.asc'* format before they could be used in the present research to model the July 2011 flooding in the Lagos area.

6.1.1.2 LiDAR DEM used in the present research

The present research used a *2-m* horizontal resolution LiDAR DEM, which represents earth features in a logically reasonable accuracy, and these are discussed in the test cases presented in chapter 7. This LiDAR data is pliable to being filtered into digital terrain model (DTM) and digital surface model (DSM), although a specific approach is needed to represent two dimensional features in the case of the DTM. This, plus the development of techniques for extracting two dimensional features, are major concerns in urban flood modelling using high resolution datasets (Chen *et al.,* 2012). It would have been faster to run the model using the coarser and freely available DEMs from GTopo, SRTM and ASTER, etc., However, findings by van der Sande *et al.* (2012) and Elmoustafa *et al.* (2015) suggest that using coarser datasets will lead to significant uncertainty in the model outputs in terms of water flow depth and extent as well as flow velocity.

6.1.2 Neighbourhood

Neighbourhood in CA can be defined as a set of objects or points, within a cellular space, whose distance from a given origin is clearly defined. The neighbourhood system is critical to CA (Santé *et al.,* 2010). There are three types of neighbourhood system used in CA – the von Neumann, Moore and Hexagonal (see figure 6-4). The von Neumann type of neighbourhood, which was considered in the present CA framework consist of five cells with the principal cell located at the center of the mesh and four adjacent cells bounding the cardinal directions (east, west, south and north) (figure 6-1a). Simplicity is a key merit of von Neumann neighbourhood (Yamamoto *et al.,* 2007; Xiong *et al.,* 2013). Simulation of dynamic system can be accomplished within a local neighbourhood of five cells, although some studies argue that such limited number of cells forming a neighbourhood system is inadequate to provide a more realistic impression of flow (Cirbus & Podhoranyi, 2013). Hexagonal and Moore neighbourhoods are two other types of neighbourhood systems that are being applied in various CA frameworks. Moore neighbourhood includes the four diagonal neighbours, making a total of 9 cells within the neighbourhood system (figure 6-1b). Recent CA studies are increasingly adapting to the Moore neighbourhood system (for example see, Dijkstra *et al.,* 2001; Liu & Phinn, 2003; Feng *et al.,* 2011). Unfortunately, the difficulty in representing diagonal spacing leads to inaccurate timing of the dynamic systems motion (Parsons & Fonstad, 2007). Hexagonal neighbourhood is an attempt to ensure that all cells within the neighbourhood system maintain a symmetric distance from the principal cell (figure 6-1c). Symmetric distance from the principal cell is required to keep the time needed to move water from cell to cell at uniform value and therefore reduces the computation cost (Nagy, 2003). However, hexagonal neighbourhood system is difficult to work with since they are unsupported by some important fluid flow theories and most GIS databases (Birch *et al.,* 2007).

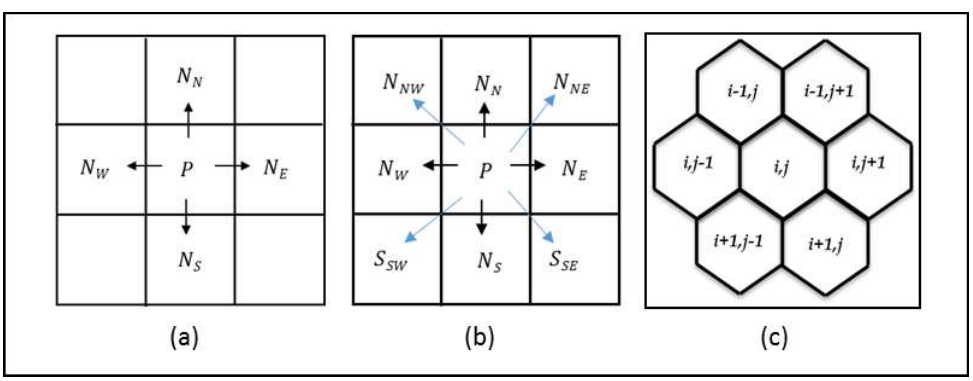


Figure 6-4: Three types of neighbourhood applied in CA. The von Neumann neighbourhood, the Moore neighbourhood and the hexagonal neighbourhood are represented as (a), (b) and (c) respectively. P, N_E, N_W, N_N, N_S, N_{NE}, N_{NW}, S_{SE} and S_{SW} designate the principal cell, the cardinal cells and the diagonal cells respectively. The indices of the cells are given as *i* and *j*.

6.1.3 Transition rules

Transition rules can be defined as a set of principles based on mathematical expressions that direct the CA procedure. This is the most important component of the CA system. The transition rules control how the neighbouring cells interact with each other, and in turn the model performance by dictating what takes place at each stage of the model iteration. CA systems are characterised by different rules, and few studies relating to CA in the literature suggest that there is no standard regarding the number of rules or their functions (Dijkstra *et al.,* 2001; Liu *et al.,* 2008). The basic assumption seems to be that a transition rule must function optimally to accomplish the main objectives of the modelling operation.

In the present CA formation, a set of four transition rules, which are schematised in figure 6-5, were implemented. They include: (1) rule for adding rainfall into the individual cells and excluding abstraction and losses especially through infiltration and evapotranspiration. Although the test cases presented in chapter 7 did not include these losses due to lack of data relating to hydrological losses, sufficient provisions are made for them in the model. The other three rules include: (2) rule for determining the length of time water stays in the cells before distribution, (3) rule for water distribution from the principal cell to the neighbouring cardinal cells and (4) rule for minimum water level which each cell can retain.

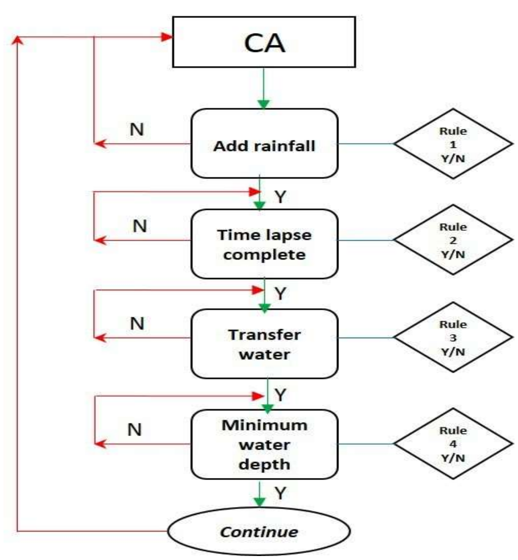


Figure 6-5: Schematisation of transition rules for the present research

The first rule directs addition of rainfall into the model cells. This rule is specifically designed to ensure that effective rainfall depth is added to individual cells at every time step. To implement this rule, a function converts rainfall intensity into effective rainfall depth. If infiltration and abstraction rates are known, the function considers those variables too. The computed rainfall depth is inputted into the model at every time step. Similarly, the second rule that determines the length of time water stays in a cell was adopted from Parsons & Fonstad (2007). The rule uses Manning's formula (*equation 6.1*) to calculate the velocity and then uses this velocity to determine the time it will take the water to leave the cell.

$$V = \frac{h^{\frac{2}{3}} * \sqrt{S_f}}{n}$$

Equation 6-1: Manning's formula with V as the subject

V (LT^{-1}) is the velocity, h (*L*) is the water depth, and S_f (L) is the water surface slope, computed using the method proposed in Zevenbergen and Thorne (1987).

The third rule dictates water movement in-between the cells. It uses simple mathematical proportions implemented on program conditionals to determine the amount of water transferrable from the principal cell to the neighbouring cells. The rule computes the amount of water to be transferred as flux from the principal cell into neighbouring cell using of *equation 6.2*. In actual fact, the differences in water depth between the principal cell and the neighbouring cells drive water movement.

$$flux(i,j) = \frac{(principal\ cell(i,j) - neighbour\ cell(i,j))}{denominator} * water\ in\ principal\ cell$$

Equation 6-2: Flux calculation within cells

The fourth rule accounts for the minimum amount of water that a cell can retain. This rule is not frequently considered in many CA formulations. The rule for water level uses a value to determine this minimum amount of water. In the present model, water depth <= 0.01 is considered zero. By doing this, the model separates flooded cells from empty cells, and thus reflects the concept of wetting and drying which is fundamental in urban flood modelling.

6.1.4 Boundary conditions

Boundary conditions are rules that apply to the cells bounding the margins of the mesh of cellular space. Allowing that these border cells do not have a complete neighbourhood system, certain formulations are applied to them. In the present CA, absorptive and reflective boundary conditions (somewhat like the Dirichilet boundary condition in a regular numerical modelling, refer to: Bazilevs & Hughes, 2007) were used (see figure 6-6). The absorptive boundary is a 'one-way permeable boundary in which case water flowing off the boundaries disappears. Reflective boundary condition assumes virtual cells for the missing sides of the boundary cells for all model variables. The values contained in these virtual cells are considered as nullity, and thus suggest that water does not go beyond the edges. These types of boundary conditions can raise critical issues in relation to modelling flooding over a small section of a larger area. However, the results of investigations in the present research show that restricting water flow by cell edges as a result of using these boundary conditions does not cause significant effects on the simulated flood extent (refer to discussion in Appendix H). Besides the two boundaries mentioned earlier, periodic boundary condition is also known to be applicable in CA (Burstedde *et al.,* 2001; Weng *et al.,* 2006). The periodic boundary is used when the flows across two opposite planes of the mesh of cells are symmetrical. In this case flow is allowed through one end of the boundary in order to re-enter the next grid of cell.

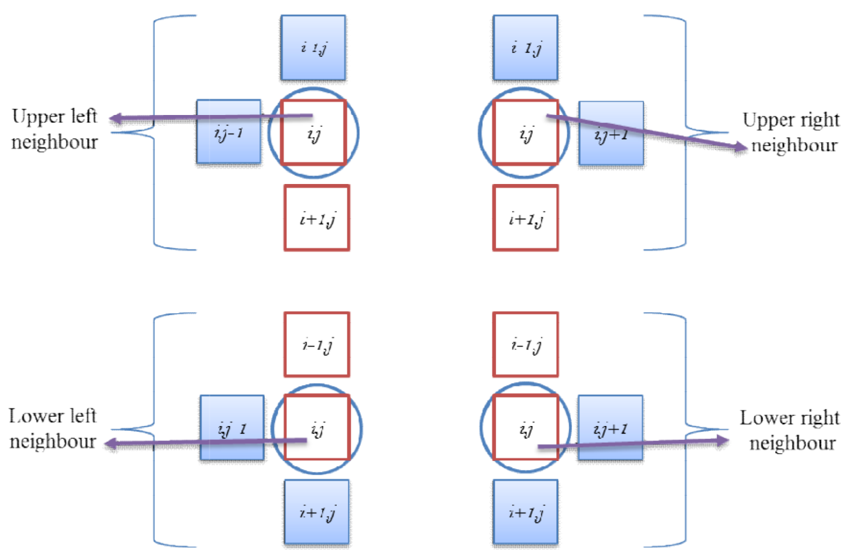


Figure 6-6: Boundary condition imposed on boundary cells in the present research

6.2 The SIFDS

The SIFDS is can be defined as a numerical formulation that provides a solution to the SWEs using a combination of explicit and implicit numerical schemes (Casulli & Cheng, 1992). Explicit schemes are associated with computation cheapness in models, while implicit schemes are associated with unconditional stability, and these are key issues in urban flood modelling. Thus, the SIFDS was a previous attempt, which Casulli (1990) used to incorporated these independent schemes into a single flood simulation model, and to provide a realistic flow solution at a reduced computation cost without compromising model stability.

More recent studies in the literature (see for examples, Martin & Gorelick, 2005; Zhang & Baptista, 2008; Casulli & Stelling, 2011; Tavelli & Dumbser, 2014; Casulli & Stelling, 2013; Casulli, 2014; Dumbser *et al.,* 2015) that considered the SIFDS within the contexts of flood modelling are based on the original work of Casulli (1990). The results of these studies indicate that the SIFDS underlie models that are fast, accurate and mass-conservative, although solution to a large system of equations can be problematic in practical flood modelling situations.

The SIFDS is an important flood modelling tool, but the majority of its applications has been limited to fluvial flooding, especially those resulting from dam break and the failure of other hydrological structures (Casulli & Stelling, 2013; Dumbser *et al.,* 2015). Application of the scheme to urban flooding as well as combining it with other mathematical frameworks has not been adequately studied, and this is what the present research addresses. The new flood model combines the capabilities of this scheme and the CA mathematical framework to simulate pluvial flooding in an urban location. This provides a basis to investigate the response to the physics of flood hazard, demonstrated by the synergistic framework (see figure 6-7).

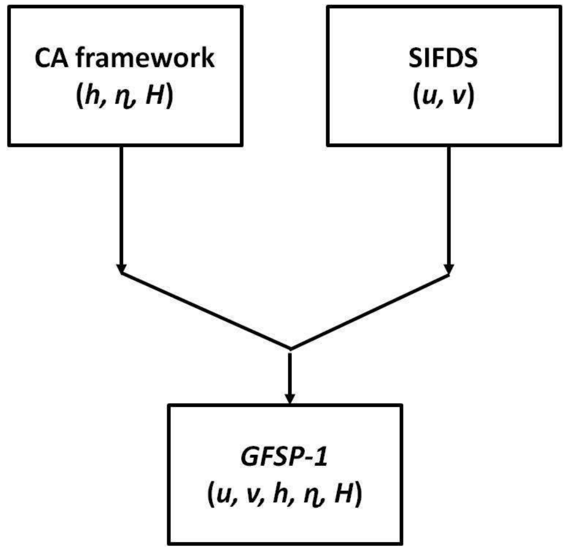


Figure 6-7: Schematisation of the synergistic framework in the present research. The CA framework contributes the water depth and extent, whilst the SIFDS schemes contribute the horizontal velocity components.

The governing equations for the formulation of SIFDS are the SWEs which were presented in chapter 5 (see equations 6-3 to 6-5):

$$\frac{\partial H}{\partial t} + \frac{\partial (HU_x)}{\partial x} + \frac{\partial (HV_y)}{\partial y} = 0$$

Equation 6-3: Continuity equation for SIFDS

$$\frac{\partial (HU)}{\partial t} + \frac{\partial (HUU)}{\partial x} + \frac{\partial (HUV)}{\partial y} + gH\frac{\partial \eta_x}{\partial x} + gH\mathcal{S}_f = 0$$

Equation 6-4: U Momentum equation for SIFDS

$$\frac{\partial (HV)}{\partial t} + \frac{\partial (HUV)}{\partial x} + \frac{\partial (HVV)}{\partial y} + gH\frac{\partial \eta_y}{\partial y} + gH\mathcal{S}_f = 0$$

Equation 6-5: V Momentum equation for SIFDS

H (*L*) is the water depth, t (*T*) is the time, U and V (LT^{-1}) are the horizontal velocity components in the x and y axes respectively, η (*L*) is the free water surface elevation, x (*L*) and y (*L*) are the displacement measures from the origin, g (LT^{-2}) is the acceleration due to gravity, and $\mathcal{S}_f$(-) is the friction slope.

These system of equations form a quasilinear hyperbolic partial differential equation with three unknowns: *U, V* and *H* (or U, V and '*η*' in the non-conservative form), and three independent variables *x, y* and *t.* The starting point to SIFDS is to understand the behaviors of the terms forming these equations. Casulli (1990) performed a characteristics analysis of these equations and derived two parts - one which depends on the fluid velocity (i.e. U and V), and another which depends on celerity (i.e.$\sqrt{gH}$), which also was shown to be the determining factor of model's instability. The latter component was shown to determine the stability of a model. Further investigations by Casulli (1990) indicate that these key terms, *g* and *H,* were found to emerge from the off diagonal terms in the matrices that resulted from the characteristics analysis. From equations 6-3 to 6-5, these terms are coefficients of η_x in the first momentum equation and η_y in the second momentum equation and the coefficient of U_x and V_y in the continuity equation. As a result of this mathematical dependence, Casulli (1990) showed that to obtain a solution whose stability is independent of celerity, it is required that the derivatives of these variables are discretized implicitly. This is the underlying framework of the SIFDS.

In discretizing the system of equations above, a staggered grid, (which consists of a mesh of N_x * N_y rectangular cells of vertical and horizontal lengths, Δ*x* and Δ*y*) is introduced. Each cell is numbered at its center with indices *i* and *j*. The discrete *U* velocity is then defined at half integer *i* and integer *j*, *V* is defined at integer *i* and half integer *j*. The free water surface height, *η* is defined at integer *i* and integer *j* (see figure 6-7).

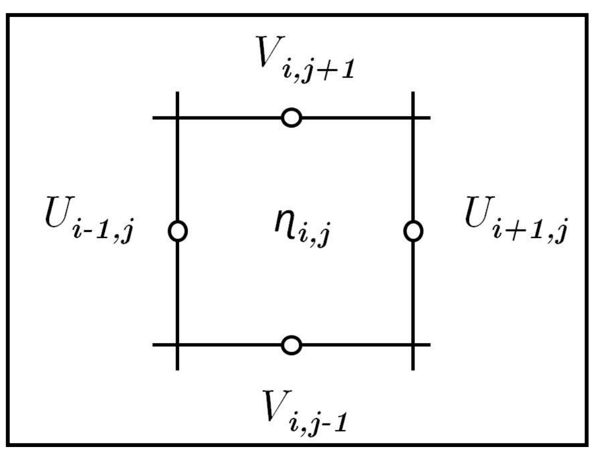


Figure 6-8: Schematic diagram of the discretization of horizontal and vertical velocity and free water surface heights components

Casulli (1990) assumed that the bottom profile was prescribed everywhere, and that the discrete total water depths at the grid locations are enforced to be non-negative. Thus equations 6-6 to 6-8 represent the water depths in theory.

$$H_{i,j}(\eta^n_{i,j}) = max(0, h_{i,j} + \eta^n_{i,j})$$

Equation 6-6: SIFDS water depth at the center of cell

$$H_{i+\frac{1}{2},j}\left(\eta^n_{i+\frac{1}{2},j}\right) = max\left(0, h_{i+\frac{1}{2},j} + \eta^n_{i+\frac{1}{2},j}\right)$$

Equation 6-7: SIFDS water depth when i = 0.5

$$H_{i,j+\frac{1}{2}}\left(\eta^n_{i,j+\frac{1}{2}}\right) = max\left(0, h_{i,j+\frac{1}{2}} + \eta^n_{i,j+\frac{1}{2}}\right)$$

Equation 6-8: SIFDS water depth when j = 0.5

Where $\eta^n_{i+\frac{1}{2},j}$ and $\eta^n_{i,j+\frac{1}{2}}$ are determined from the nearest grid values by taking for example, the average, the upwind or the maximum. Thus, Casulli (1990) derived a semi-implicit finite discrete scheme for equations 6-3 to 6-5 on a staggered grid by using implicit discretization for the free water surface slope in the momentum equations and for the velocity in the continuity equations. This removes the stability of the model from wave celerity. Besides the friction terms which are discretized implicitly, other terms are in the SWEs are discretized explicitly. The resulting SIFDS are shown as equations 6-9 to 6-11 with '*F*' representing an explicit operator of the non-linear terms representing advection and viscosity.

$$U^{n+1}_{i+\frac{1}{2},j} = FU^n_{i+\frac{1}{2},j} - g\frac{\Delta t}{\Delta x}\left(\eta^{n+1}_{i+1.j} - \eta^{n+1}_{i.j}\right) + \Delta t\,\frac{\gamma^n_T U^{n+1}_a - \gamma^n_{i+\frac{1}{2},j} U^{n+1}_{i+\frac{1}{2},j}}{H^n_{i+\frac{1}{2},j}}$$

Equation 6-9: SIFDS U-velocity discretisation

$$V_{i,j+\frac{1}{2}}^{n+1} = FV_{i,j+\frac{1}{2}}^{n} - g\frac{\Delta t}{\Delta x}\left(\eta_{i.j+1}^{n+1} - \eta_{i.j}^{n+1}\right) + \Delta t\,\frac{\gamma_T^n V_a^{n+1} - \gamma_{i,j+\frac{1}{2}}^{n} V_{i,j+\frac{1}{2}}^{n+1}}{H_{i,j+\frac{1}{2}}^{n}}$$

Equation 6-10: SIFDS V- velocity discretisation

$$H_{i,j}\left(\eta_{i,j}^{n+1}\right) = H_{i,j}\left(\eta_{i,j}^{n}\right) - \frac{\Delta t}{\Delta x}\left(H_{i+\frac{1}{2},j}^{n} U_{i+\frac{1}{2},j}^{n+1} - H_{i-\frac{1}{2},j}^{n} U_{i-\frac{1}{2},j}^{n+1}\right) - \frac{\Delta t}{\Delta x}\left(H_{i,j+\frac{1}{2}}^{n} V_{i,j+\frac{1}{2}}^{n+1} - H_{i,j-\frac{1}{2}}^{n} V_{i,j-\frac{1}{2}}^{n+1}\right)$$

Equation 6-11: SIFDS for water depth discretisation

Solution to the system of *equations 6-9* to *6-11* will require solving a large number of matrix-forming equations at every time step. Because much of the computer time will be spent solving a set of matrices, Casulli (1990) proposed a conjugate gradient (CG) method, to enable efficiency and quick convergence to approximate solution regardless of the size of the matrices to be transformed. Of all the various methods for solving matrices available in the current literature, the CG methods are shown to be suitable for symmetric, tri-diagonal and positive definite matrices (Chan & Ng, 1996). Within computational mathematics literature, there are other methods for solving both linear and non-linear system of equations, along with a set of direct and iterative approaches for matrix decomposition (refer to Ding & Chen, 2005; Momani & Odibat, 2007).

6.3 Global evolution of water depth in *GFSP-1*

This is the most important stage of the new flood modelling technique, especially within the CA framework, in which the final water depth and extent for each time step is updated. In the present flood model, the fluxes into the cells are first summed up for each time step using *equation 6-12*. Then the total fluxes are divided by the areas enclosed by the cell (i.e. $dx * dy$) and multiplied by the model time step, using *equation 6-13*. Ghimire *et al.* (2013) raised the issue of using a variable cell area to reflect the reduced space occupied by topographic feature, especially built-up structures, which intervene in the flow path of water. This idea is logical but it can be difficult to implement. More current approaches of representing building in urban flood models are referred in Bellos & Tsakiris (2015). Within the present model, it may lead to a significant increase in the computation cost since creating new variables, initializing and updating them within a single iteration can overwhelm the speed of MATLAB computation. However, the down-gradient flow assumption ensures that water flows completely around large obstructions, rather than being enclosed and accumulating.

$$Total\ flux(i,j) = \sum\{influx(i-1,j), influx(i+1,j), influx(i,j-1), influx(i,j+1)\}$$

Equation 6-12: Total flux calculation

$$Water\ depth(i,j) = water\ depth(i,j) + \frac{Totalflux(i,j)}{(dx*dy)} * \Delta t$$

Equation 6-13: Water depth calculation

6.4 Dynamic link between CA and SIFDS

The two components, which *GFSP-1* combines, interact at a strategic point to simulate a typical urban flooding event. From figure 6-9, the link between these components (i.e. CA and SIFDS) determines the time step or simulation time of the model. Once the model begins to run, an initial time step (*traverse time*) is computed using Manning's flow formula. This time step is the minimum that is required to keep the simulated results at a maximum principle (which means not compromising the stability). Midway through the simulation period, a new time step (∂t) emerges from the SIFDS. This time step is needed to simulate horizontal velocity components (*u, v*) and to keep the model through a complete iteration. At the point of intersection between the two model components, the time step that emerged from the SIFDS is compared with the time step initiated at the start of the simulation. The minimum of the two is then used to advance up to a full iteration.

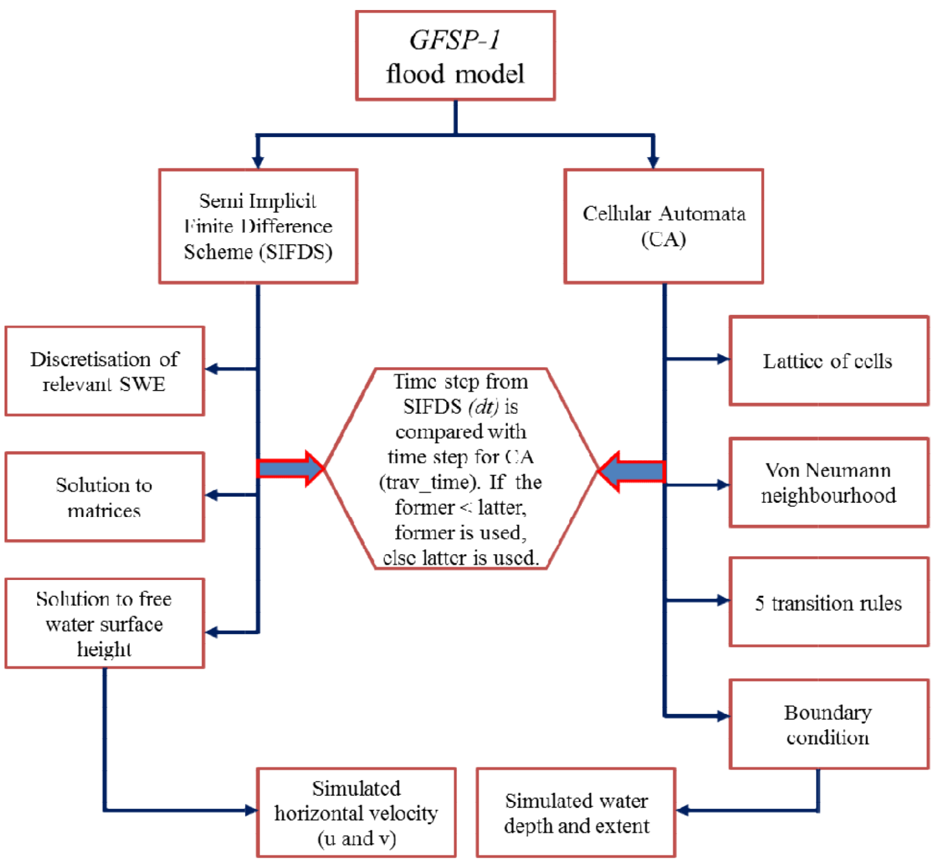


Figure 6-9: Schematics showing the dynamic link between the CA and the SIFDS in the GFSP-1 model.

6.5 The main model algorithm and programming in MATLAB^{TM}

Computer modelling of hydrological phenomena (for example: flooding) adopts programming languages that are powerful, easy to implement with several in-built functions, capability for modularity and for object-oriented programming (OOP) (Chen & Chau, 2006; Todini 2007). Whilst many programming languages including Java, C, C++, C#, VBASIC, Python, MATLAB^{TM}, have been used extensively in physical and engineering sciences, only FORTRAN and C++ have found widespread usage in flood modelling (see for examples: LISFLOOD-FP, HECRAS, Flo-2D). The choice of the programming language to use is often difficult to make. Among other factors, this can be based mainly on the programmer's skill and experience, purpose of programming, program sustainability, system support, language robustness and the program development environment (Palumbo, 1990; Van Hoff, 1997; Spinellis, 2006). These seem to undermine the widespread availability of flood modelling code, and thus suggest the need to implement flood modelling in a programming language that is robust, but also adaptable to different computing environments.

Programming flood models on MATLAB^{TM} platform is still an emerging procedure. Only few flood models known to the author are essentially programmed in MATLAB^{TM} (see MoD2-Flow model: Martin & Gorelick, 2005; Kulkarni *et al.,* 2014), and this can be a major research issue within the context of efficient modelling of urban flooding. MATLAB^{TM} is a powerful OOP language with extended capabilities for handling and manipulating matrices. As a commercial programming language, access to end-users in low income societies can be limited. However, MATLAB^{TM} codes can easily be exported and adapted to freely accessible windows integrated program development environments (IDEs). This new flood model implements several essential commands within the general framework of MATLAB^{TM} input and output, variable definition, and execution of mathematical operations, loops and conditionals. This is an attempt to advance research towards using MATLAB^{TM} potentials and capabilities to improve flood modelling techniques.

Within the MATLAB^{TM} framework, the new flood model uses some commands and implements some key functions to simulate flood water depth and extent, as well as water flow velocity. Once the program starts, variables are created and initialized. Then, the LiDAR DEM, which is in arc grid standard, is immediately read into the code. Manning's value, rainfall intensity, less abstractions, if applicable, is read into the code. Rainfall intensity is of critical importance to the performance of the new flood model. Rainfall is usually measured in inches or millimeters over a period of spell, but this is converted into rainfall intensity using equation *6-14*, and read into the code as a single variable, assuming a uniform rainfall over the study area (see figure 6-10). Gridded rainfall datasets are increasingly becoming available at global scale, but they do not correspond with the LiDAR DEM in terms of resolution and coverage, and thus cannot be used in the new flood model.

$$Rainfall\ Intensity = \frac{Total\ amount\ of\ rainfall\ (mm)}{Duration\ of\ rainfall\ (hours)}$$

Equation 6-14: Rainfall intensity calculation

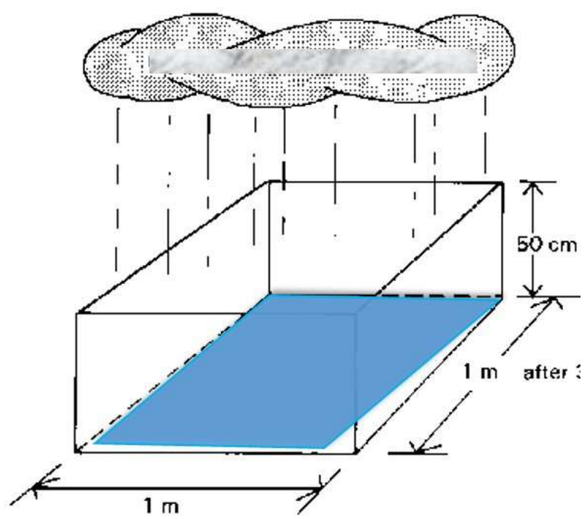


Figure 6-10: Schematics of a uniform rainfall over an area. The whole area represented as a box is assumed to receive the same amount of rainfall.

The next stage within the MATLAB™ framework involves arithmetic computations, and this mainly takes place within the neighbourhood system. First, the model imposes the boundary conditions. Then, the traverse time is computed and the time loop is initiated, using the difference between the fixed simulation final time and zero. Next, the transition rules are executed at each stage of the iteration. Finally, water depth is updated, with the final water depth written as arc grid files.

6.6 Running the *GFSP-1* flood model

GFSP-1 requires MATLAB™ program to be pre-installed and operating on a computer system. To enhance the computation speed of the model, a minimum processing speed of 2.0GHz, with a minimum RAM of 2GB will be desirable. The model provides a link with the user through an input file (input.txt) which must be located in the same folder as the DEM and the model code. The input file is editable and allows the user to enter the DEM name, Manning's value, rainfall intensity and amount. Initial and final times of simulation are also entered in the input file. Using equation 6-14 (refer to page 169), the rainfall intensity is computed from the minute by minute rainfall data for Portsmouth, and the 'daily amounts' data for Lagos.

From figure 6-11, input data including DEM, Manning's friction values, and effective rainfall, which is assumed to land uniformly on the domain are read once the model begins to run. Hydrological losses if applicable are also excluded. Then, execution of rules and assignment operations are carried out. Water depth is output at interval based on the user's specification. This is to enable the user have a closer idea of the time-variant flood water depth and extent, and also to provide a check for the final simulation time. In the test cases reported in Chapter 7, water depth is output at 30 minutes, 2 hours, 5 hours, 8 and 11 hours for Portsmouth and up to 14 and 17 hours for Lagos. LISFLOOD-FP specifies a regular interval say 10 minutes to output water depth which means that on a simulation that will last two hours, twelve outputs of simulated flood water depth and extent are expected. The model stops operation once the final time is reached. Else, it transfers control to the execution stage.

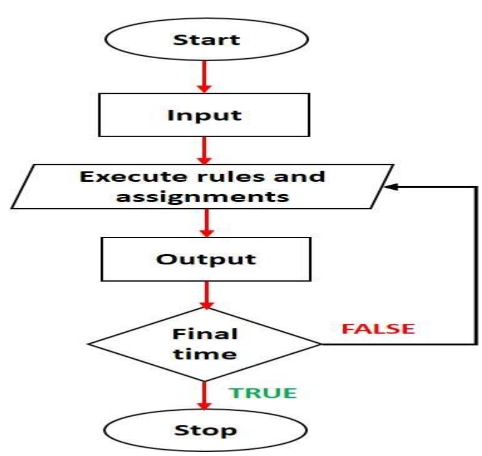


Figure 6-11: Simulation flow chart for *GFSP-1*

6.7 Major assumptions made in the present research

The present research makes a number of critical assumptions which are deemed necessary to achieve its main aim and objectives. The table 6-1 below summarises these assumptions and how they may have impacted or otherwise the modelling carried out in the present research

Table 6-1: Various assumptions made in the present research and their impacts or otherwise on the modelling procedure

S/No	Assumptions	Impact on the modelling procedure
1.	Single value rainfall intensity and Mannings' Coefficient	This assumption should not have any significant effects on the modelled output as long as the rainfall intensity value is accurately calculated, and appropriate Manning's value is chosen. However, the size of the catchment might show some sensitivity to this assumption. Modelling flooding in small catchment areas (for example fewer LGAs in the context of Lagos), on the basis of this assumption could be recommended. However, there are likelihood that this could propagate significant errors and undesirable results if the size of the catchment becomes, but this is subject to further investigations.
2.	Assumption of uniform rainfall within an area	This assumption has been made in several other studies for example Ghimire *et al.* (2013). There is no chances that it can affect the modelled output.
3.	Topography as an indicator for flood hazard in the construction of the SocVI	This can overestimate the social vulnerability metrics, depending on the accuracy of elevation data available.
4.	Infiltration was assumed zero	This can lead to lead to 'ponding' of the surface water in most locations rather than being removed from the catchment area.
5.	Absorptive and reflective boundary conditions	This should have no significant impacts on the modelling procedure. However, the assumption is to enabled the new model in the treatment of incomplete neighbourhood at the boundaries of the cellular mesh
6.	The model considered only flooding from pluvial sources.	As there are no evidence that fluvial or sea level influence on the catchment, ignoring other sources of water into the model should not impact on its performance.

6.8 Summary

The new flood model, *GFSP-1*, the development and technical framework for which have been described in this chapter, form the key novelty and innovation of the present research. *GFSP-1* combines the capabilities of CA and SIFDS in relation to simulating flooding in an urban environment, and this is an original contribution to the science of flood modelling. The present CA framework is made up of the Von Neumann neighbourhood system, a set of four transition rules and absorptive and reflective boundary conditions within a mesh of cellular space provided by LiDAR DEM. The present SIFDS is adopted from Casulli (1990) which combines the implicit and explicit finite difference numerical schemes. Two specific features of the model are: (1) the ability to run with a minimum of input data – suitable DEM, Manning's value, and rainfall intensity or amount, and (2) outputs format that can be accessed easily using any available GIS program.

Within the framework of the present research, it is essential to investigate the performance of *GFSP-1* flood model, and how it answers the research questions 4 and 5 (refer to page 17 of the thesis), both of which relate to urban flood modelling. Thus the testing and validation procure of this new flood model was carried out using two test cases – Portsmouth city, United Kingdom and Lagos, Nigeria, and this is reported in the next chapter.

7 Testing and validation of *GFSP-1* Urban Flood Model

This chapter presents the performance test of GFSP-1, using two test locations – Portsmouth, United Kingdom and the Lagos metropolis of Nigeria. The key focus is on data acquisition and preparation, in addition to investigating the actual performance of the new model. The test cases have been chosen on the basis of availability of data and the researcher's knowledge of the areas. The model was first tested using the flooding event of September 15th 2000 in Portsmouth. Then, various spatial and temporal scenarios of the July 11th 2011 flooding in some selected locations in the Lagos area were simulated.

7.1 Model testing and validation

The unexpected nature of urban flooding from severe pluvial events makes it difficult to accurately measure flood water depths and extent, and this hinders validation of urban flood models (Smith *et al.,* 2015). Flooding events are often imaged by remote sensing satellite, which provides real-time imagery. However, accessibility to satellite datasets is often hindered by limited funds and technical requirements to analyses the imagery and extract useful flood hazard information. For the present research, in addition to the lack of funds to acquire such validation datasets for Lagos, the limited time and maintenance available for international students to complete their PhD programme and exit United Kingdom were major issues to the rigorous testing and validation of the new flood model. To address these issues, the new model was firstly applied to Portsmouth city, United Kingdom, since the map of hotshots of surface water flooding, and photographs of a historical flooding event are available for validation purpose.

Portsmouth, together with Southampton, is an urban area in the South Hampshire conurbation. Portsmouth is the second largest city in the United Kingdom, and is located on the south coast of England (figure 7-1). The city is situated on the Portsea Island, which is the United Kingdom's only island city. With a population of 205,400, within a land area of about 40 Km^2, Portsmouth is the only city in the United Kingdom with a greater population density than London. The city's population density and its coastal setting appear to be important factors of concern with regards to urban flooding in the area. Although the city gets around 645 mm of rain annually, high intensity short duration rainfall occasionally occurs, and triggers flooding event.

Urban flooding in Portsmouth is mainly the surface water flooding, caused by heavy pluvial events, which produces water that exceeds the capacity of drainage system (EA, 2010). Although there are fluvial and components in Portsmouth flooding, they are not the concern of the present research. During the events, road side drains overflow, and flood access roads, public utilities and individual households. The coastal and drainage team in the Transport and Environment section, Portsmouth City Council (PCC) have identified fourteen areas of within Portsmouth that are most at risk of surface water flooding. These include Cosham, Farlington, Anchorage Park, Copnor road I, Hambrook Street, Stamshaw, Ordinance row, Copnor road II, Northern parade, War department Sewer, Quartremaine road, Great Salterns golf course, Pier road, Southsea (see figure 7-2). Reducing the risk of flooding in these areas has been the main focus of flood risk management strategy in Portsmouth (PCC, 2014).

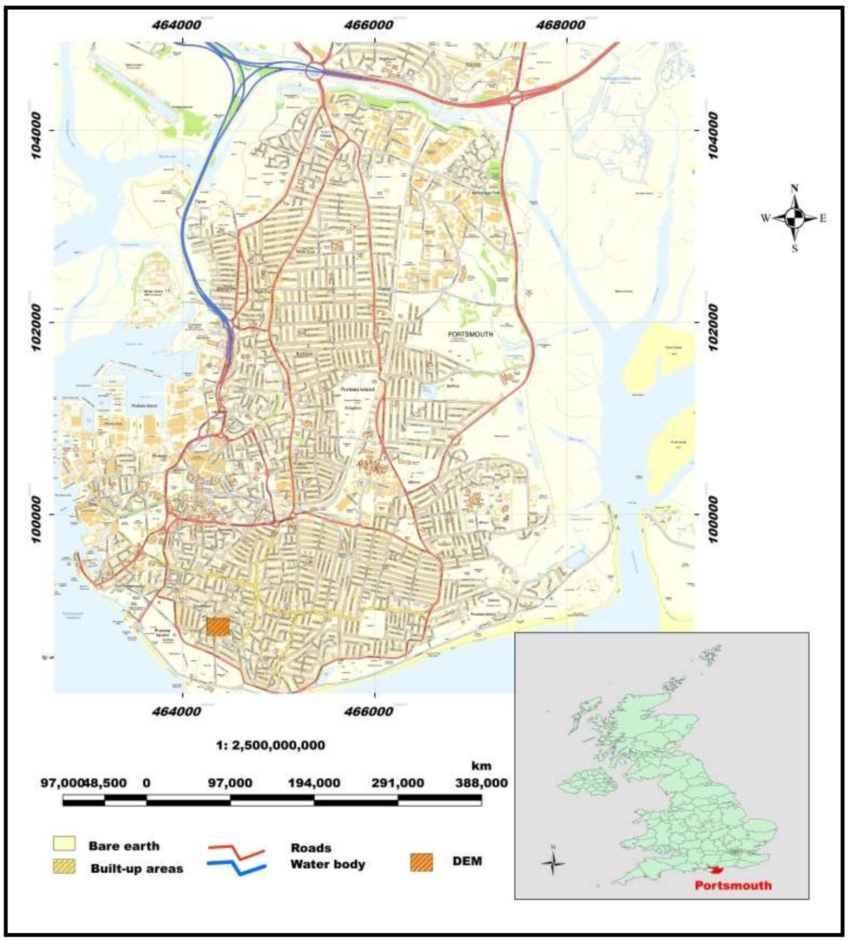


Figure 7-1: The city of Portsmouth. Inset is the location of Portsmouth in UK

The flooding of September 15th 2000 was a result of intense pluvial event. Based on the rainfall data obtained from Geography department, University of Portsmouth, 55.6mm of rainfall was recorded in approximately 11 hours (see table 7-1). The flooding was compounded by the failure of Eastney water pump and the Southern

Interceptor which runs along the south of Portsea Island (PCC, 2014). Flood water lasted for a significant amount of time in the central Southsea, and old Portsmouth, covering Broad Street and Clarendon road. Transport system and properties were potentially affected. Estimated 750 properties in the vicinity of Eastney were flooded, while a standing water depth of 0.6m and above was recorded at some places (PCC, 2014). All flooded land area suffered pollution from sewage.

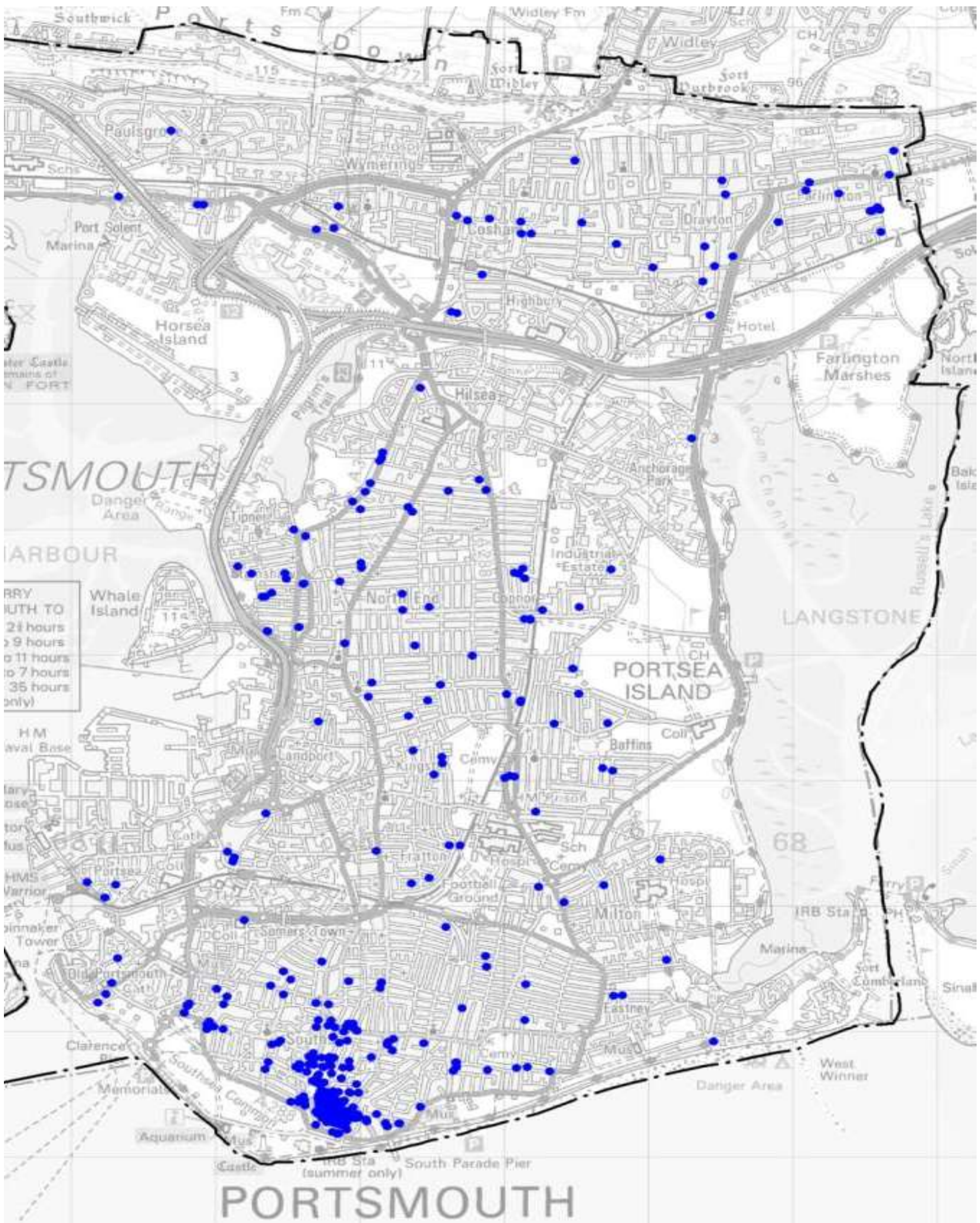


Figure 7-2: Hotspots of Surface water flooding in Portsmouth

Table 7-1: Rainfall data for the September 15th 2000 flooding event. Source: Department of Geography, University of Portsmouth, Portsmouth

Time (H:mm)	Time (min)	Rainfall (mm)	Time (H:mm)	Time (min)	Rainfall (mm)	Time (H:mm)	Time (min)	Rainfall (mm)	Time (H:mm)	Time (min)	Rainfall (mm)	Time (H:mm)	Time (min)	Rainfall (mm)	Time (H:mm)	Time (min)	Rainfall (mm)
9:01	0	0.2	9:48	47	0.4	10:16	75	0.4	11:28	147	0.8	11:45	164	0.4	12:34	213	0.2
9:03	2	0.2	9:49	48	0.2	10:18	77	0.2	11:29	148	0.8	11:46	165	0.6	12:35	214	0.2
9:08	7	0.2	9:50	49	0.6	10:19	78	0.2	11:30	149	0.8	11:47	166	0.4	12:36	215	0.2
9:11	10	0.2	9:51	50	0.2	10:21	80	0.2	11:31	150	0.6	11:48	167	0.4	12:37	216	0.2
9:16	15	0.2	9:52	51	0.2	10:22	81	0.2	11:32	151	0.6	11:49	168	0.2	12:38	217	0.2
9:19	18	0.2	9:53	52	0.4	10:25	84	0.2	11:33	152	0.4	11:50	169	0.4	12:40	219	0.2
9:22	21	0.2	9:54	53	0.4	10:26	85	0.2	11:34	153	0.2	11:51	170	0.4	12:41	220	0.2
9:24	23	0.2	9:55	54	0.4	10:27	86	0.2	11:35	154	0.4	11:52	171	0.6	12:44	223	0.2
9:27	26	0.4	9:56	55	0.4	10:29	88	0.2	11:36	155	0.2	11:53	172	0.4	12:52	231	0.2
9:28	27	0.4	9:57	56	0.2	10:30	89	0.2	11:37	156	0.6	11:54	173	0.2	13:00	239	0.2
9:29	28	0.2	9:58	57	0.4	10:31	90	0.6	11:38	157	0.6	11:55	174	0.4	13:07	246	0.2
9:30	29	0.4	9:59	58	0.2	10:32	91	0.6	11:39	158	0.4	11:57	176	0.2	13:11	250	0.2
9:31	30	0.2	10:00	59	0.2	10:33	92	0.4	11:40	159	0.8	11:59	178	0.4	13:14	253	0.2
9:32	31	0.2	10:01	60	0.4	10:34	93	0.2	12:12	191	0.2	12:00	179	0.2	13:19	258	0.2
9:33	32	0.2	10:02	61	0.2	10:35	94	0.2	12:13	192	0.2	12:01	180	0.2	18:22	561	0.2
9:34	33	0.2	10:03	62	0.2	10:37	96	0.2	12:14	193	0.2	12:02	181	0.2	18:27	566	0.2
9:35	34	0.2	10:04	63	0.4	10:42	101	0.2	12:16	195	0.2	12:03	182	0.2	19:57	626	0.2
9:36	35	0.2	10:05	64	0.4	10:54	113	0.2	12:17	196	0.2	12:04	183	0.2	20:01	660	0.2
9:38	37	0.2	10:06	65	0.6	11:18	137	0.2	12:22	201	0.2	12:05	184	0.2	20:07	666	0.2
9:39	38	0.2	10:07	66	0.6	11:19	138	0.6	12:23	202	0.2	12:06	185	0.2	20:13	672	0.2
9:40	39	0.4	10:08	67	0.4	11:20	139	0.6	12:24	203	0.2	12:08	187	0.2	20:18	677	0.2
9:41	40	0.2	10:09	68	0.4	11:21	140	1	12:25	204	0.2	12:09	188	0.2	20:23	682	0.2
9:42	41	0.4	10:10	69	0.4	11:22	141	0.8	12:27	206	0.2	12:10	189	0.2	20:27	686	0.2
9:43	42	0.2	10:11	70	0.4	11:23	142	1	12:29	208	0.2	12:11	190	0.4	**Total**	***11.26 Hrs***	***55.6***
9:44	43	0.2	10:12	71	0.2	11:24	143	1	11:41	160	0.6	12:30	209	0.4			
9:45	44	0.4	10:13	72	0.4	11:25	144	0.8	11:42	161	1.2	12:31	210	0.2			
9:46	45	0.2	10:14	73	0.2	11:26	145	0.8	11:43	162	1.6	12:32	211	0.2			
9:47	46	0.2	10:15	74	0.2	11:27	146	0.6	11:44	163	1.2	12:33	212	0.2			

7.1.1 Portsmouth LiDAR DEM

A 2-m horizontal resolution LiDAR DEM covering the whole city of Portsmouth was acquired from Environment Agency (EA) Geomatics archive data team. Figure 7-3 shows one of the LiDAR tiles measuring 500 m on all sides (i.e. 500 columns and 500 rows), with a vertical accuracy of +/-5cm. The LiDAR data comes compressed as an ArcGIS 'ascii' file, and is released on non-commercial license, as EA makes LiDAR datasets available for everyone to use for free. The agency's LIDAR data archive contains digital elevation data derived from surveys carried out by the agency's specialist remote sensing team, which sampled the whole of England, using airborne stereo-photogrammetry and ground survey conducted in 1995. This data has been gathered over the last 17 years using lasers to map and scan the English landscape from above to enable work such as flood modelling and tracking of changing coastal habitats to be carried out (EA, 2010).

Figure 7-3: Sample of LiDAR DEM for the Portsmouth study area.

Altogether, 40 tiles of the LiDAR DEMs were used in the simulation, and this produced 10,000,000 cells. To simulate flooding on such a large number of cells would require a very fast machine, and this would still take several months to complete. This is a major problem in flood modelling which the present research attempts to overcome. No further processing was required to read this file into the *GFSP-1* flood model. This is an advantage, which the new model has over many flood simulation models.

7.1.2 Simulation of Portsmouth September 15th 2000 flooding

In addition to the LiDAR DEM dataset, rainfall intensity was computed from the table 7-1 above, using the formula in section 6.5 of chapter 6 (i.e. equation 6-14 above on page 175), whilst a roughness coefficient (Manning's frictions value) of 0.02, suitable for simulation of flooding in urban areas was taken from Chow *et al.* (1988). Simulations of the September 15th flooding was carried out on one tile at a time, and then the resulting simulated water depth were mosaicked to create a complete scenario of flood inundation. For each tile, flood was simulated for 11 hours, to accommodate the duration of the pluvial event. Simulated water depth and extent were output and written as 'ascii' files at discrete time marks: 30 minutes, 2 hours, 5 hours, 8 hours and 11 hours. Figure 7-4 shows locations in which *GFSP-1* simulated flood inundation, and these are comparable to the hotspots of surface water flooding. From figure 7-4, considering the area within the simulation zone, there are sixty-seven hotspot locations overlapped by simulated flood and twenty-six hotspot locations not overlapped by simulated flood. Thus, the percentage of hotspot locations simulated are 72%. (i.e. % of points simulated $=\frac{67}{93} * 100\%$). Ten locations delineated in the surface water flooding hotspots map (figure 7-2 above) are selected (figure 7-5). These areas include central Southsea, Landport community, Old Portsmouth, Cosham, Somers town, Fratton, North end, Hilsea, Portsea island area, and Tipner area. The simulated September 15th flooding inundation in these locations were further investigated in terms of the spatial extent of flood inundation (figures 7-6 to 7-15) and the temporal variations (figures 7-16 to 7-25).

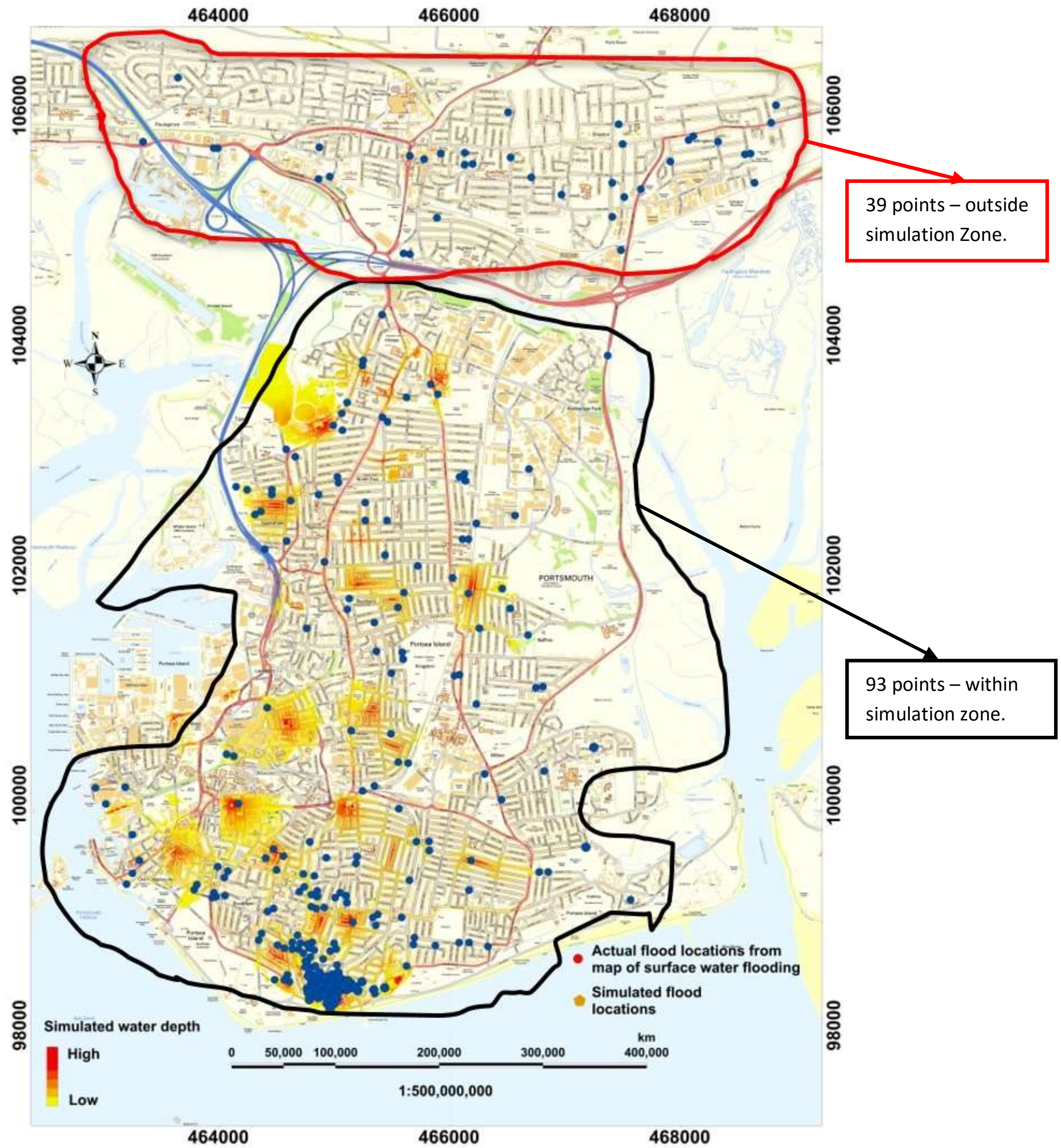


Figure 7-4: Simulated flood locations compared to surface water flooding hotspots

Number of hotspot locations overlapped by simulated flood	=	67
Number of hotspot locations overlapped by simulated flood	=	26
Total number of hotspot locations in the simulation zone	=	93
Percentage of hotspot locations simulated	=	
$\frac{67}{93} * 100\%$	=	72%

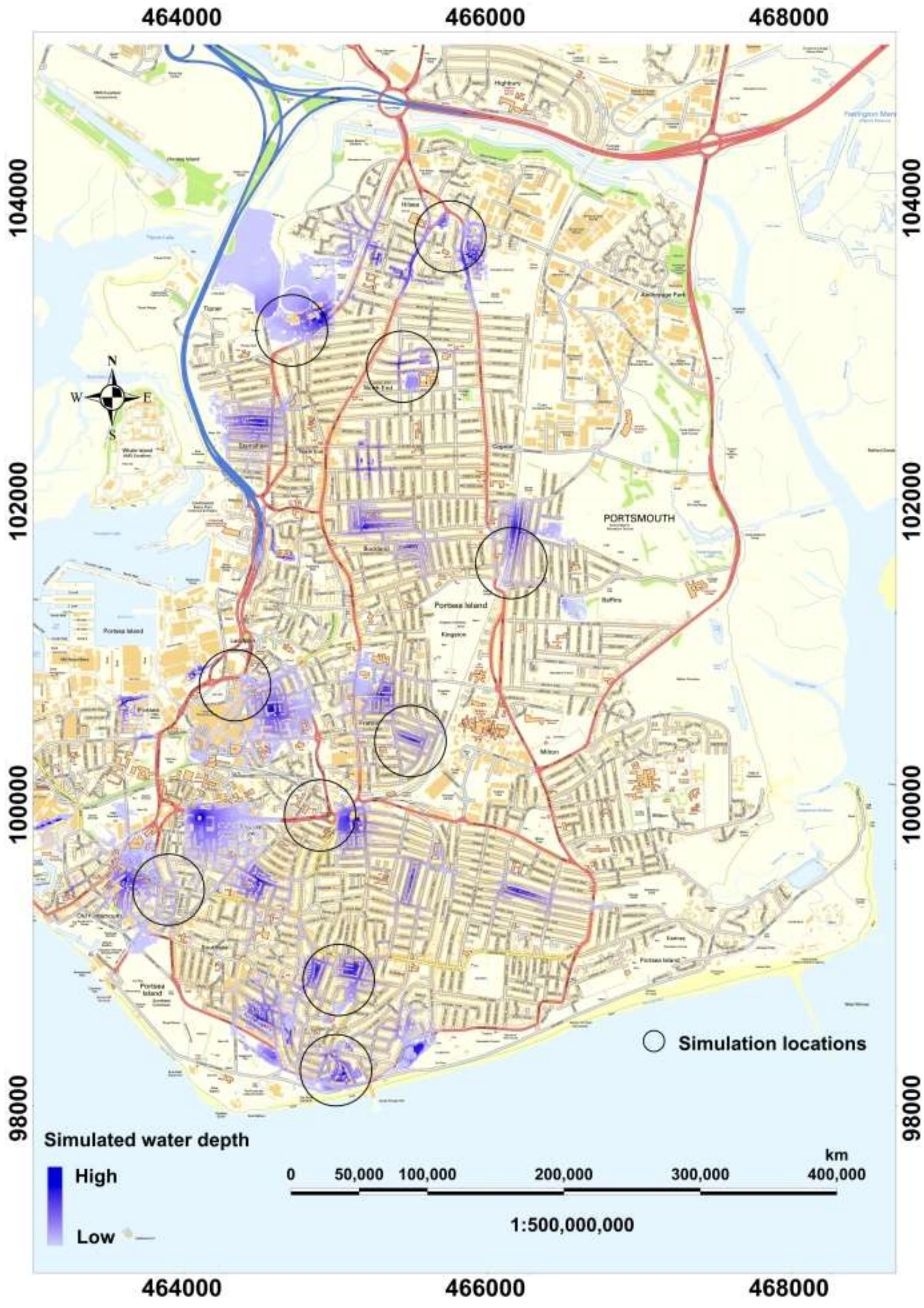


Figure 7-5: Locations where flooding inundation were simulated using the GFSP-1. When compared to the map of surface water flooding hotspots (figure 7-2), this model accurately simulated ten locations of flood inundation in Portsmouth area.

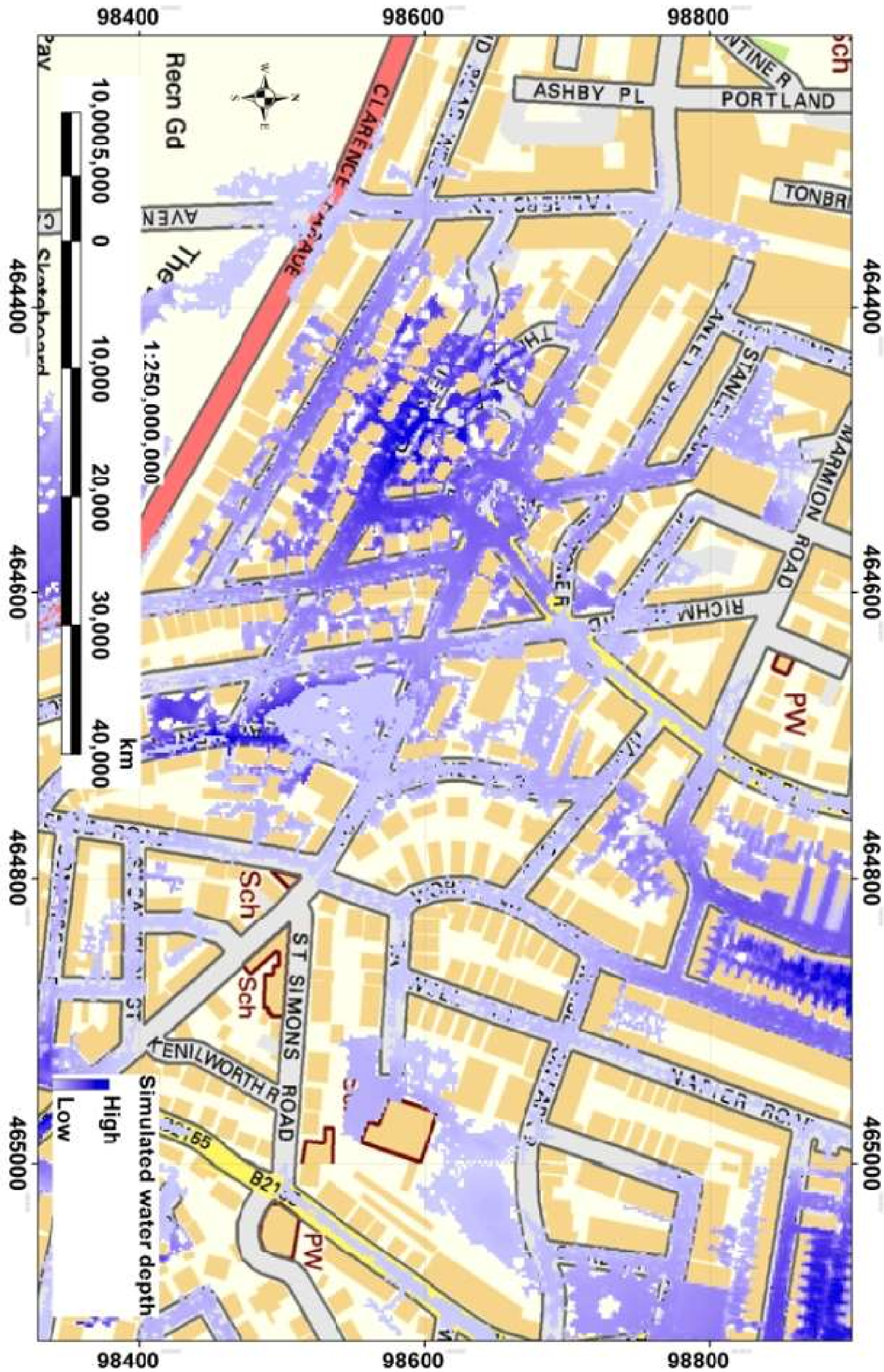


Figure 7-6: Simulated flood inundation at Clarendon area, Central Southsea

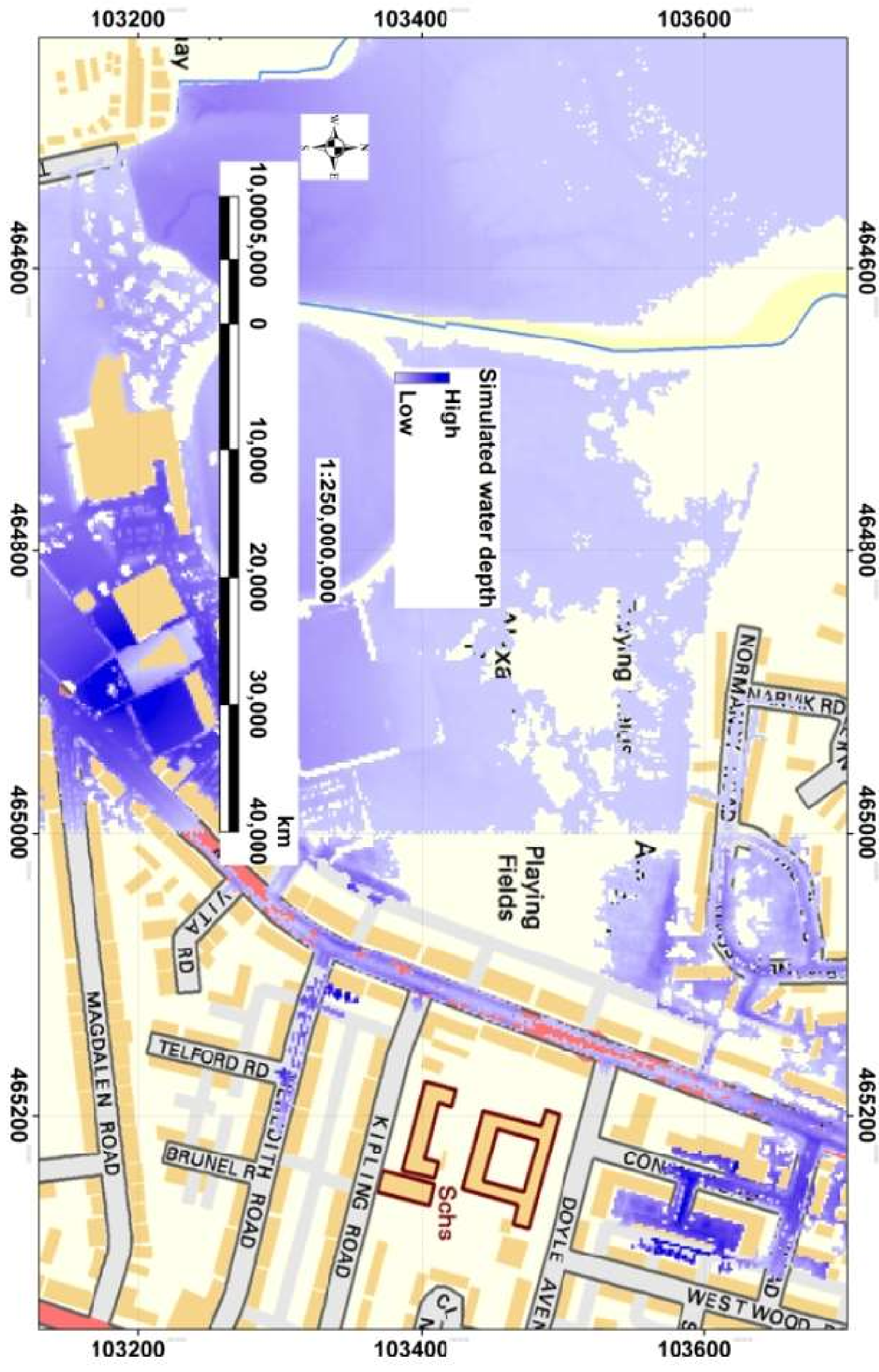


Figure 7-7: Simulated flood inundation at Tipner

Figure 7-8: Simulated flood inundation at Southsea

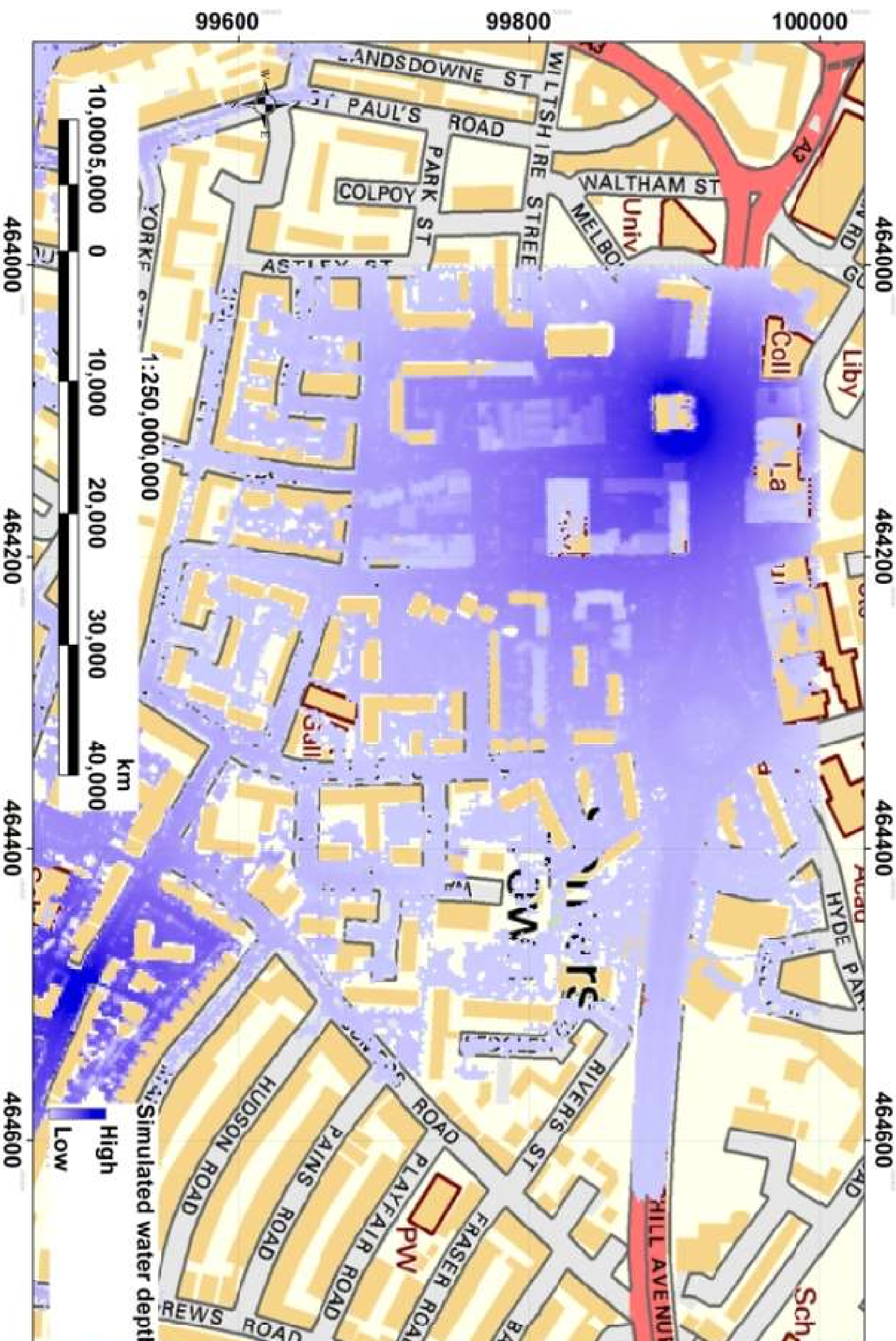


Figure 7-9: Simulated flood inundation at Somerstown and Bradford Junction

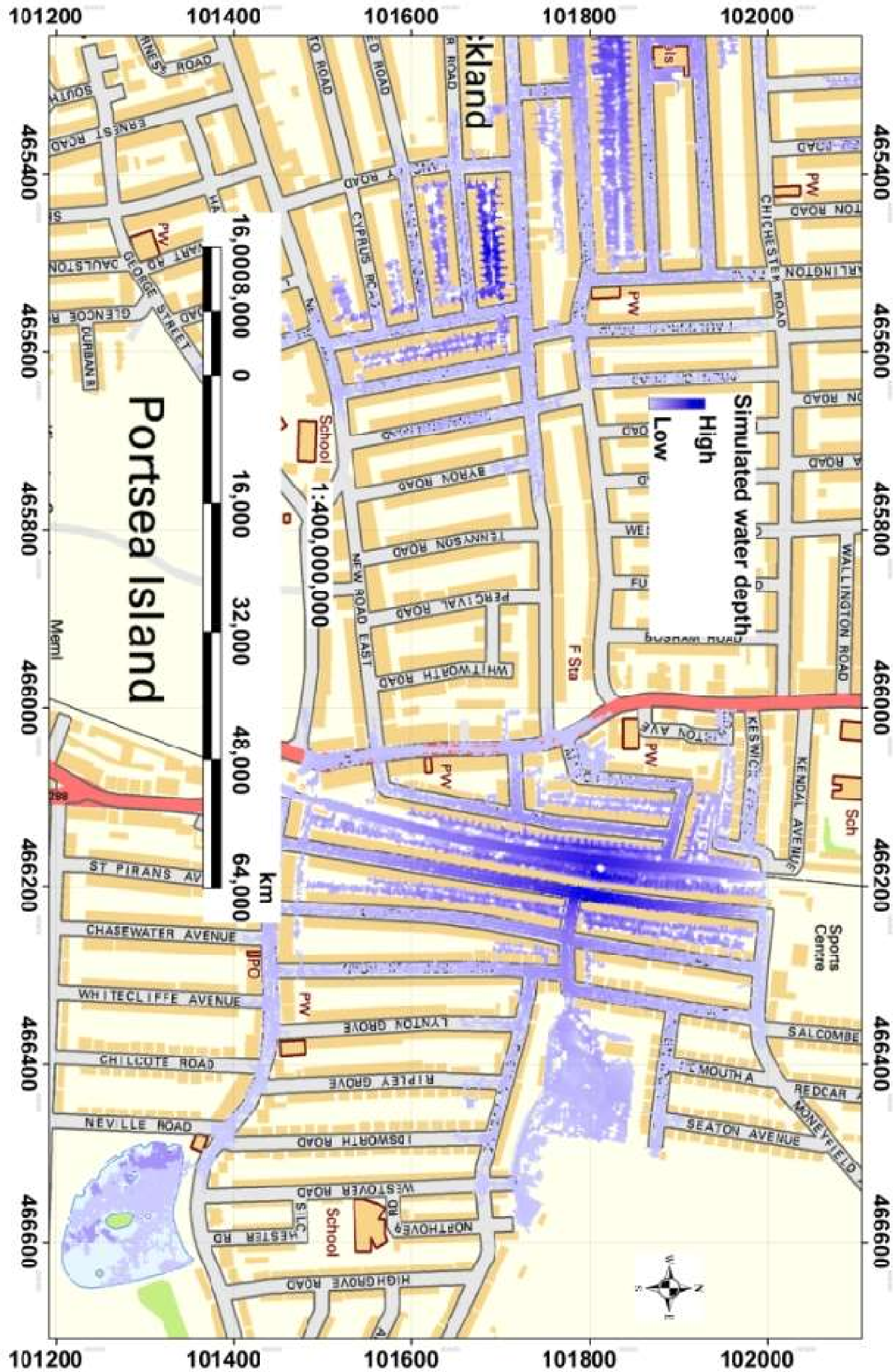


Figure 7-10: Simulated flood inundation near Portsea Island

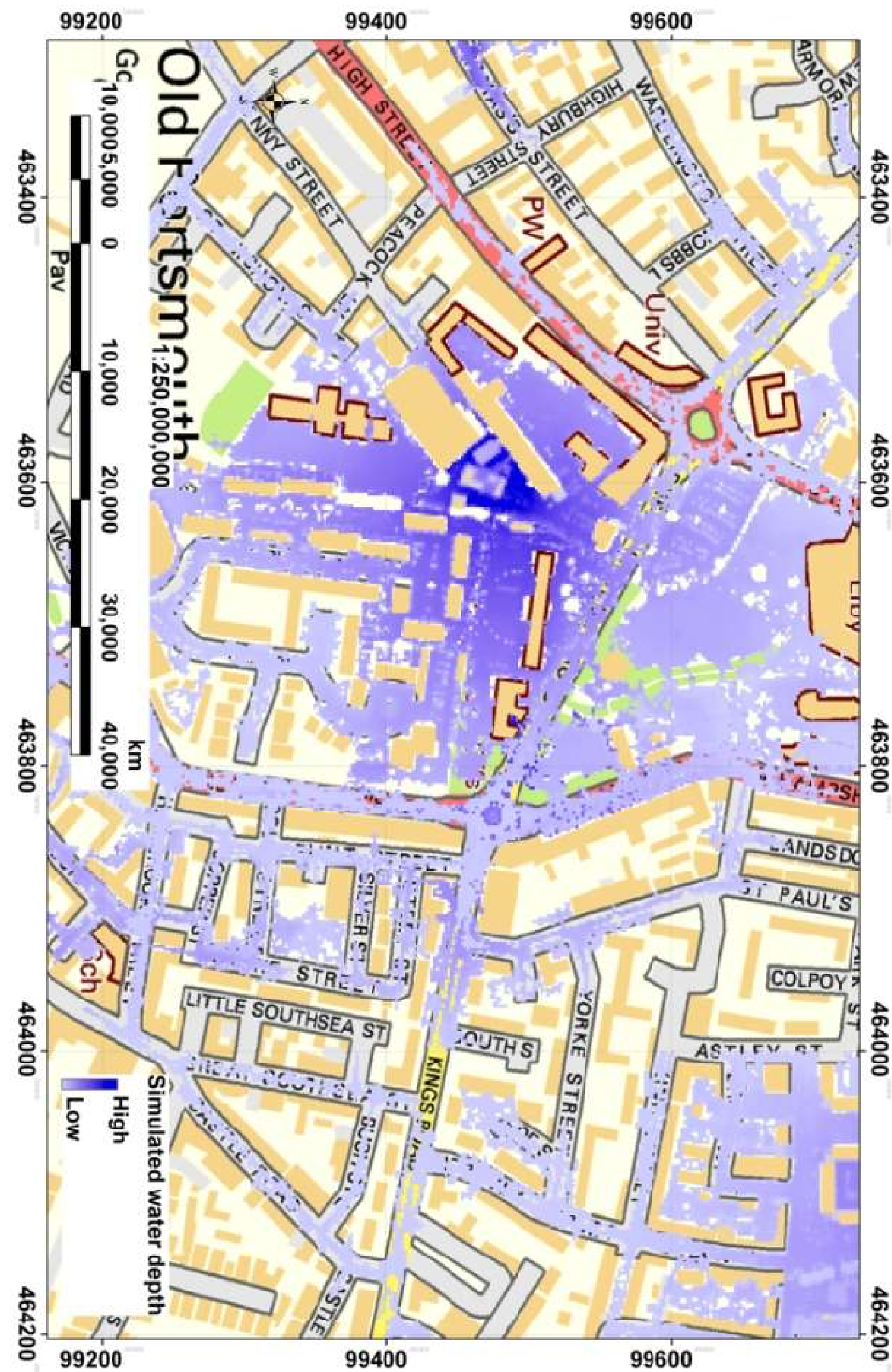


Figure 7-11: Simulated flood inundation at Old Portsmouth

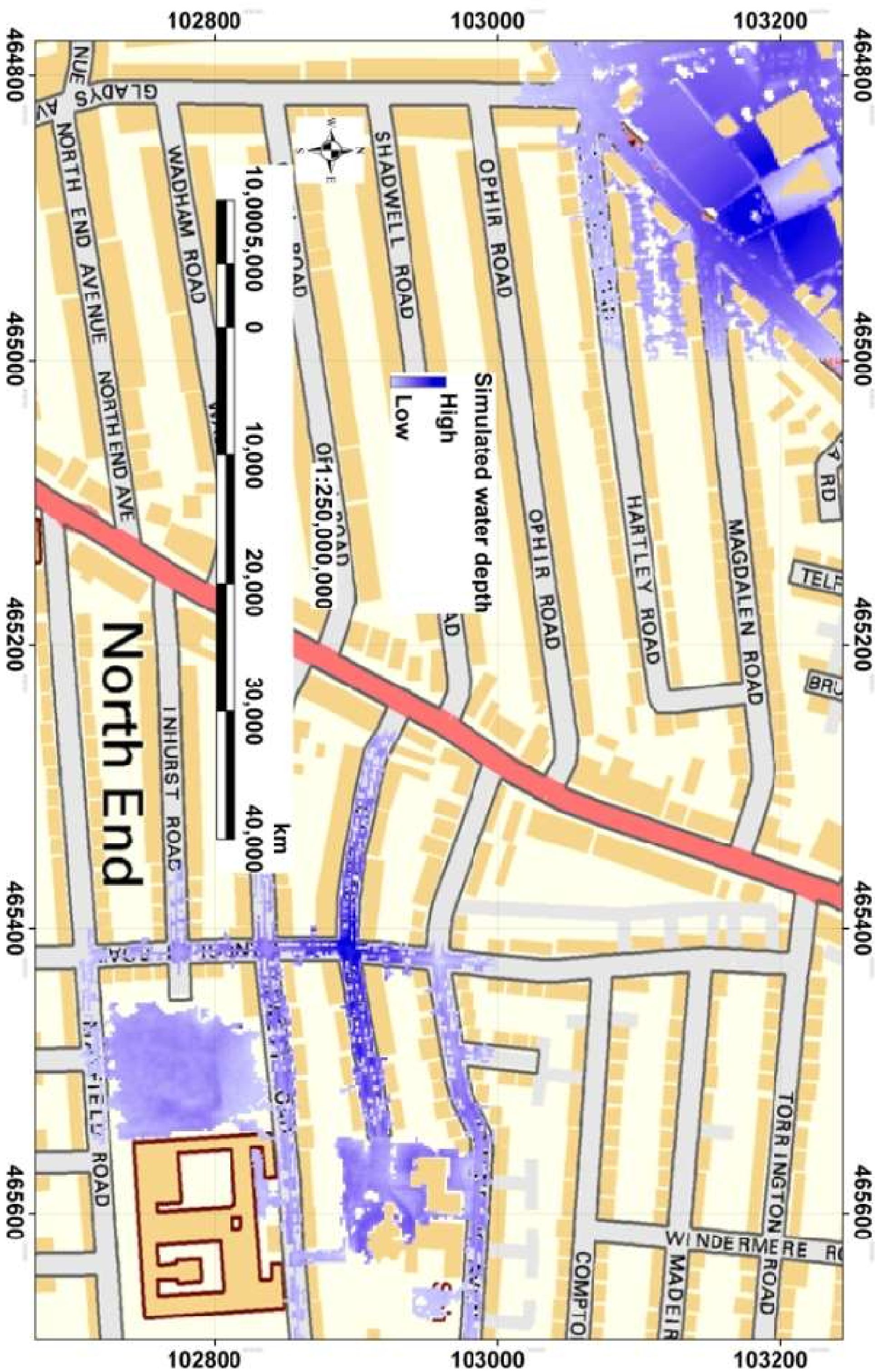


Figure 7-12: Simulated flood inundation at North end

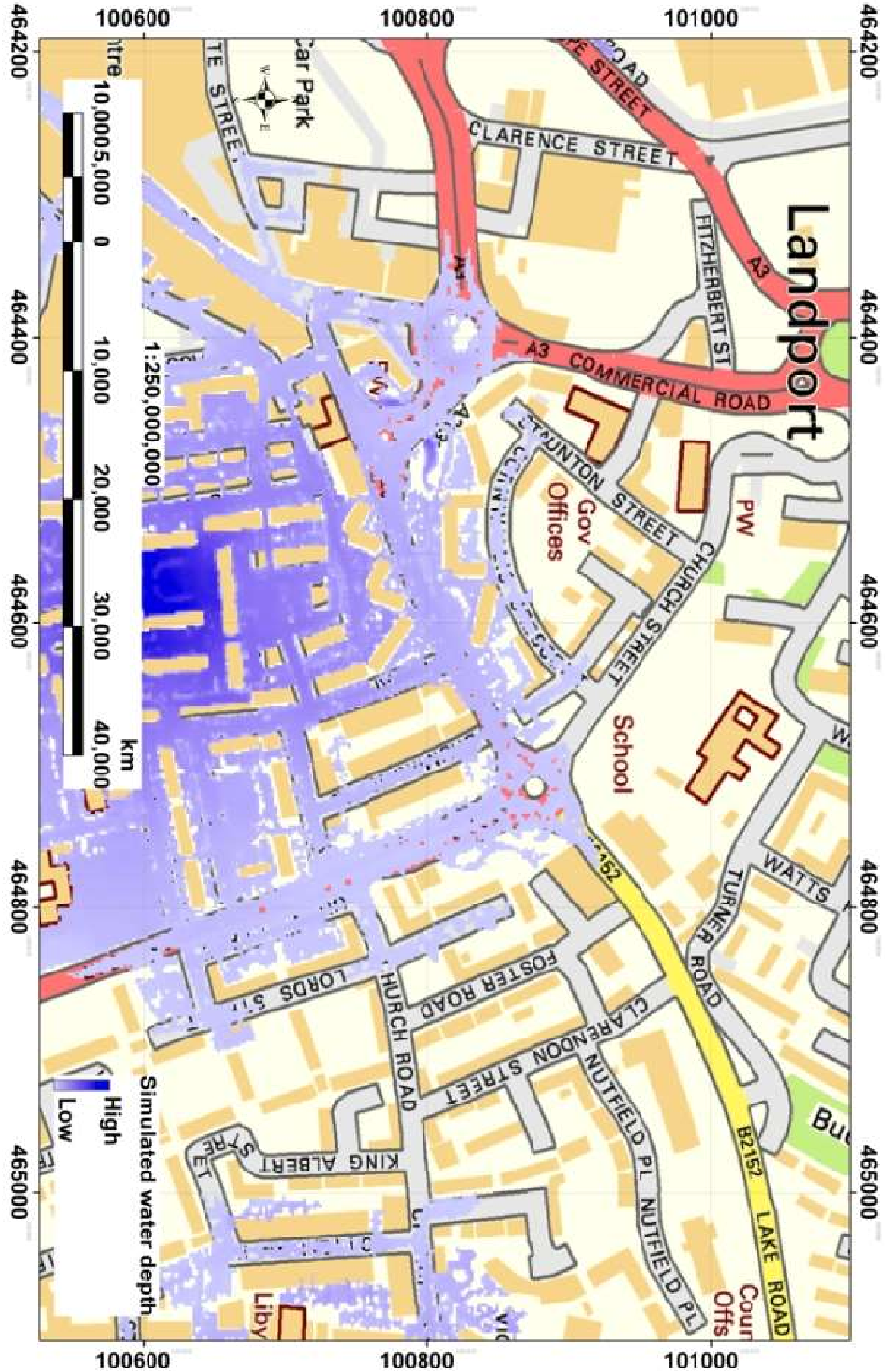


Figure 7-13: Simulated flood inundation at Landport

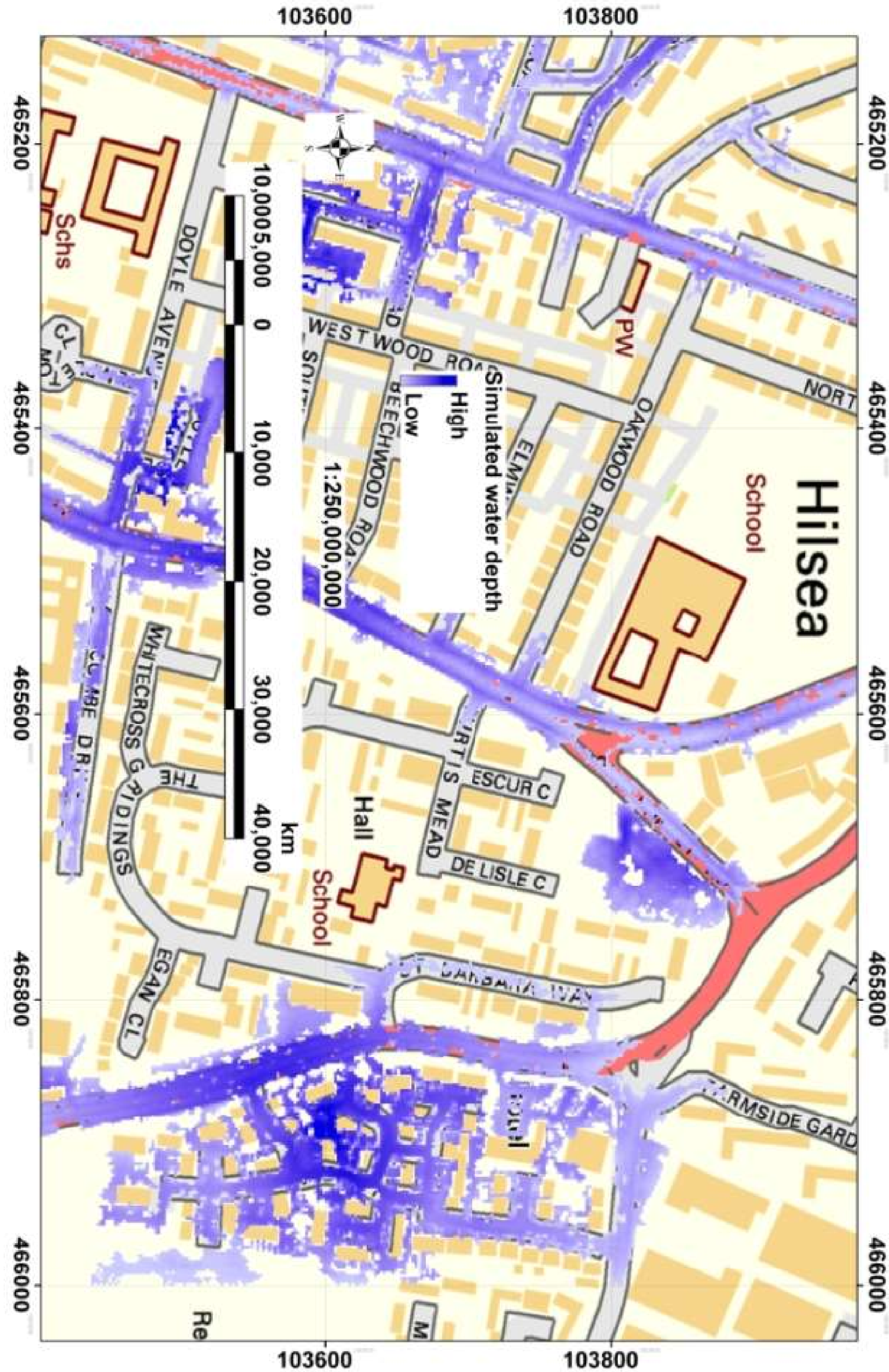


Figure 7-14: Simulated flood inundation at Hilsea

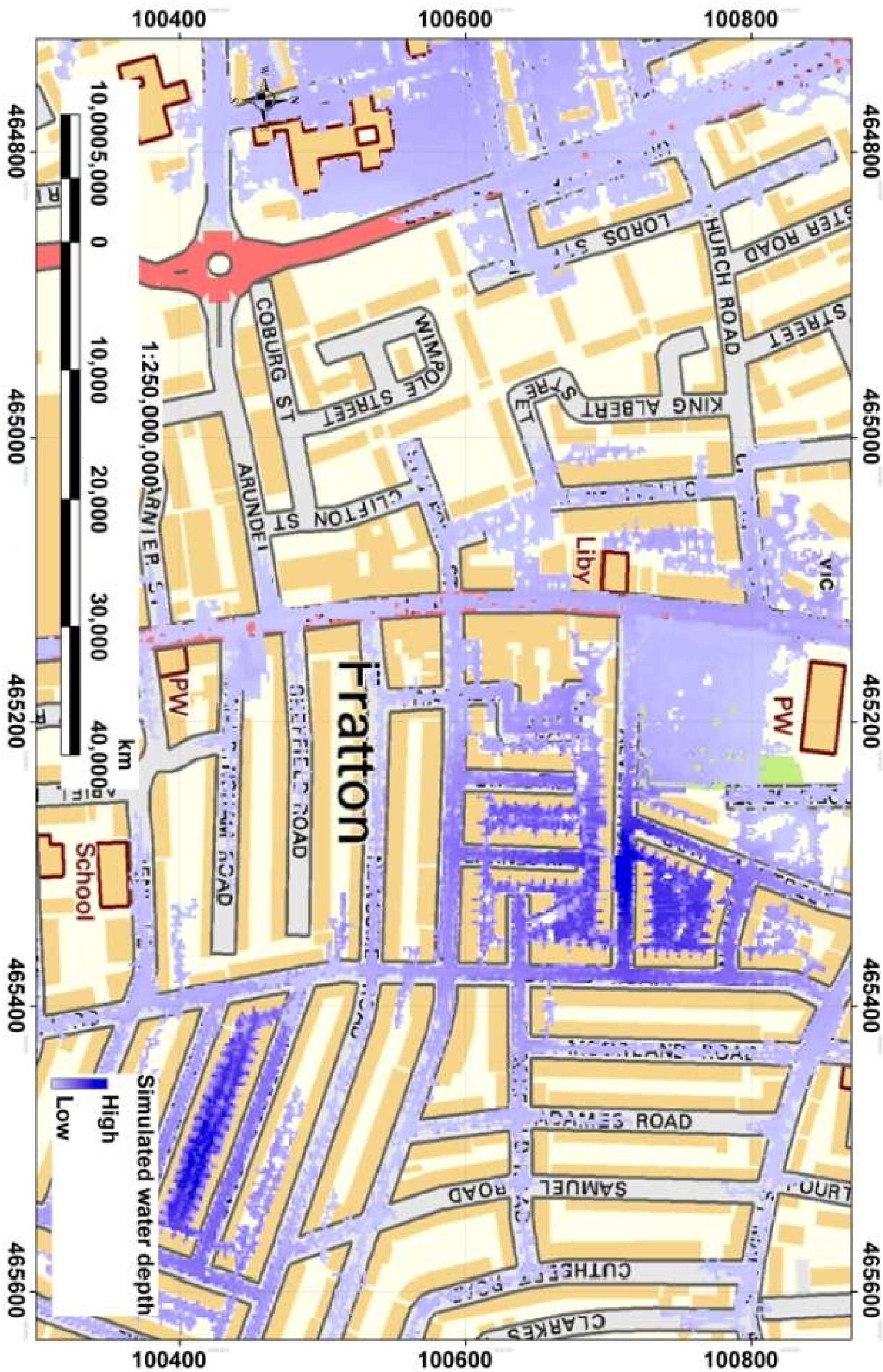


Figure 7-15: Simulated flood inundation at Fratton

From table 7-2, higher inundation depths were simulated at Old Portsmouth (0.87m), Landport community (0.98m) and Bradford junction (0.77m). This was mainly due to the lower nature of the terrain at those locations. The simulated maximum inundation depth is nearly similar for Portsea Island (0.66m), Central Southsea (0.65m), Tipner area (0.60m), and Southsea (0.68m). Simulated flood depth for places around Fratton was not so high (0.55m). Low water depth was simulated at Hilsea (0.26m) and North-end (0.08m). In all the ten locations, flood water extent was extensive and covered major roads (A and B), a number of built-ups including schools, residential houses and open land spaces. In the old Portsmouth and Broad Street areas, simulated flood covered up to quarter of a mile of the road connecting Broad Street and Portsmouth Anglican Cathedral.

Table 7-2: Highest water depth simulated at the ten simulation location in Portsmouth

S/No.	Location	Highest simulated water depth (m)
1.	Central Southsea	0.649
2.	Tipner area	0.604
3.	Southsea	0.683
4.	Bradford Junction	0.769
5.	Portsea Island	0.658
6.	Old Portsmouth	0.817
7.	North end	0.079
8.	Landport area	0.981
9.	Hilsea	0.267
10.	Fratton	0.554

The temporal variations of inundation depth at the chosen locations are shown in figures 7-16 to 7-25. At all the various test locations, the simulated water depth increased rapidly within the first two hours of the onset of the rainfall. Results of flood simulation throughout the rest of the duration of rainfall show that water depth gradually increased or remained constant. It is likely that at these time intervals water is being transferred from filled higher cells (possibly the higher grounds) to lower cells (i.e. the downstream sub catchment areas). However, exclusion of storm drainage systems from the model, and the use ‘daily amount’ rainfall data might also influence the behaviours of the model at those time intervals.

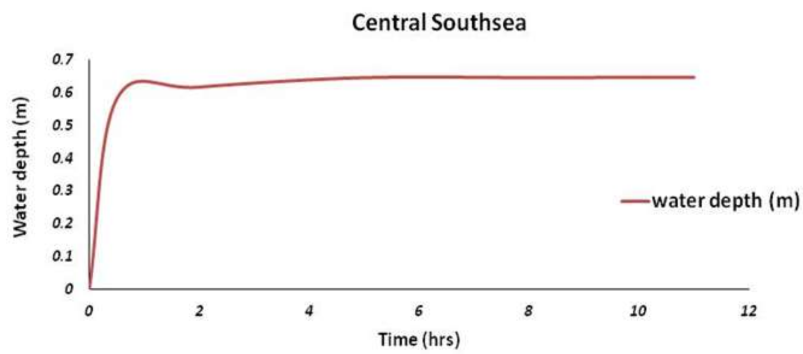


Figure 7-16: Plots of simulated water depth vs. time for Central Southsea

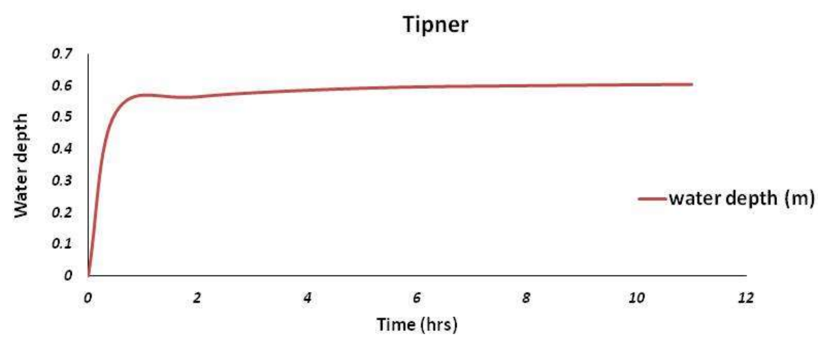


Figure 7-17: Plots of simulated water depth vs. time for Tipner

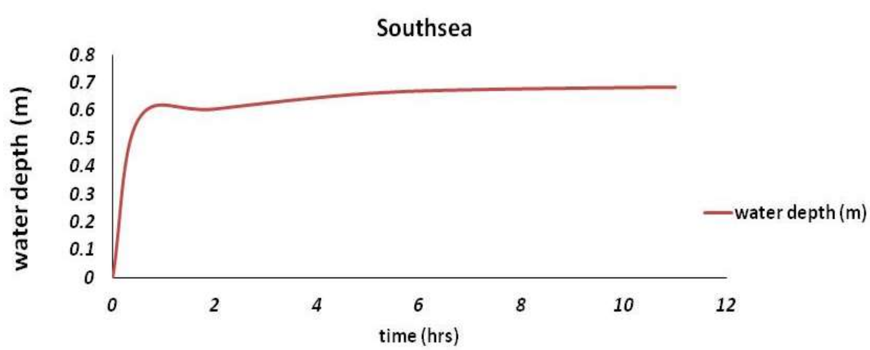


Figure 7-18: Plots of simulated water depth vs. time for Southsea

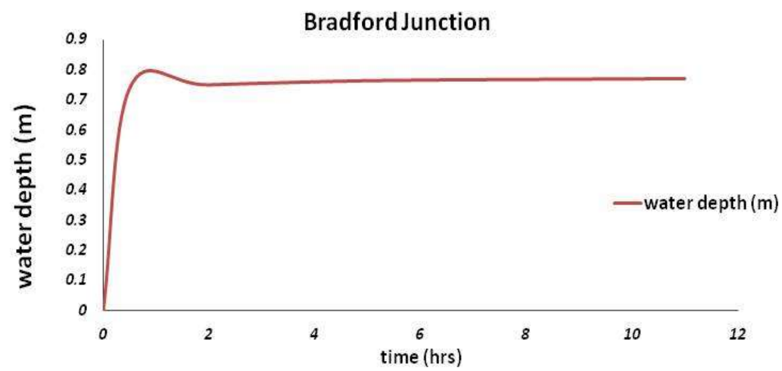


Figure 7-19: Plots of simulated water depth vs. time for Somerstown and Bradford Junction

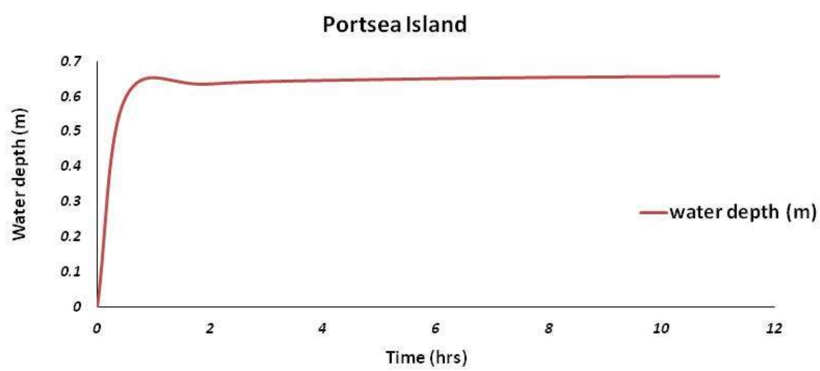


Figure 7-20: Plots of simulated water depth vs. time for Portsea Island

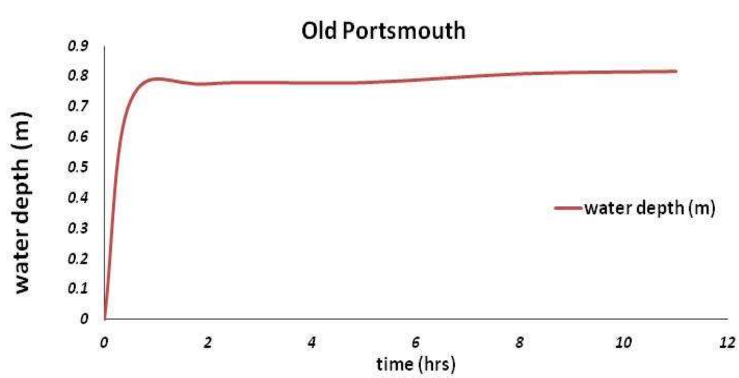


Figure 7-21: Plots of simulated water depth vs. time for Old Portsmouth

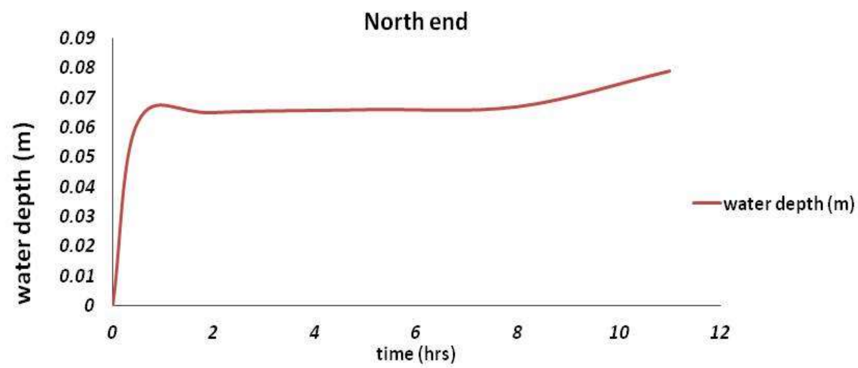


Figure 7-22: Plots of simulated water depth vs. time for North end

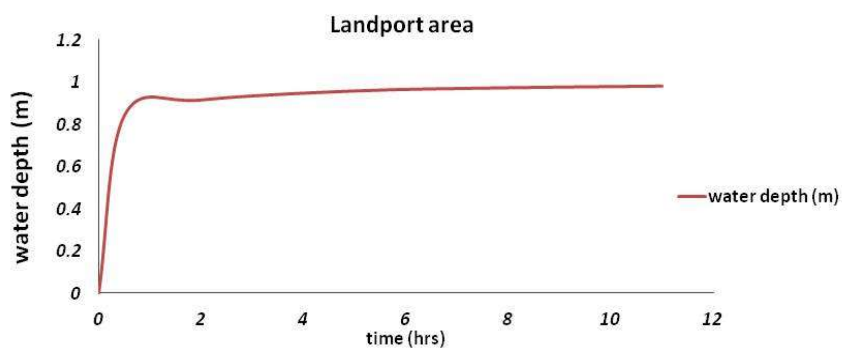


Figure 7-23: Plots of simulated water depth vs. time for Landport

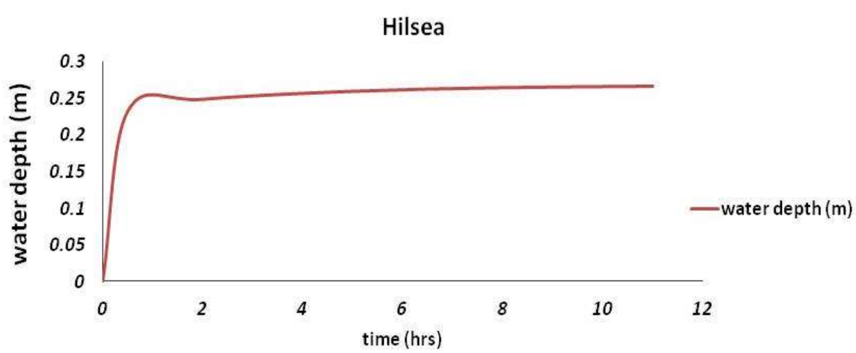


Figure 7-24: Plots of simulated water depth vs. time for Hilsea

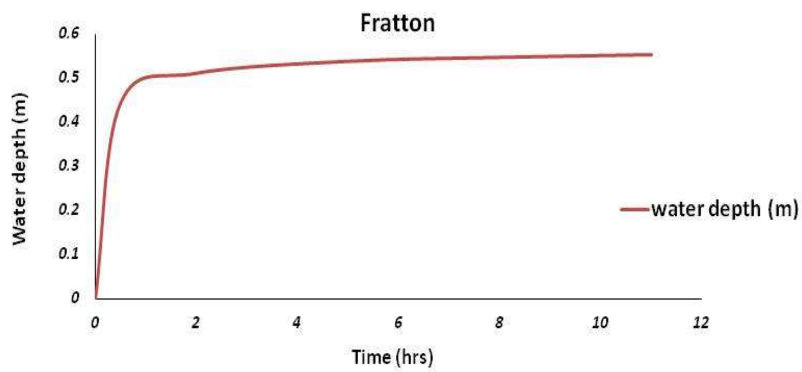


Figure 7-25: Plots of simulated water depth vs. time for Fratton

The smooth curves in figures 7-16 to 7-25 show that the water depths simulated by the model are stable despite the absence of a stability condition, which is often used in many numerical flood models. Manning's friction coefficient used in the *GFSP-1* is important to estimate an average velocity for water flowing in-between the cells. This will enable the model to maintain a gradual movement of water and thus might eliminate such phenomena as shocks, hydraulic jumps, subcritical and supercritical flows, all of which could render the results of the model unstable.

7.2 Model validation

The ability of a flood model to simulate a known flooding event in terms of water depth and extent is taken as a precondition for the model's predictive performance (Chen et *al.,* 2009). In order to estimate the goodness of fit in model prediction, simulated flood water depth is compared with actual or estimated flood water depth, derived from quantitative or qualitative sources and field measurements of a known flooding event. For example, Bates & De Roo (2000) used SAR (Synthetic Aperture Radar) satellite data to validate the performance of LISFLOOD-FP. Chen *et al.* (2009) used measured flood depth to test and validate the performance of GUFIN (GIS Urban Flood Inundation Model). Liu *et al.* (2015) used videos acquired from street-monitoring closed-circuit television (CCTV) to validate a 2-D flood model for city emergency management. Comparing the performances of two different models is also applicable in flood model validation. A typical example is the study by Ghimire *et al.* (2013) which compared the predictive capabilities of GUFIN and CADDIES 2-D, as a means to validate the latter.

As these rigorous validation datasets were not readily available to the present research due to some limitations, which have been mentioned earlier, *GFSP-1* has been validated against the map of hotspots of surface water flooding for Portsmouth, and social media-based information, especially photographic images of September 15th flooding in Portsmouth (available at Portsmouth City Council: PCC, and online) and July 11th 2011 flooding in Lagos (available online).

7.2.1 Model validation using the map of hotspots of surface water flooding

The map of hotspots of surface water flooding was georeferenced in ESRI ArcGIS 10.2, and assigned a global coordinate system (WGS, 1984), to enable a seamless correspondence with the simulated water depths. The geographic coordinates of randomly selected surface water flooding hotspots locations were extrapolated and used to build a geodatabase. Then, those selected points were plotted against the simulated flooded locations on the basemap of Portsmouth. The result of this operation (see figure 7-26) shows that a significant number of the hotspot location points matched with the simulated flooded locations, and thus suggest that *GFSP-1* is capable of simulating flood inundation extent.

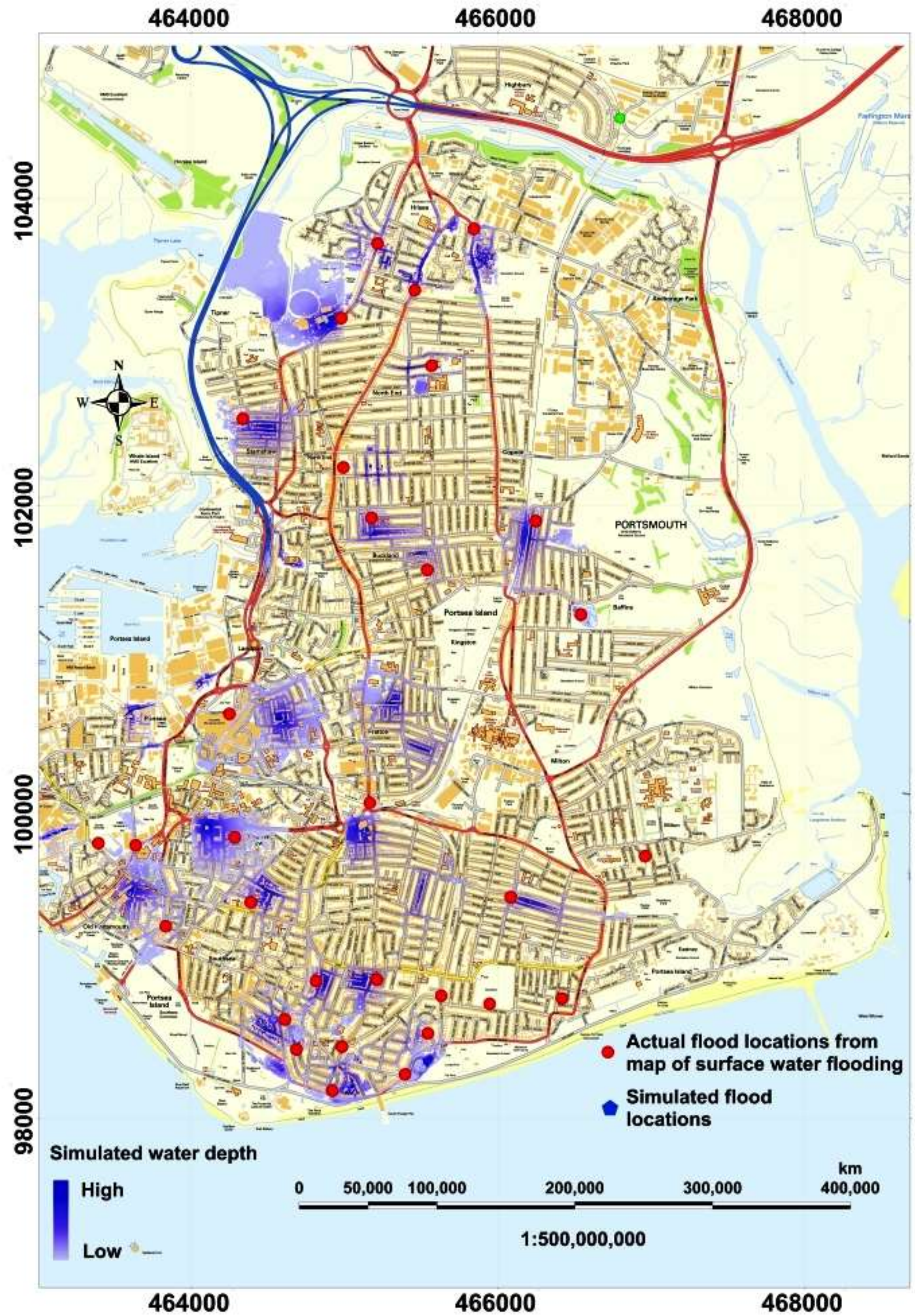


Figure 7-26 : Simulated flood locations compared with flood location shown on the map of hotspots of surface water flooding in Portsmouth

7.2.2 Model validation using social media-based information

Social media-based information has been used since there is ample evidence to show the increasing utility of such dataset in the management of disasters and crises (Latonero & Shklovski, 2011; Murthy & Longwell, 2013; de Albuquerque *et al.,* 2015; Alexander, 2015; Houston *et al.,* 2015). Social media is an excellent source of information, which has been extensively used in flood inundation studies, and this closes the data gap when authoritative and field-based datasets are lacking (Schnebele *et al.,* 2014; Fohringer *et al.,* 2015). The majority of previous studies that considered flooding in Lagos, for examples Adeaga (2008), Aderogba (2012a) and Ajibade *et al.* (2013) relied heavily on social media-based dataset such as Flickr, Twitter, newspaper reports, online photographs, anecdotal and eye-witnesses evidence. This is crucial to the present research, considering the need to explore and utilise these datasets in a more effective way.

In relation to the utility of social media-based information, research is still ongoing towards filtering relevant datasets from a large volume of social media sources, and the accuracy and reliability of information extracted from the social media (Poser & Dransch, 2010; Fohringer *et al.,* 2015). Although there is a number of well-known filtering techniques in the literature, the present research adopts 'filtering by key words' which has proved to be useful towards improving utility of the social media-based information (Smith *et al.,* 2015). The vital objective of applying this filtering technique is to ensure that the temporal and spatial features of social media-based information correspond to the particular flooding event under study, and this will helped to address the issue of accuracy and reliability. Fohringer *et al.* (2015) treated the issue of accuracy and reliability of social media-based information from the point of view of expediency. The study argues that the growing need for flood inundation data should not outweigh data availability with its reliability. Thus suitable data should be defined and used on the basis of availability, enabling the flexibility for updating or replacement by more authoritative datasets, and this is the driving principle of the model validation carried out in the present research.

In the present research, photographs have been used to validate *GFSP-1* because they show contextual information and situational relationship between water level and some parts of the environment such as buildings, submerged cars, and pavements. These enable the estimation of water depth depending on the extent to which the parts of the environment delineated by the photographs have been submerged by flood water. In estimating the flood water depth, the present research adopts the method of visual inspection of the photographs, in line with the study by Fohringer *et al.* (2015), which produce inundation maps of on the basis of photographs that were visually inspected to estimate inundation depth of the recent 2013 flooding in Dresden Germany. This method which is also applicable in photogrammetric and analogue remote sensing image interpretation is an expert elicitation technique which uses image properties such as shape, size, situation, shadow, etc., to estimate information from photographs.

In applying this technique to the present research, ten photographs were selected from archived documents of PCC to ensure that the appropriate pictures of the flooding events were selected. These photographs are shown in appendix E, but their thumbnails and used here to show how water depths have been estimated for the present research. Then the selected photographs were hotlinked to their appropriate flooded locations on the Portsmouth basemap (see figure 7-27). To extract the water depths from these photographs, the present research considered the assumption that a true value is unrealistic, and that redundant measurements are often made, and average taken, to obtain the most probable value (*mpv*). To implement this assumption, a range of values are estimated for water depth, considering the extent to which environmental feature have been submerged. For example if an adult is trapped in a flood water up to the knee level, then the water depth is estimated to lie between 0.5m and 0.7m. When a car is submerged up to the bonnet, water depth is estimated to lie between 0.7m and 0.9m. Submerged buildings are difficult in this regard, whilst water depth estimated within the interiors of houses differ markedly from that estimated outside the building compound. In the present research, only the outside flood water is considered. Knowing that many houses measure up to 1m from the flood to the window, it is easier to estimate that water depth lies between

1.5m and 2m for a building that has been submerged up to the top lintel. When a building is completely submerged, water depth is estimated to lie between 2.5m and above.

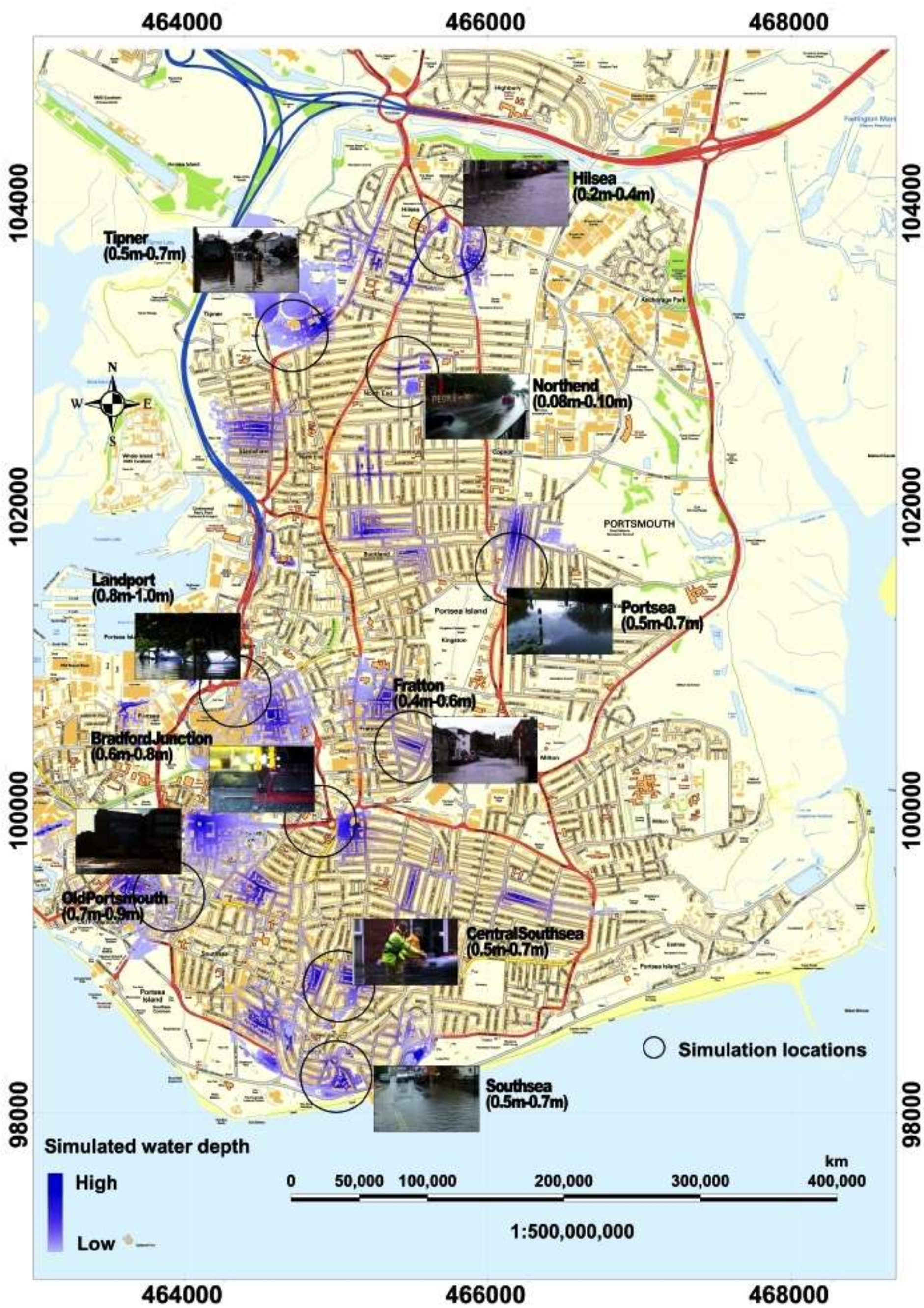


Figure 7-27: Thumbnails of selected photographs hotlinked to appropriate flooded locations on the Portsmouth basemap

The range of values estimated for maximum water depths, and their respective averages for each of the ten locations are tabulated with the maximum values water depths simulated by *GFSP-1* (table 7-3). These values were described as bar charts (figure 7-28) and scatter plots (figure 7-29), to give various representations of the relationship between simulated maximum water depth values and those estimated from photographs. From the scatter plot, the Pearson correlation coefficient *(r)* between the simulated and estimated water depths at the ten locations was found to be 0.986, which indicates model robustness. Thus, the table and the plots show that simulated maximum values compared relatively well with averages of estimated maximum ranges of values at the ten locations, although some significant variations occurred at Landport, Southsea, and Bradford junction. This might be due to the presence of retention ponds in those areas that were not accounted for in the LiDAR DEM used for the simulation.

Table 7-3: Estimated maximum water depths, respective averages compared with the maximum water depths values simulated by *GFSP-1* for Portsmouth

S/No.	Location	Estimated Maximum range water depth (m)	Average of estimated range of values (m)	Maximum simulated water depth (m)
1.	Central Southsea	0.5 - 0.7	0.6	0.649
2.	Tipner area	0.5 - 0.7	0.6	0.604
3.	Southsea	0.5 - 0.7	0.6	0.683
4.	Bradford Junction	0.6 - 0.8	0.7	0.769
5.	Portsea Island	0.5 - 0.7	0.6	0.658
6.	Old Portsmouth	0.7 - 0.9	0.8	0.817
7.	North end	0.08 - 0.1	0.09	0.079
8.	Landport area	0.8 - 1.0	0.9	0.981
9.	Hilsea	0.2 - 0.4	0.3	0.267
10.	Fratton	0.4 - 0.6	0.5	0.554

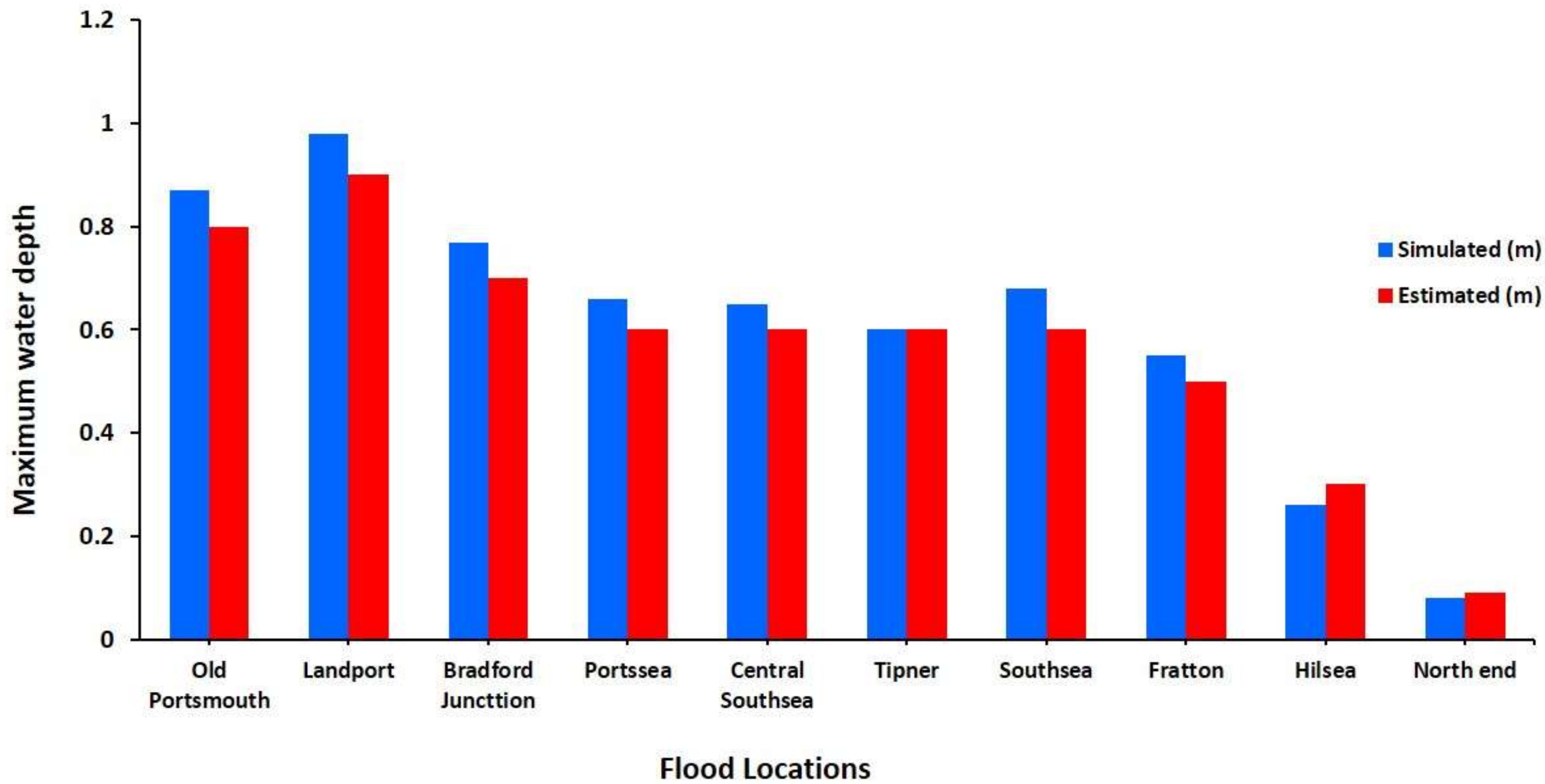


Figure 7-28: Bar charts showing the relationship between maximum flood water depth simulated using *GFSP-1*, compared with average water depths estimated from photographs of flooding in Portsmouth.

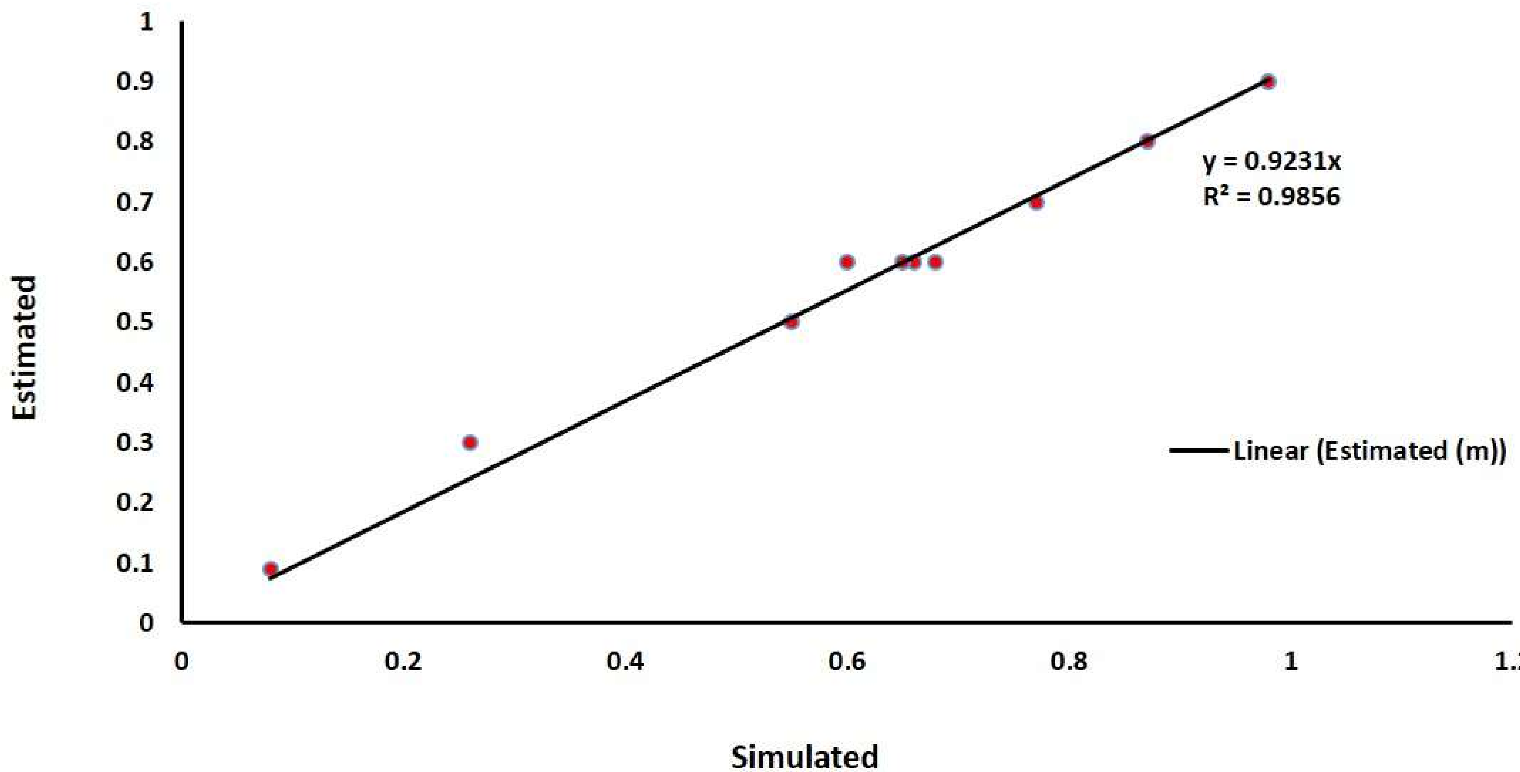


Figure 7-29: Scatter plot showing the relationship between maximum flood water depth simulated using *GFSP-1*, compared with average water depths estimated from photographs of flooding in Portsmouth. The correlation coefficient is computed here as 0.985

7.3 Simulation of Lagos July 11th 2011 flooding

This flooding event was reported in detail in chapter two. Key studies, for examples IFRC (2011), Aderogba (2012a) and Adelekan (2015) argued that the event, which resulted in economic losses estimated at millions of USD, was due to a severe pluvial event that lasted 17 hours producing about 463.3 mm amount of rainfall. There were no realistic scientific measurements available for water depth and extent, although Aderogba (2012a) claimed that measured flood depth in some places was over 6 feet. The area considered in this simulation covers places in the Lagos Island and Eti-Osa LGAs (see figure 7-30). These places were chosen based on the Lagos LiDAR dataset available for the model validation.

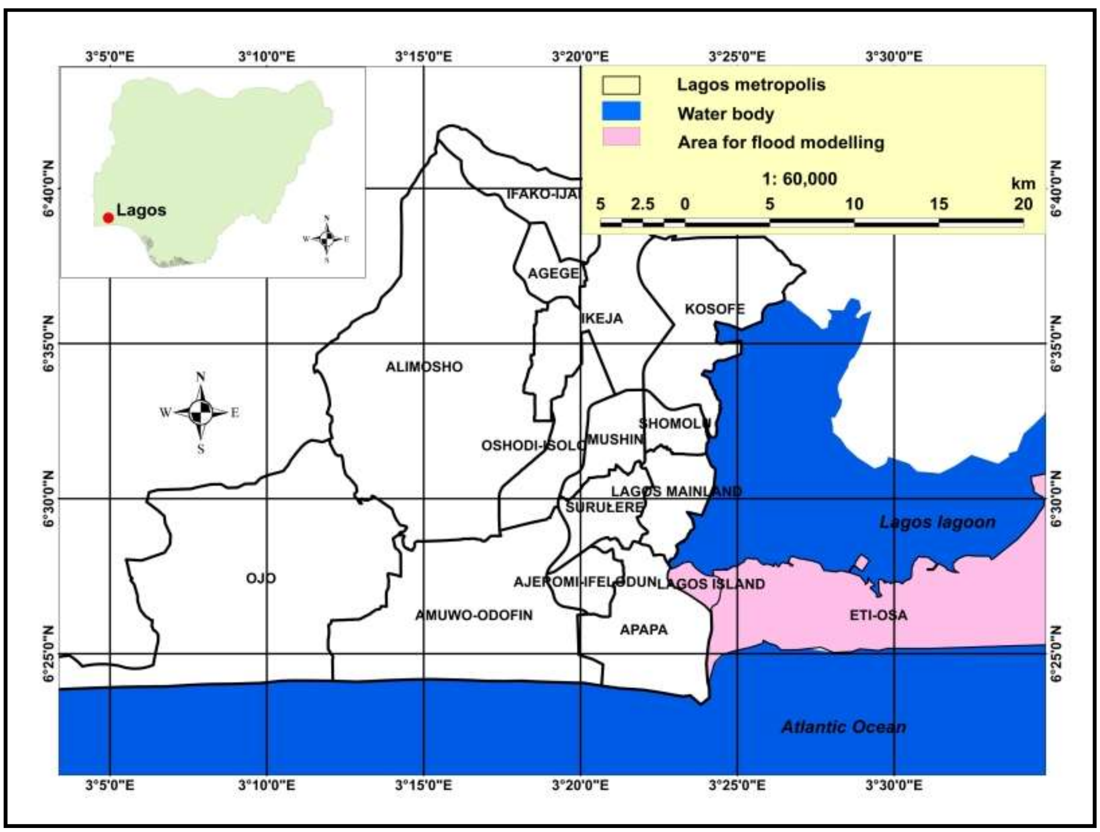


Figure 7-30: The Lagos area of Nigeria showing the location where flood simulation for the present study was undertaken. Inset delineates the location of Lagos within Nigeria

7.3.1 Data acquisition and processing

7.3.1.1 On-site survey

An on-site survey was conducted over the areas covered by the acquired Lagos LiDAR data. During this survey, thirty flood inundation locations were identified, whilst up to fifty anonymous residents were questioned, and this provided detailed eye witnesses' testimonies of the flooding event (see table 7-4). The geographical coordinates (Longitudes and Latitudes) of these locations were measured with the help of a handheld Global Positioning System (GPS) gadget. Photographs were taken of the physically perceived flooding inundation.

Table 7-4: Locations identified based on media reports and living evidence

S/No	LGA	Specific location	Longitude (Decimal degree)	Latitude (Decimal degree)	Source
P1	Lagos-Island	Balogun street	3.384	6.455	Vanguard
P2	Lagos-Island	Broad street	3.385	6.454	Vanguard
P 3	Lagos-Island	Macaulay street	3.397	6.453	Nkwunonwo *et al.,* (2016)
P 4	Lagos-Island	Idumago avenue	3.390	6.460	Eye witness
P 5	Eti-Osa	Osborne phase 6	3.411	6.460	Eye witness
P 6	Eti-Osa	Dolphin Estate	3.413	6.456	Vanguard
P 7	Eti-Osa	Federal Secretariat	3.413	6.456	Vanguard
P 8	Eti-Osa	Dolphin Estate	3.432	6.458	Street Journal
P 9	Eti-Osa	Obalande	3.432	6.444	Etuonovbe, (2011)
P 10	Eti-Osa	Falomo	3.421	6.443	Akanni & Bilesanmi, (2011)
P 11	Eti-Osa	Ikoyi	3.431	6.455	Ajibade *et al.,* (2013)
P 12	Eti-Osa	Ikoyi	3.431	6.446	IFRC, (2011)
P 13	Eti-Osa	Ikoyi	3.436	6.459	Etuonovbe, (2011)
P 14	Eti-Osa	Ikoyi	3.442	6.444	Vanguard
P 15	Eti-Osa	Ikoyi	3.447	6.461	PM news
P 16	Eti-Osa	Ikoyi	3.447	6.452	Etuonovbe, (2011)
P 17	Eti-Osa	Ikoyi	3.449	6.444	Nairaland forum
P 18	Eti-Osa	Ikoyi	3.444	6.440	CNNiReport
P 19	Eti-Osa	Castle estate	3.459	6.430	Eye witness
P 20	Eti-Osa	Castle estate	3.457	6.425	Eye witness
P 21	Eti-Osa	Castle estate	3.450	6.428	Eye witness
P 22	Eti-Osa	Castle estate	3.439	6.433	Eye witness
P 23	Eti-Osa	Victoria Island	3.437	6.427	Aderogba (2012)
P 24	Eti-Osa	Victoria Island	3.431	6.434	Ajibade *et al.,* (2013)
P 25	Eti-Osa	Victoria Island	3.428	6.439	Aderogba, (2012)
P 26	Eti-Osa	Victoria Island	3.429	6.431	Nkwunonwo *et al.,* (2016)
P 27	Eti-Osa	Victoria Island	3.419	6.430	IFRC, 2011
P 28	Eti-Osa	Victoria Island	3.410	6.435	IFRC, 2011
P 29	Eti-Osa	Victoria Island	3.413	6.428	Aderogba (2012)
P 30	Eti-Osa	Victoria Island	3.411	6.424	Oyinloye (2013)

7.3.1.2 Rainfall data and Manning's friction coefficient

The rainfall dataset were acquired from NIMET. Two months rainfall data at daily amount were acquired (see table 7-5). Similar to Portsmouth test case, the formula in section 6.5 of chapter 6 (i.e. equation 6-14) was applied to compute effective rainfall intensity, using rainfall data in table 7-5. Using this approach, the effective rainfall amount was calculated to be 0.623 mm/hr. Abstractions and other loses were not considered in the present simulation due to lack of data relating to them. Roughness coefficient (Manning's frictions value) of 0.02, suitable for simulation of flooding in urban areas was taken from Chow *et al.* (1988).

Table 7-5: Rainfall data for the July 11th 2011 flooding event. Source: NIMET

Date	July	August	Date	July	August	Date	July	August
1	2.5	0.0	*12*	0.0	0.1	*23*	0.0	0.0
2	50.6	44.3	*13*	8.1	2.6	*24*	0.0	0.0
3	1.3	0.0	*14*	11.1	0.0	*25*	0.1	0.1
4	0.0	1.4	*15*	0.1	0.0	*26*	0.1	1.6
5	25.8	0.1	*16*	1.4	0.0	*27*	0.0	4.0
6	2.5	4.2	*17*	49.2	0.0	*28*	4.0	2.0
7	14.6	0.0	*18*	0.0	0.0	*29*	0.0	0.0
8	0.2	3.4	*19*	0.0	0.0	*30*	3.1	4.9
9	0.8	0.0	*20*	0.0	0.0	*31*	0.0	14.5
10	252.4	0.0	*21*	1.2	0.0			
11	34.4	0.0	*22*	0.0	4.0	**TOTAL**	**463.5**	**87.2**

7.3.1.3 Lagos LiDAR DEM

The LiDAR DEM for this test case was acquired from GIS section of Lagos state office of Lands and Survey. As reported in chapter 2, Lagos is the only region in Nigeria that has acquired such dataset. Similar to the Portsmouth LiDAR DEM, each tile of Lagos LiDAR data forms a box of dense DSM, measuring 500 meters on all sides (i.e. 500 m column and 500 m row) (see figure 7-31). The Lagos LiDAR data is sold at a price, and comes in the original *(.las*) format with a horizontal resolution of 1m, and vertical accuracy of 10cm. Unlike the Portsmouth LiDAR DEM, this presents a major data acquisition and processing challenge for the present research. Each tile cost about twenty thousand Nigerian naira (i.e. £90 using the 2013 exchange rate). It was reported in chapter 2 that the cost of acquiring these datasets remains a significant constraint to flood modelling in Lagos. However, for the present research, 32 tiles (which produced about eight million cells) were acquired, to delineate flood hazard on a relatively wider spatial extent.

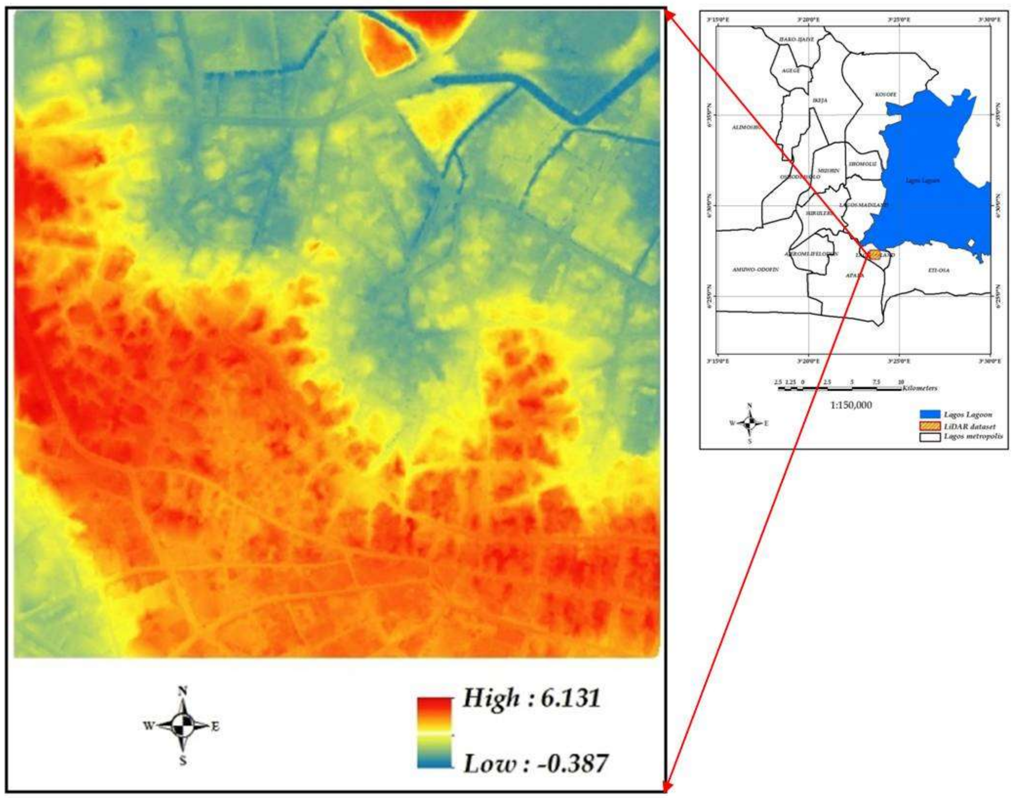


Figure 7-31: Sample of Lagos LiDAR DEM produced from point clod LiDAR dataset. The author converted the traditional (.las) files into readable 'ascii' format and then applied the natural neighbour interpolation resampling technique to generate a 2-m horizontal resolution DEM.

To prepare this data, a more rigorous three stage-process was used in this research. Firstly, LASSTOOLS open source program was used to convert the LiDAR (.las) DEM file to ASCII (.txt) text file. The resulting text file was not gridded and could not be read easily in ArcGIS program and by the code. Secondly, to generate gridded text files, the ASCII (.txt) text files were exported to Golden SURFER program and resampled. SURFER program applied a number of resampling algorithms, but the Nearest Neighbour resampling algorithm was chosen for the present research because of its suitability in many studies (Yates *et al.,* 2003; Fewtrell *et al.,* 2008). A pixel size of 2m was specified for grid output. The gridded data could not be recognized as a raster file in ArcGIS and was not read into the flood model. Finally, to deal with this problem, an open source program, GRID CONVERT, was used to convert the SURFER gridded DEM files to an ArcGIS recognisable ('.asc') files which was read easily into the flood code.

7.3.2 Simulation of flood water depth and extent

Similar to Portsmouth case, simulations of water depth and extent for the July 11th flooding was carried out on one tile at a time, and then the resulting simulated water depth were mosaicked. For each tile, flood was simulated for 17 hours in order to accommodate the duration of the pluvial event. Simulated water depth and extent were output and written as ascii files at 30 minutes, 2 hours, 5 hours, 8 hours, 11 hours, 14 and 17 hours. For the July 11^{th} flooding event, *GFSP-1* simulated flood inundation locations that matched the actual locations, identified during the on-site survey (figure 7-32). Only *P3* location, an area known as Onikan within Lagos-Island was wrongly predicted, as there was no evidence of flood inundation there.

From table 7-6, higher inundation depths were simulated around Balogun and Broad Street (2.15m), Adeyinka Oyekan Avenue (1.22m) in Lagos Island, and the area around Adetokumbo Ademola road (1.51m) in Victoria Island. This was mainly due to the relatively flat nature of the terrain at those locations. Apparently, the point with the lowest relative elevation in Lagos state, measured from 30-m horizontal, 20-m vertical resolution ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometers) global DEM is 6m, and the point is located within Lagos Island. A large amount of flood water tends to accumulate in the areas from the relatively higher areas and topographic features. The maximum depths of inundation simulated for the Dolphin estate and the eastern part of Victoria Island are 0.55m and 0.49m respectively. The area is characterised by built-up features that are nearly equal in elevation. There are a number of bifurcations, bridges and road junctions, around which flood water is often difficult to simulate using less efficient flood modelling methodologies (Hunter *et al.,* 2007). A low water depth (0.26m) was simulated at

Castle estate towards the Lekki area and bar beach. The area is characterised by few regular blocks of building and much open spaces and lawns within which water can be stored. In all the six locations, flood water extent was extensive and covers major and minor roads, a number of built-ups including schools, residential houses and open land spaces.

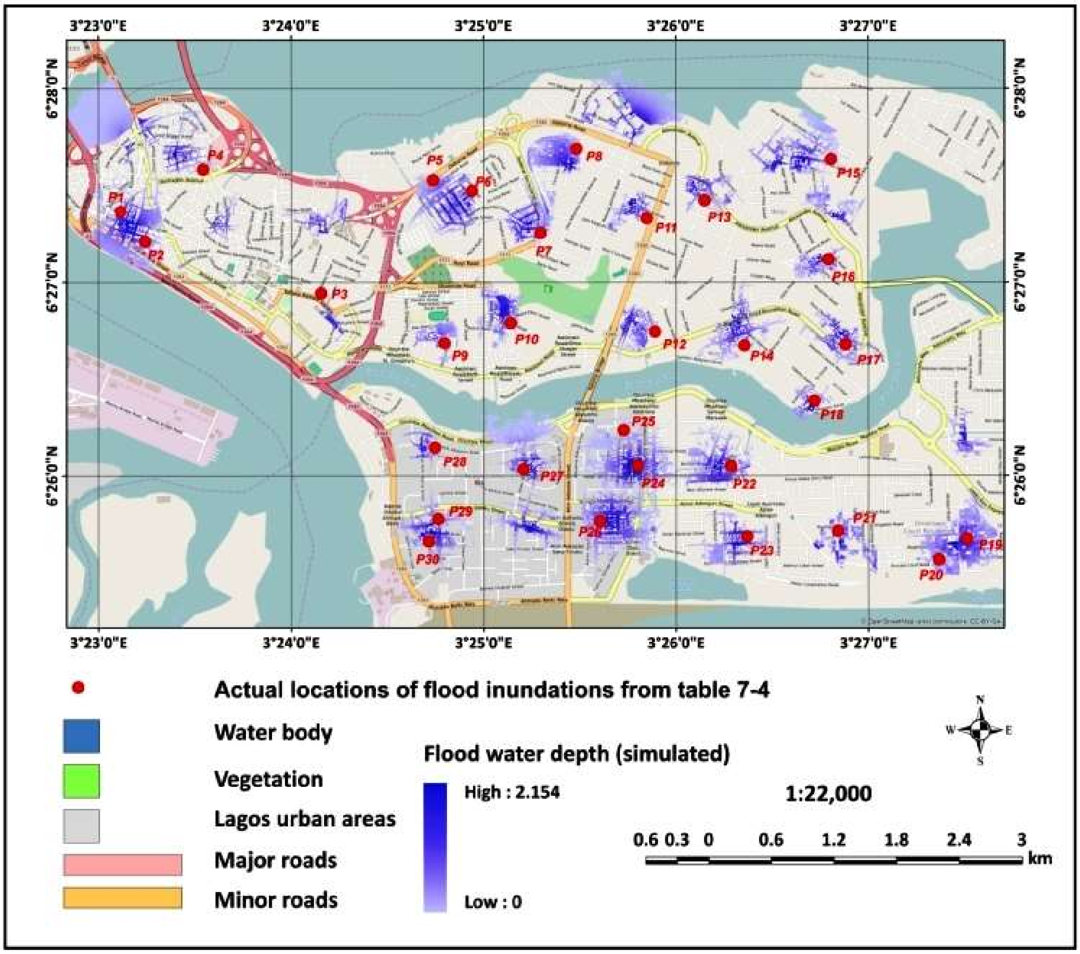


Figure 7-32: Simulated flooding inundation mapped against actual inundation locations based on secondary sources and eye witness evidence of the July 2011 flooding in Lagos.

To understand the true pattern of the July 11th 2011 flooding within the Lagos case study in terms of spatial and temporal flow variability, six locations were selected and studied. These locations are spatially distributed within Lagos-Island, Victoria Island, Dolphin estate, and Castle field estate. Results obtained from simulating the 2011 flooding event in these locations are shown in figures 7-33 to 7-38, and this indicate locations of flood inundation extent within the study area. The plots of water depth vs. time (figure 7-39 to 7-44) indicate that the simulated results are relatively stable solutions of flood hydrodynamics with respect to flood water depth and extent.

Table 7-6: Highest water depth simulated at the six simulation location in Lagos

S/No.	Location	Highest simulated water depth (m)
1.	Broad and Balogun Street	2.154
2.	Dolphin Estate	0.545
3.	Lagos Island	1.222
4.	Castle Road	0.262
5.	Victoria Island_2	0.486
6.	Victoria Island	1.511

From the temporal variations of inundation depth at the chosen locations shown in figure 7-39 to 7-44, the simulated water depth generally increased rapidly within the first two hours of the rainfall. Throughout the duration of simulation, results of simulated flood inundation show that water depth gradually increased or remained constant. It is likely that at these time intervals water is being transferred from filled higher cells (possibly the higher grounds) to lower cells (i.e. the downstream sub catchment areas).

Similar to the results of Portsmouth test case, the smooth curves in figures 7-39 to 7-44 show that the model simulation results are stable despite the absence of a stability condition, which is often used in many numerical flood models. Manning's friction coefficient used in the *GFSP-1* is important to maintain a gradual of water between cells in order to eliminate subcritical and supercritical phenomena which could render the results of the model unstable.

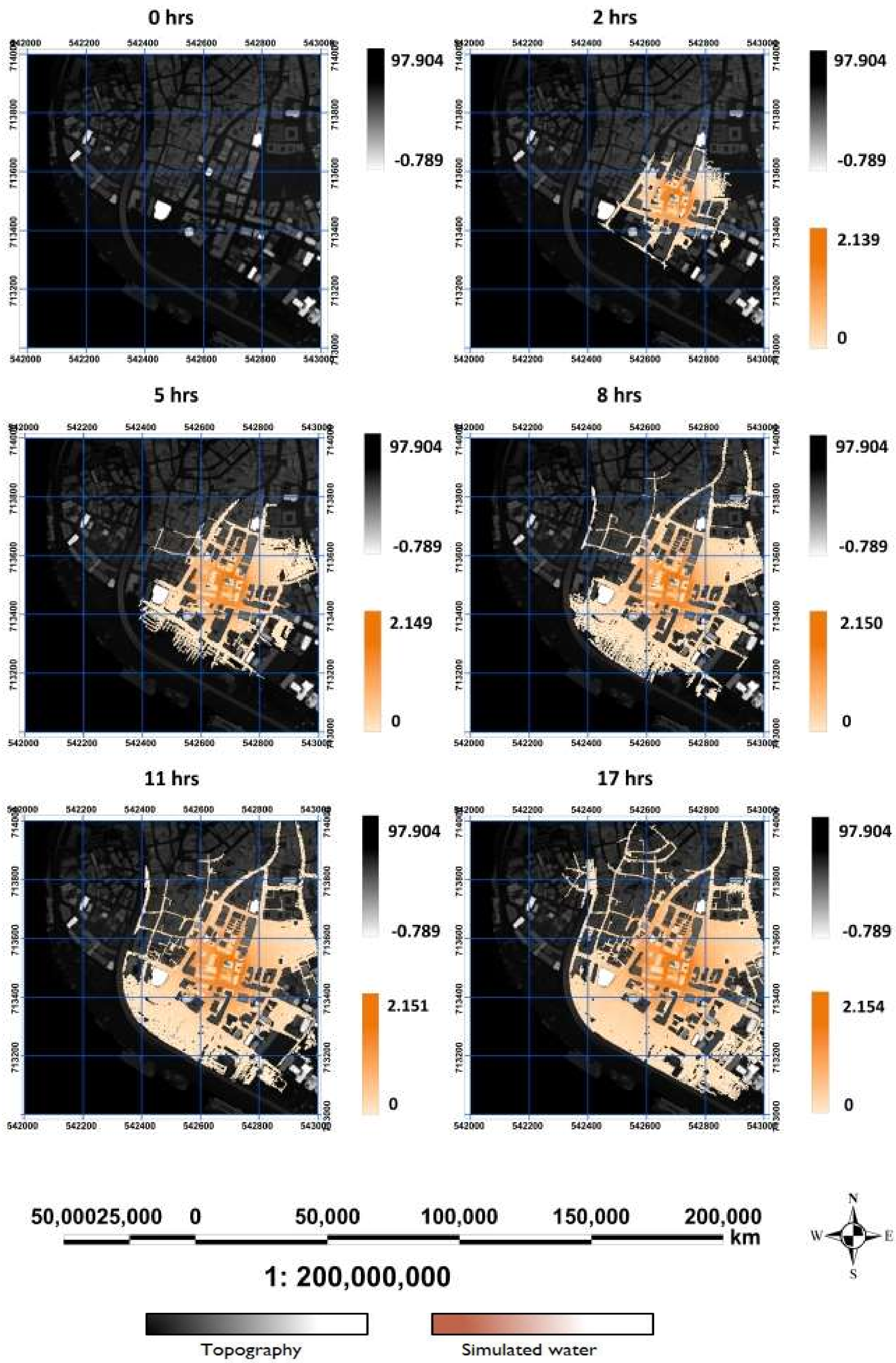


Figure 7-33: Simulated water depth at Broad and Balogun Street areas, Lagos Island.

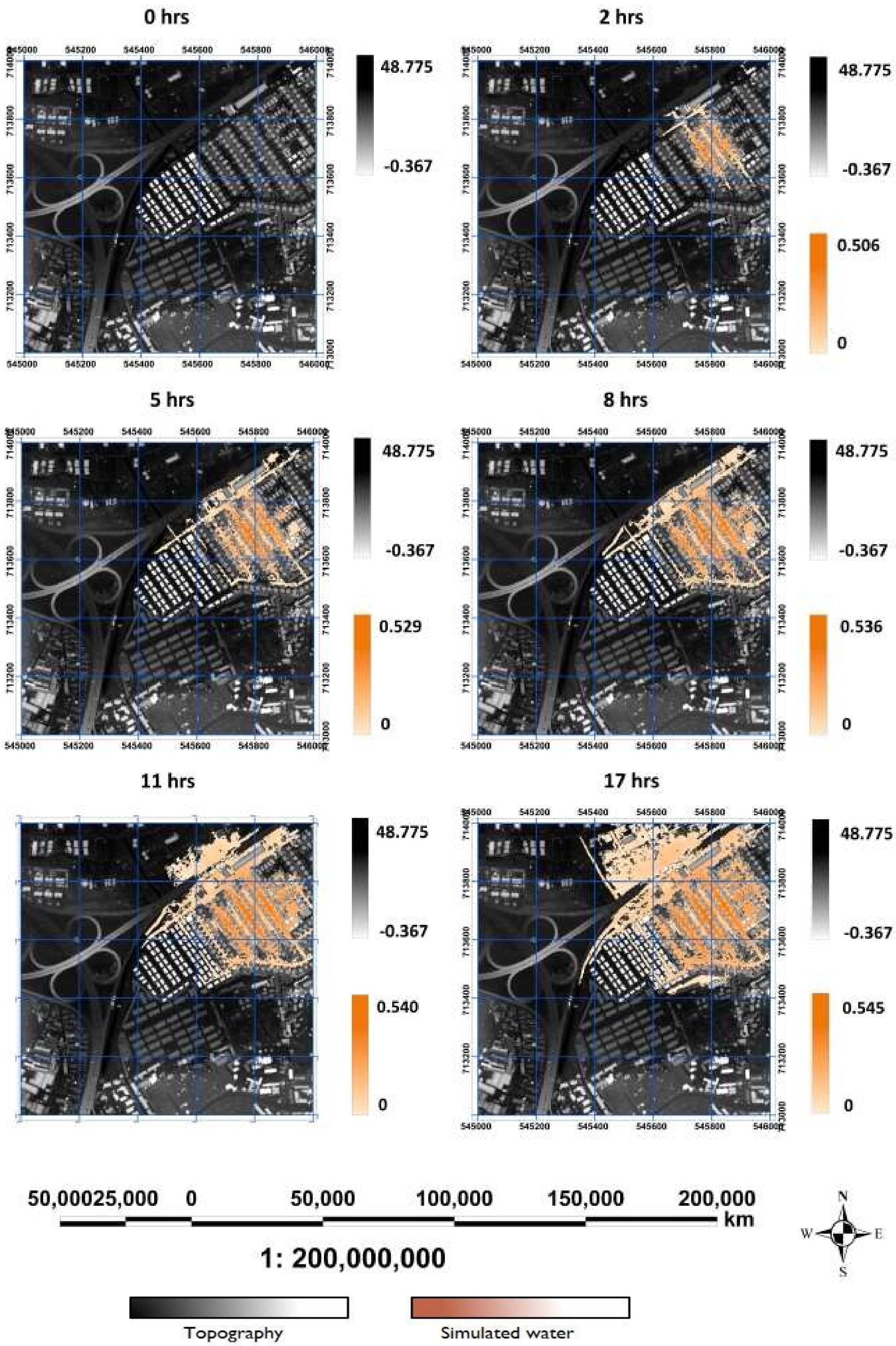


Figure 7-34 : Simulated water depth at Dolphin estate

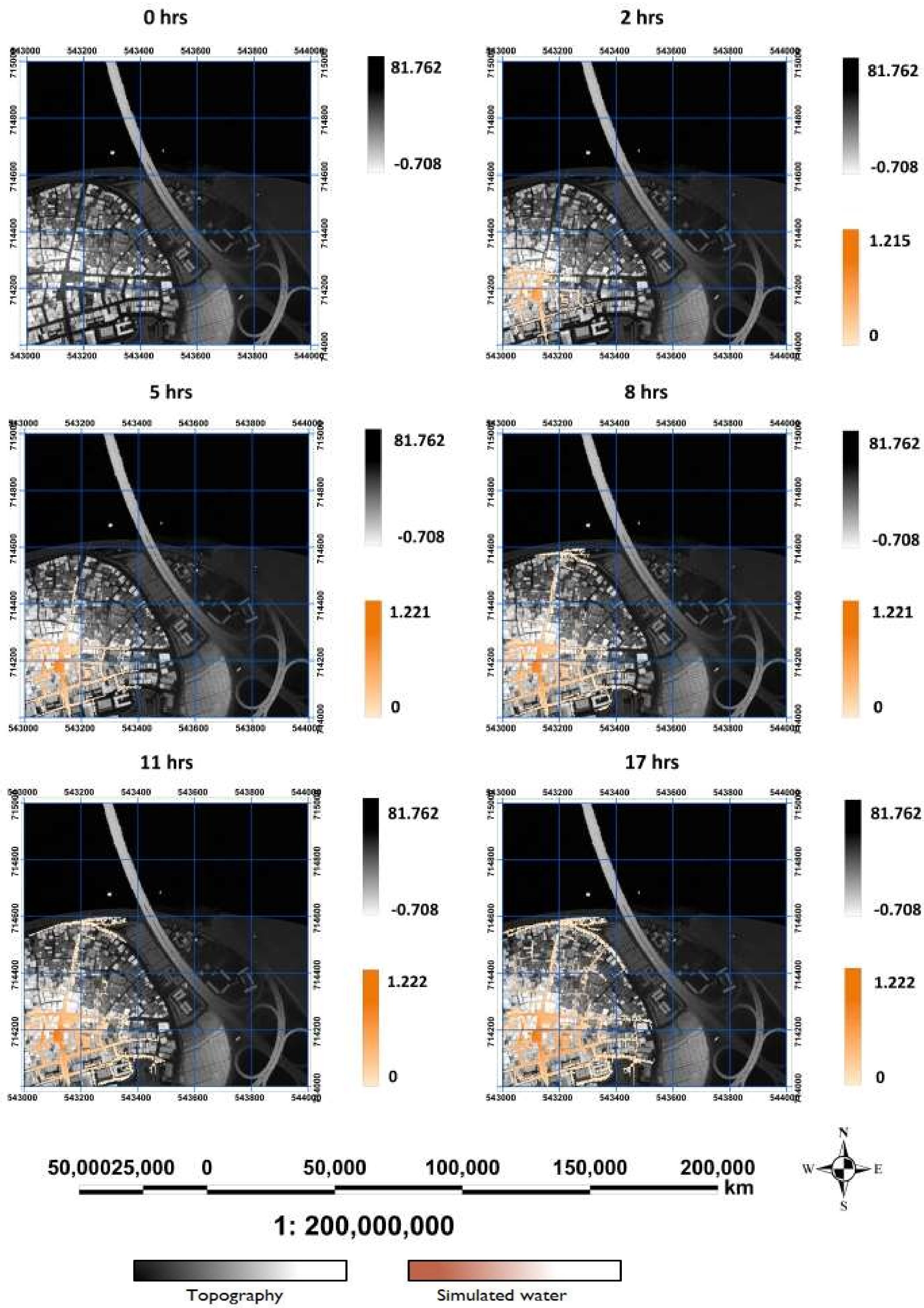


Figure 7-35: Simulated water depth at Lagos Island

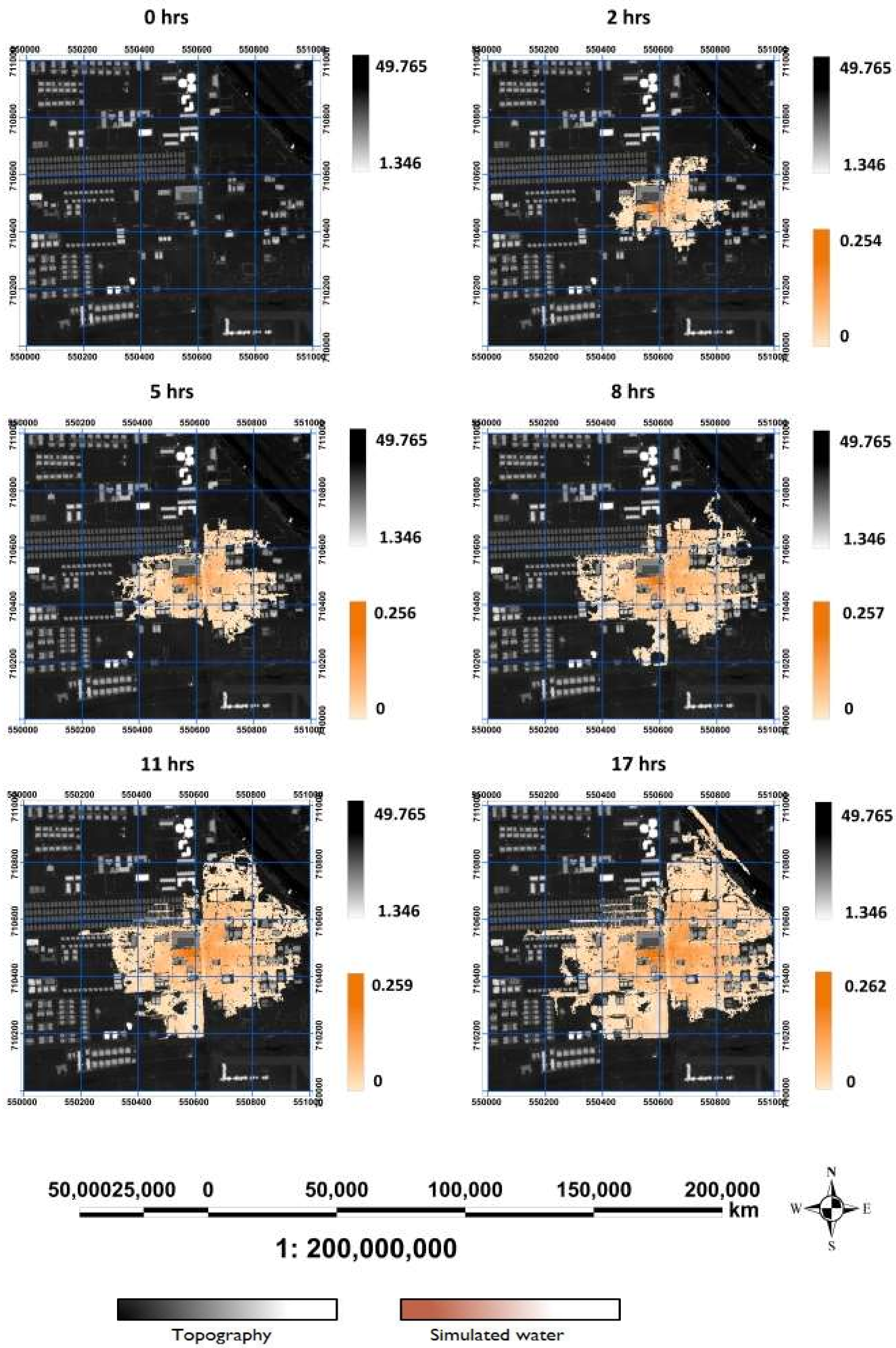


Figure 7-36: Simulated water depth at Castle estate

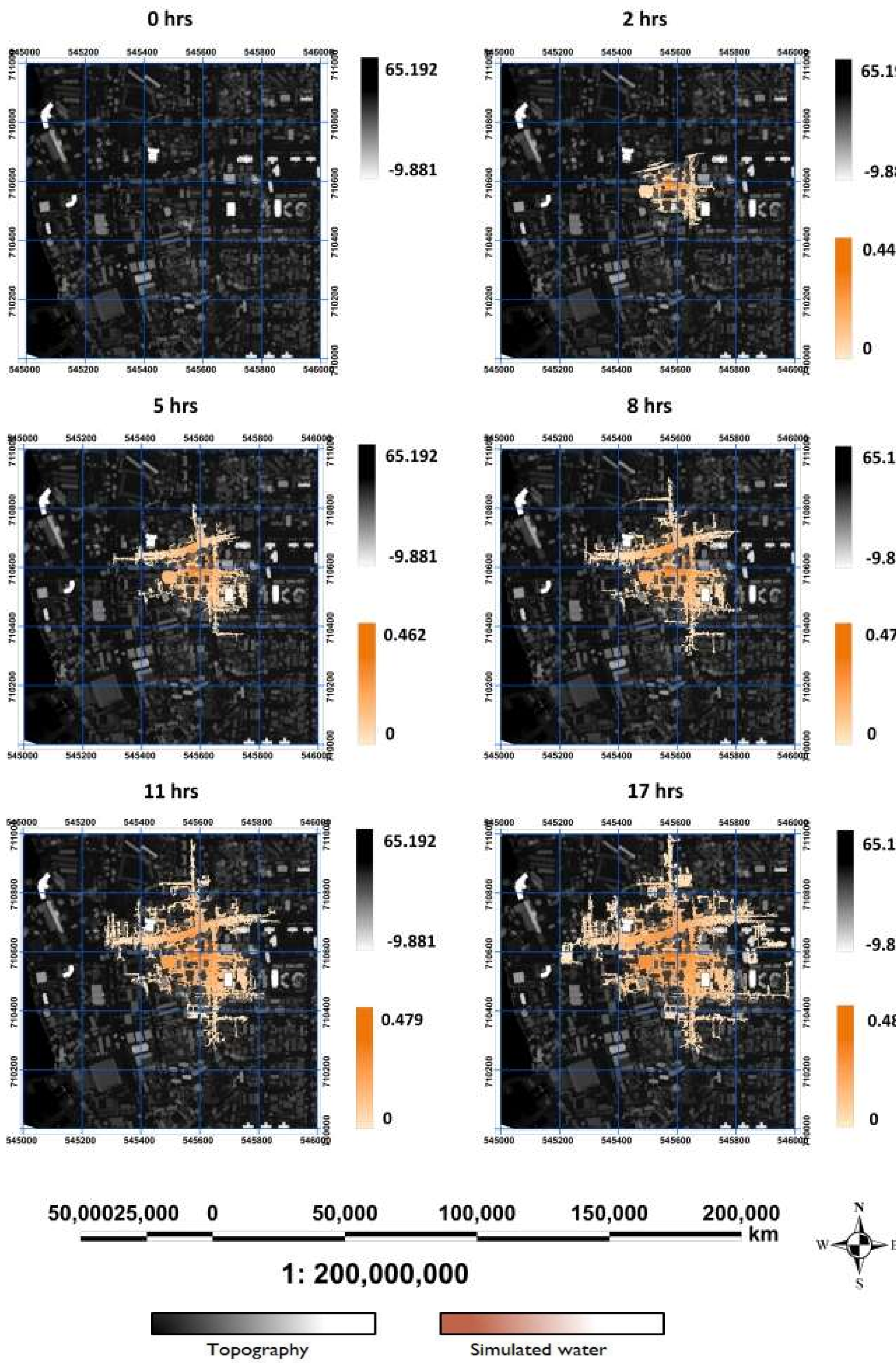


Figure 7-37: Simulated water depth at Victoria Island

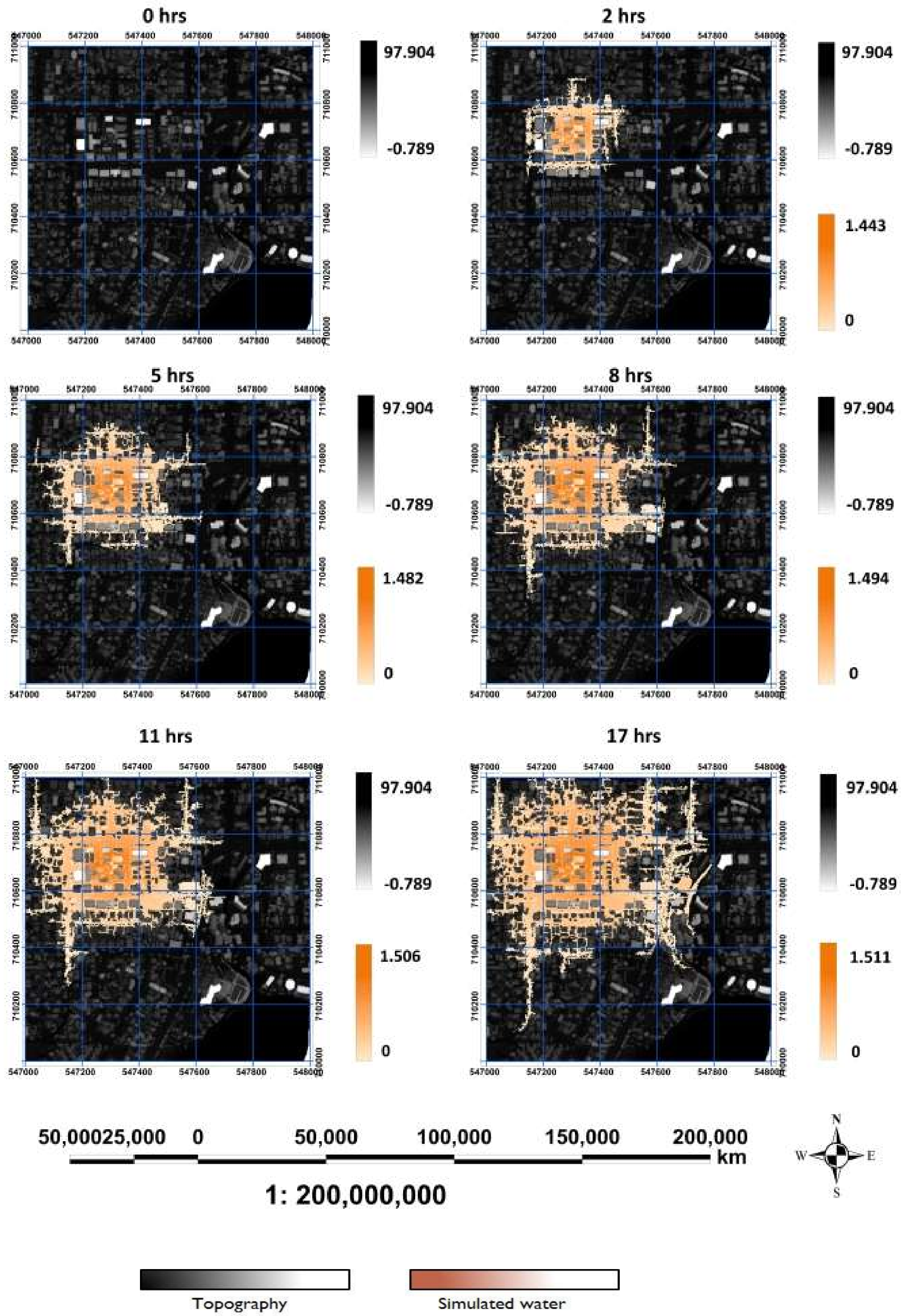


Figure 7-38: Adetokumbo Ademola road in Transit area, Victoria Island

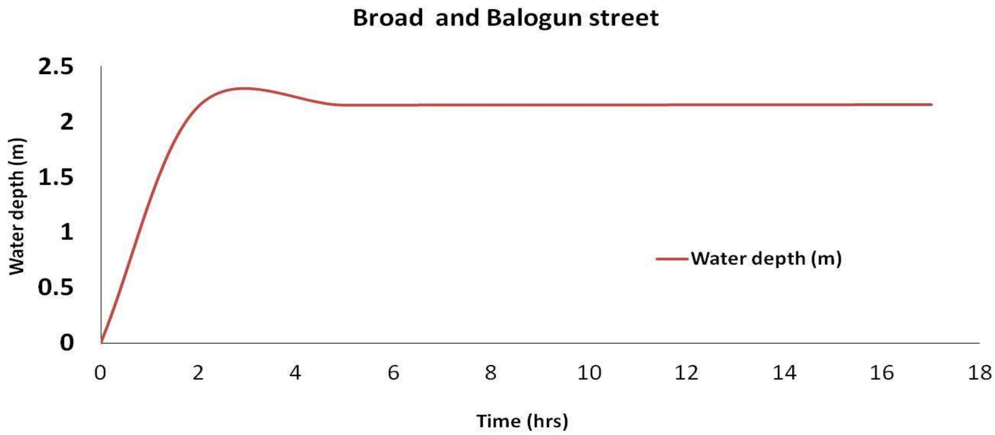


Figure 7-39: Plots of simulated water depth vs. time for Broad and Balogun street

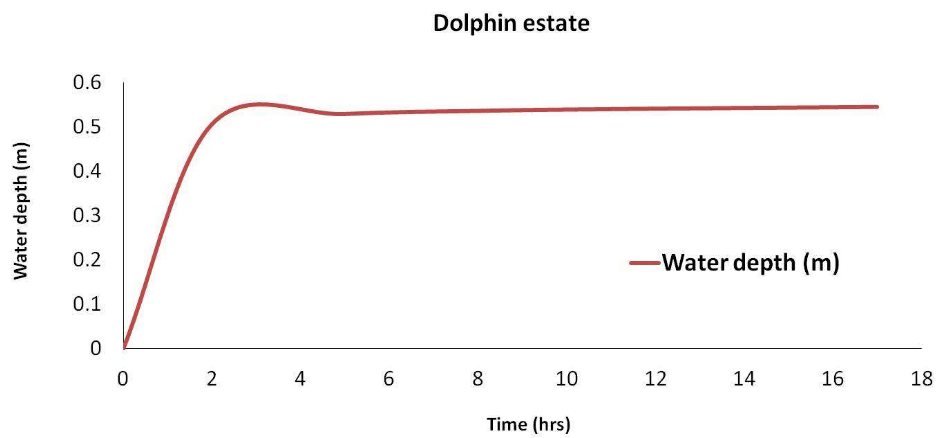


Figure 7-40: Plots of simulated water depth vs. time for Dolphin estate

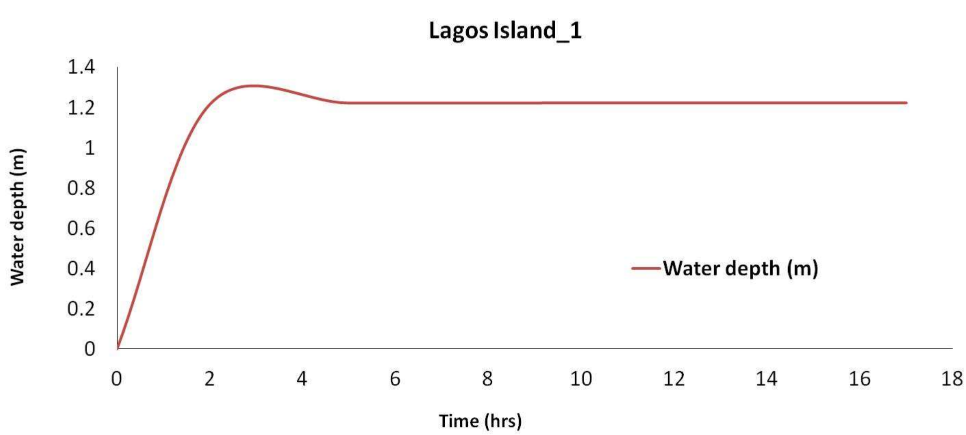


Figure 7-41: Plots of simulated water depth vs. time for Lagos Island 1

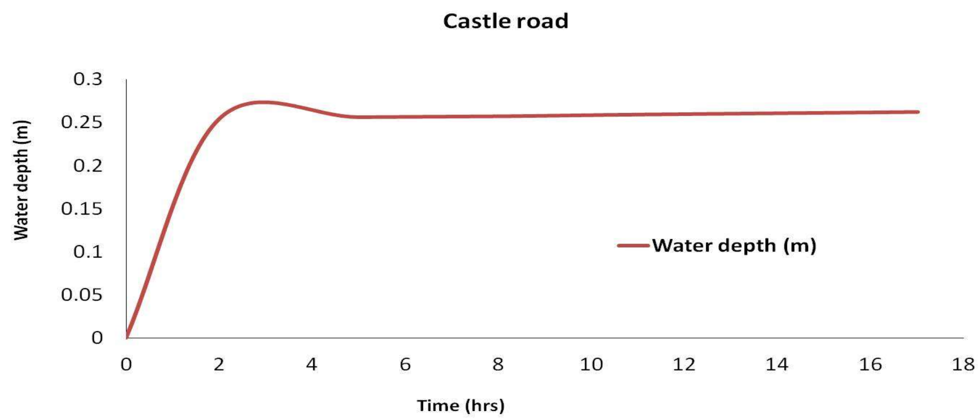


Figure 7-42: Plots of simulated water depth vs. time for Castle Road

Figure 7-43: Plots of simulated water depth vs. time for Victoria Island 2

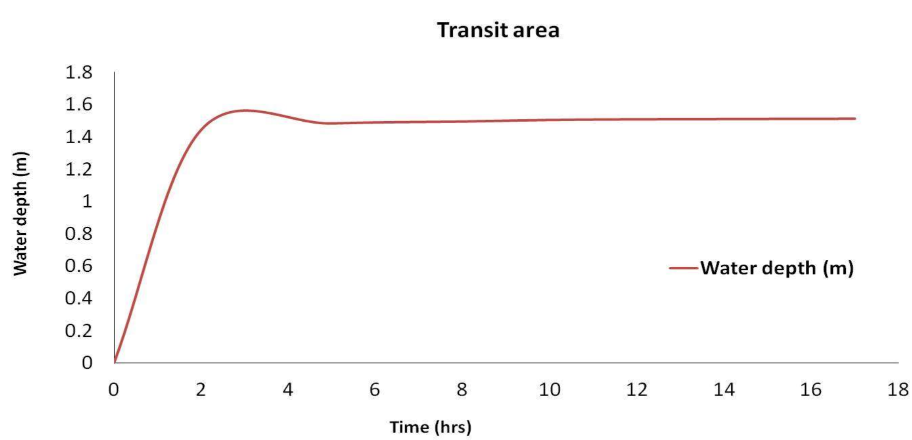


Figure 7-44: Plots of simulated water depth vs. time for Transit area / Victoria Island

7.3.3 Validation of simulated flood water depths

This operation was carried out using the method already described in the Portsmouth test case (see pages 203-205). For the Lagos test case, six photographic images of July 11th 2011 Lagos flooding carefully selected from online sources (shown in appendix F) were used to estimate ranges of flood water depth. Similar to Portsmouth case, these photographs were hotlinked to their appropriate flooded locations within the case study areas on the Lagos basemap (figure 7-45).

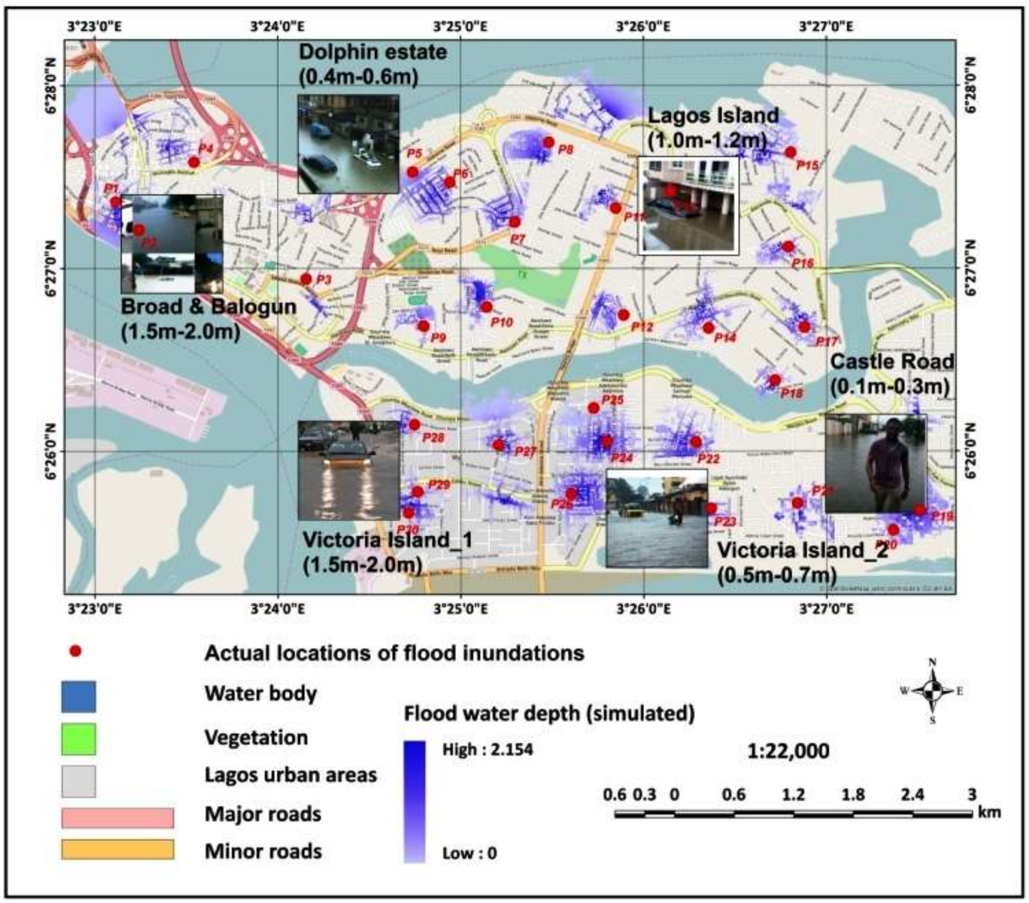


Figure 7-45: Thumbnails of selected photographs hotlinked to appropriate flooded locations on the Lagos basemap

The range of values estimated for maximum water depths, and their respective averages for each of the six locations are tabulated with the maximum values water depths simulated by *GFSP-1* (table 7-7). These values were outlined as bar charts (figure 7-46) and scatter plots (figure 7-47), to show various representations of the relationship between simulated maximum water depth values and those estimated from photographs. From the scatter plot, the Pearson correlation coefficient (r) between the simulated and estimated water depth was found to be 0.968, which is strong and indicative of robustness of the new flood model. Thus, the table and the plots show that simulated maximum values compared relatively well with averages of estimated maximum ranges of values at the six locations, although some significant variations occurred at Broad and Balogun street, Castle, and Lagos Island areas. This might be due to the presence of retention ponds in those areas that were not accounted for in the LiDAR DEM used for the simulation.

Table 7-7: Estimated maximum water depths, and their respective averages compared with the maximum water depths values simulated by *GFSP-1* for Lagos.

S/No.	Location	Maximum estimated range of water depth (m)	Average Maximum estimated range of water depth (m)	Highest simulated water depth (m)
1.	Broad and Balogun Street	1.8 - 2.0	1.9	2.154
2.	Dolphin Estate	0.4 - 0.6	0.5	0.545
3.	Lagos Island	1.0-1.2	1.1	1.222
4.	Castle Road	0.1 - 0.3	0.2	0.262
5.	Victoria Island_2	0.5 - 0.7	0.6	0.486
6.	Victoria Island	1.5 - 1.7	1.6	1.511

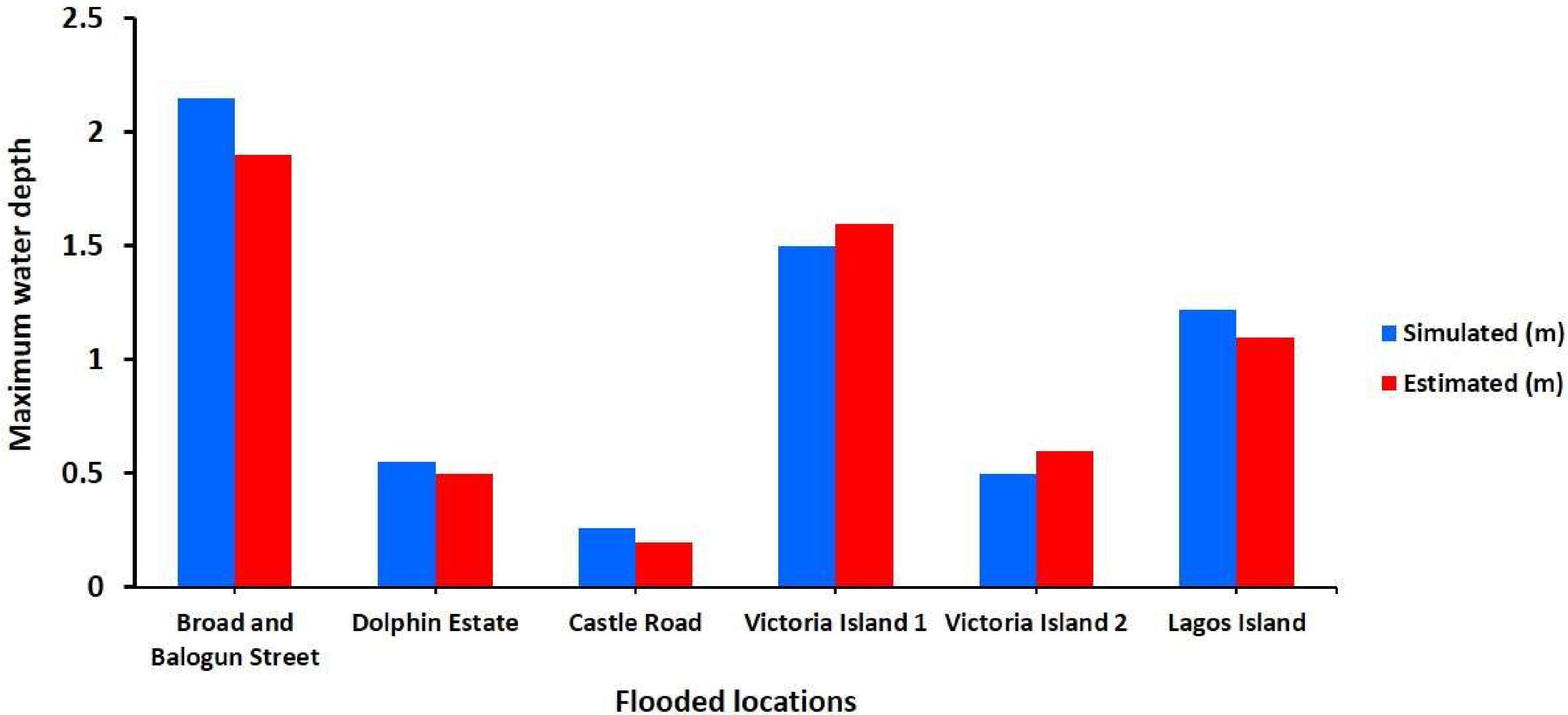


Figure 7-46: Bar charts showing the relationship between maximum flood water depth simulated using *GFSP-1*, compared with average water depths estimated from photographs of flooding in Lagos.

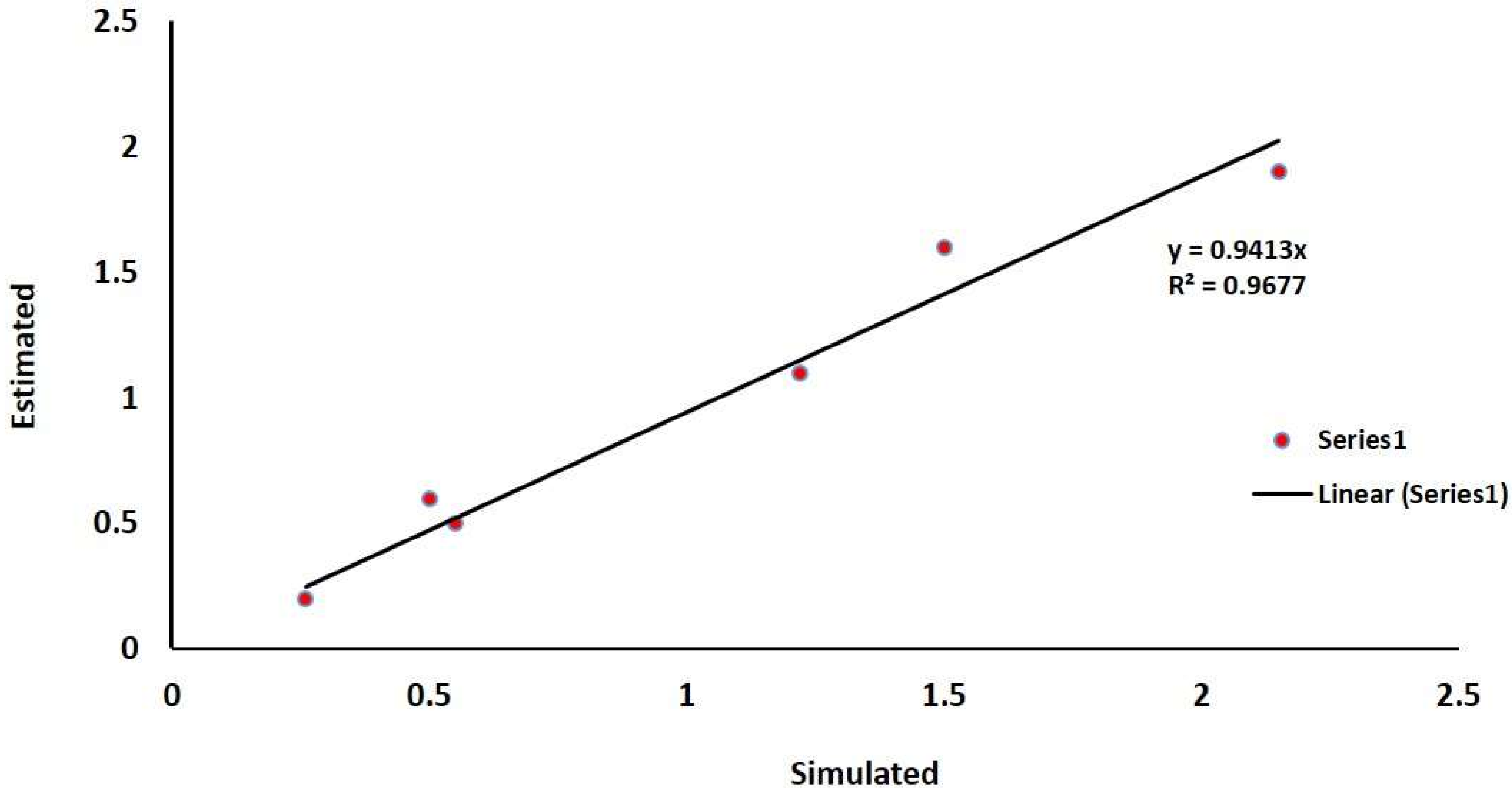


Figure 7-47: Scatter plots relationship between maximum flood water depth simulated using *GFSP-1*, compared with average water depths estimated from photographs of flooding in Lagos. Computed correlation coefficient is 0.968.

7.4 Summary

The lack of funds to acquire detailed validation datasets, and the limited time and maintenance available for international student to complete their PhD and leave the United Kingdom, were major issues to the rigorous model testing and validation in the present research. However, *GFSP-1* flood model was firstly applied to Portsmouth, United Kingdom, and this simulated a realistic flooding event that occurred on September 15th 2000, for which photographic images, and map of hotspots of surface water flooding were available to enable a pragmatic and heuristic model validation. The model also simulated spatial and temporal scenarios of the Lagos flooding event that occurred in July 11th 2011. These testing procedures were all carried out using a 2-m horizontal resolution LiDAR DEM, rainfall intensity value and Manning's friction coefficient.

GFSP-1 simulated flooding at locations that are similar to actual flood locations. Simulated maximum water depth at selected locations in Portsmouth and Lagos compare well with maximum water depths, estimated from available photographs with strong correlation coefficients at both locations. This indicates that the new model performs optimally in terms reconstructing urban flood characteristics. Additionally, the plots of water depth vs. time which produce a smooth curve throughout the simulation, and the short time used up in the simulation show that the model's outputs are unconditionally stable, and inexpensive from a computational point of view. This suggests the possibility to analyse flood hazard over a selected specific area in Lagos in terms of the flood water depth, extent, and duration, and thus answers a key question of the present research.

Coupling of SIFDS and CA within the framework of a new flood model is the key innovation of the present research, and significant contribution to the science of flood modelling, but it also addresses the fourth research question in relation to the capability of combined CA and SIFDS method for modelling urban flood hazard in Lagos vis-a-vis model convergence, stability and computation cost. These issues are and others relating to the present research are discussed in the next chapter.

8 General Discussions from the Results

This chapter presents various discussions emerging from the study and these include: the implications of the gaps and other issues arising from the review of Lagos urban flooding and management presented in chapter 2. This chapter also discusses those factors, which contribute to social vulnerability in Lagos urban flooding, as well as some social science concept which may be useful in view of future expectations in addressing the challenges of social vulnerabilities to Lagos urban flooding. Finally, the chapter also presents further discussions on the strengths and weaknesses of GFSP-1 using the results of the test cases.

8.1 Implications of gaps in flood risk management in Lagos

The current situation of flood risk management in Lagos, given the potential gaps in knowledge, is arguably indicative of a whole system failure, which suggests the need for holistic management approach including political, environmental and economic decision-making. Based on the review of Lagos urban flooding and management, presented in chapter 2, a number of significant issues were identified. These include: (1) lack of data relating to flooding and its consequence, (2) poor perception of urban flooding and its related threats, (3) limitations in present flood risk management efforts, (4) lack of more scientific procedures such as flood modelling, and (5) 'unidentifiable' method of flood risk assessment.

The understanding that issues such as these are main drivers of research is prominent in the current literature (see for example Samuels *et al.* 2006; Merz *et al.,* 2010; Kundzewicz *et al.,* 2014). Unfortunately, the specific implications of these gaps and how they are intimately linked to sustainable human and urban development within Lagos context has not been attempted by research. Thus, discussion directed towards the implications of these gaps on urban flooding, its management as well as urban development in the Lagos area of Nigeria is of critical importance. It is intended to identify specific research needs and directions for developing policies towards addressing the challenges of urban flooding in Lagos and thus bridging the gaps in knowledge.

Various studies in the literature which provide ample evidence of the effects of such gaps in other places can be extended towards Lagos. For example the result of a study in Slovenia reveals that lack of data on social variables undermines information management and public responses to flood mitigation measures and causes differences in flood threats levels perceived by residents (Brilly & Polic, 2005). There is an indication that the lack of a sound flood risk assessment and mitigation strategy exacerbates the challenges of flooding at various spatio-temporal scales (Mashael, 2010; Molinari *et al.,* 2016). Flood risk in terms of human and environmental impacts within Lagos context is expensive from economic point of view. Development programs are often interrupted, in addition to economic potentials of the area being undermined by disruption of small and medium scale enterprises (SMEs), which is a vital aspect of Lagos' economy (Aremu & Adeyemi, 2011). Whilst the level of urban poverty is escalating, human capital is being gradually lost as a result of deaths, injuries and long-term trauma suffered by individuals who were affected by flooding. The cost of reconstruction and rehabilitation following urban flooding event is significant and in most cases leads to diversion of funds originally planned for sustainable urban development programmes (OCHA, 2012).

Collaborations at global, regional and national levels increase the potentials for proper management of flood risk (Schanze, 2006; Almoradie *et al.,* 2015). However, it is expected that a participating member achieves a minimum standard of flood management policy (European Communion: Barredo, 2007). Despite the progress being made by many of the European countries, the lack of capacity for flood hazard and flood risk mapping alongside preliminary assessment of flood risk especially in Greece, Athens and Flanders in northern Belgium, remains a major setback towards implementation of the EU Flood Directive (Kandilioti & Makropoulos, 2012; Kellens *et al.,* 2013; Yannopoulos *et al.,* 2015). For the Lagos area, given that FRM is characterised by a weak institutional capacity, whilst flood risk and hazards maps for a preliminary assessment of flood risk are lacking, an important direction for research is the possible means to meet a minimum acceptable measure of flood risk policy for collaboration towards improved FRM.

Adapting existing methodologies to local case studies is a key to enhancing local capacities in FRM. However, the achievement of such a goal is being undermined by lack of validation and poor technical and financial capacities (Büchele *et al.,* 2006). For example, in Canada, poor access to necessary tools and guidance for risk managers to adequately undertake rigorous risk assessments constitutes a potential challenge towards implementing FEMA's HAZUS risk estimation model (Nastev & Todorov, 2013). There is a wide range of recent approaches that are being used to improve the concepts of flood modelling, cost-benefit analysis (CBA), stage-damage functions, digital city, early warning systems, etc., which can be applied within Lagos context towards improved FRM policy. However, given the limitations in the current

FRM efforts in Lagos, these approaches still require major capacities that are presently lacking in Lagos.

The notion that climate change will combine with increasing rate of urbanisation to intensify the threats of flooding in the future is a major impetus for recent developments in FRM. As discussed in chapter 3, climate change scenarios are being integrated in many FRM strategies and policies globally and regionally. This underscores the preparations being made towards the idea of living with floods. However, in the Lagos area of Nigeria, a major uncertainty surrounds the means to address these issues. With the large numbers of slums areas in addition to other critical issues, the question of preparedness in view of future uncertainties of flood hazard continues to emerge.

There is need to focus attention towards a number of important areas of research. Stage damage functions – which are presented in section 2.2 of chapter 2 – are widely accepted tools for ex-post and ex-ante FRA (Samuels *et al.,* 2006; Merz *et al.*, 2010; Hammond *et al.,* 2015). The benefits which Lagos FRA can derive from such a tool depend on the availability of data relating to water depth and extent of flooding events and this presents an important research need. Flood modelling techniques which can be used to reconstruct particular historical flooding events (such as 1 in 50, 1 in 100, 1 in 200, 1 in 500 and 1 in 1000 flood return periods) in terms of inundation depth, extent and water flow velocity also presents a research need. The use of simulated flood data to predict future occurrences of flooding in Lagos towards improving the warning systems currently in place as well as fields survey to determine properties and assets at risk needs research attention.

8.2 Relevant factors associated with social vulnerability in Lagos

8.2.1 Age distribution

The influence of age distribution on the overall social vulnerability to flooding is well recognised in the literature and across various spatio-temporal scales (Rygel *et al.,* 2006; Li et *al.,* 2014). In the UK and many other European countries, the people most vulnerable to flooding are usually between the age ranges of 0 -14 and 70 and above (Pitt Report, 2012). The majority of the people within these age groups are mainly infants and toddlers and older people who are often isolated, infirm or totally dependent on carers. Identifying how to prioritize such groups during emergencies is a critical necessity for disaster risk reduction which has been little researched (Flanagan *et al.,* 2011).

For the Lagos area, the large number of such vulnerable group suggests the need to engage stakeholders in building a community's social capacity. The result of social vulnerability analysis carried out in this research reveals that more than 30% of the total sampled population are people within the vulnerable groups (0-14 and 70-85+ age groups). Birth rate in Lagos and immigration of large number of aged people from other parts of Nigeria for health reasons, pursuance of retirement benefits and other exclusive reasons are possible responsible factors (Barredo *et al.,* 2004). Due to the housing pressure in Lagos, some of these aged migrants are forced to squat with relatives and friends. Issues experienced among squatters in Lagos such as: overcrowding, ease of evacuation and most importantly the suitability of living apartments to the health needs are too often ignored in the literature. In the event of flooding, these issues limit the capacities to cope and increase the social vulnerability of urban residents within the area.

8.2.2 Marital status

Data available for marital status in Lagos are grouped as: 'never married', 'unmarried' and 'widowed'. The distinction between the classes seems difficult to explain, although the 'widowed' class appeared to be more pronounced. Despite the nearly equal number of men and women in the highly vulnerable LGAs, up to 20% of the total sampled population are women who are either widowed or without marriage partners. Widowhood can have far-reaching implications in the context of social vulnerability to flooding in Lagos, although investigating these implications has not been attempted. Few authors such as: Cutter *et al.* (2003) and Ajibade *et al.* (2013) who considered social vulnerability argued on gendered issues which slightly can be linked to widowhood. Employment low-wage informal sectors, child care responsibilities and low earning capacity are some of the likely gendered issues that can be associated with widowhood.

Although little is known about the socio-economic status of widows in Lagos, it is argued that the majority of them are likely to be poor with little education to access financial aids and facilities. Many of them are also single parents and responsible for children (up to 8 in worst scenarios). Given the low level of income, only low quality accommodation such as in the slums can be affordable to these individuals. Due to the lack access to better urban facilities – such as good drinking water, more convenient sanitation facilities, more convenient cooking energy, quality health care and better media and communication systems – which essentially characterise these slums areas, the tendency for susceptibility and a lack of coping capacity to flooding is high. Moreover, losses incurred following flooding event are almost irrecoverable for such people since they lack the facilities to get supports from insurance companies.

8.2.3 Disability

Andrew *et al.* (2008), Ranci (2010) and Flanagan *et al.* (2011) have argued that disability is generally a well-known predisposing factor to social vulnerability, but this is more critical in the Lagos area, in which the proportion of disabled people is about 2% the total sampled population. However, being ranked with the other variables suggests that its impacts towards the overall social vulnerability to flooding in the area have been significant. Based on author's local experience, disability is a poorly treated human condition in the Lagos metropolis and indeed Nigeria. Besides those who are managed by family members or are in special needs centres, many disabled persons in Lagos are always on the streets, bus-stops, bus garages and church gates begging for alms. Although they are believed to return to 'homes', but in fact little is known about where they actually retire to after each day – streets, main roads, cemetery, etc., If they retire to homes, arguably, the standard of these is expected to be poor. A major question of social responsibility emerges in consideration of these issues and their management in Lagos. It is possible there are studies (past and present) regarding the plight of the disabled people in Lagos and how to address them, but to date, the author has not been able to identify these.

Disabled persons in Lagos substantially account for more people living in slum areas which for the best part increase the social vulnerability to flooding (NPC, 2007). Thus, the poor attention disability has receive on the average and the prevalence of flooding in Lagos suggest the need for more empirical investigation into the extent to which disability influences the overall social vulnerability to flooding in the area.

8.2.4 Family structure

The way in which families are organised in terms of size, relationships, hierarchies and income capacities is an important factor of social vulnerability (Cutter *et al.,* 2003; Iwasaki *et al.,* 2005; Brouwer *et al.,* 2007). Individual values and ideologies too often form the basis for consistent variations in family structures across different ethnic, cultural and religious backgrounds. Within this framework, a major determinant is family size and how this is controlled on the basis of birth control measures remains an issue of global significance. In the more developed countries, the level of public awareness and the advancement in medical and genetic science correlate with improved form of birth control measures (Tuladhar & Marahatta, 2008; Xu & Cheng, 2008). This is often not the case in many poor societies and the DCs where poor perception of family planning schemes among couples and the lack of efficient technology, along with cultural and religious proclivities have continued to undermine the underlined philosophies of birth control (Srikanthan & Reid, 2008).

Lagos represents societies where ethnicity, culture and religion are pre-defined factors within family context, given the myriad of rules that dictate family lifestyles and ideologies. In this context, family structure can be perceived on the basis of a unit which stretches from straightforward biological relationships within a nuclear component to a more multifaceted system including moral and social relationships, alongside obligations shared among members. There seems to be a high level of regard for extended family structure and other anomalous structures in which members, besides parents and their children also include grandparents and relatives, friends, church partners, in-laws, visitors and co-tenants. Critically, based on the author's perception of Lagos, the socio-economic conditions and the relationships each family member shares with the head of the family often reveal various levels of coping capacity to a stressor.

Family structure in Lagos constitute about 50% of the sampled population and the data available include: people without regular homes, those without a relationship with the head of family, renters, those without regular sleeping spaces, and situations in which more than four people occupy a living space (NPC, 2007). In as much as relative merits can be acknowledged within such family structures, there are possibilities that a range of behaviours such as setting priorities and scale of preferences in view of limited resources can emerge as a result of complex human interactions. Arguably, the dilemma of priority of attention which a family head would experience during emergency and in critical times such as during flooding is an important vulnerability factor. A subjective decision always has to be made with regards to who the head of the family gives priority attention - wife, son, daughter, aged mother, church partner, visitor, etc., giving available resources. What informs decisions at such critical times and how their outcomes are weighed are non-trivial issues, which can influence the overall social vulnerability to flooding. These issues particularly the dominant human behaviours, which manifest in extended family structures presents research needs.

8.2.5 Socio-economic condition

One of the important debates regarding social vulnerability in the social sciences and global environmental change literature is the socio-economic influences on individuals' responses to emergencies (Brooks, 2003; de Oliveira, 2009; Emrich & Cutter, 2011). How such influences affect vulnerability to flood hazard is well documented (Cutter *et al.,* 2000; Rygel *et al.,* 2006; Li *et al.,* 2010; Lee, 2014). Factors such as employment status, access to health facilities, literacy level, et cetera, all which vary from one person to another increases or decreases individuals' capacities to cope with stressors (Cutter *et al.,* 2003). With regards to capacity to cope with flooding, a high socio-economic status can be linked to being able to purchase flood insurance policies, live in houses located in areas less prone to flooding, and maintain a more appropriate family structure, etc., Conversely, low socio-economic status which is the major feature of the DCs, presents an important situation, given the widespread nature of flooding and its severe impacts in such places (Action aid, 2006; Adelekan 2010).

In Lagos, the lack of data describing socio-economic condition is a key limitation to research. However, the contribution of such a factor to the overall SocVI was facilitated by means of the following LSG (2012) variables: % number of development projects, % number of professionals, % average tenement, % number of primary health care, % number of births, % annual revenues for 2007. In the present research, the highly ranked SocVI areas consisted of higher population density compared to annual revenues and allocation, less of economic activities, less of political office holders, less of public health care centres, averagely educated people, while most houses are rented, the average rent for many of the houses is minimal. This findings support the study by Oyinloye *et al.* (2013) in which Kosofe LGA was considered as being adversely affected by flooding due to poverty and low socio-economic conditions among other variables.

8.2.6 Gender differences

Gender is a widely debated concept across all aspects of vulnerability (Turner *et al.,* 2003). How it is interpreted and integrated into management policies in line with ethnic and geographical differences is an issue of global concern within the context of disaster risk reduction (UNISDR, 2004). The female gender is most often more vulnerable to hazards than the male due to certain pre-defined dominant factors such as low economic capacity, family child care, and low societal positions (Cutter *et al.,* 2003; Blaikie *et al.,* 2014). In Asia and many African countries where the idea of feminism, gender equality and female empowerment or emancipation are barely accepted and societies are generally viewed as "male dominated", such gendered vulnerability is worsened (Ajibade *et al.,* 2013).

The result of the present research shows that the contribution of gender to the overall social vulnerability to Lagos urban flooding seems to emerge from the female gender. Such contribution, which is being highlighted by, in addition to generally known factors, critical issues including “house wife status”, “long term motherhood and child care” and “excessive cultural and religious practices”. This is equally compounded by poor perception of flooding among women (Ajibade *et al.,* 2013). Qualitative risk assessment from the July 2011 flooding event indicates that flooding impacts varied among income groups, residents’ locations, and gender differences (Vanguard, 2011; Ajibade *et al.,* 2013). Women living in the low-income locations recorded higher impacts, while the rate of recovery was relatively slow vis-à-vis other women living in higher income locations (Ajibade *et al.*, 2013).

However, Ajibade *et al.*, (2013) found out that Lagos women seem relaxed in their view about gendered vulnerability to flooding, given that a substantial number of the women believed flooding impacts were “gender neutral”. This is ironical in view of recorded evidences of flooding impacts in Lagos and other places across the DCs. It also highlights the poor perception of flooding which interacts with “place inequalities” and other intervening factors that placed low-income women at greater risk from flooding in Lagos area. These issues present a need for research towards building the capacities of Lagos urban poor women to cope with flooding.

8.3 Some concepts relevant to social vulnerability to urban flooding in Lagos

Appropriate understanding of social vulnerability to urban flooding within Lagos context has been utilized in the construction of SocVI for the area. However, the result of SocVI construct shows that some LGAs, such as Alimosho, Lagos-mainland and Surulere, are ranked highly both in the global social vulnerability index and in the separate vulnerabilities, measured by individual social variables. The inference is that there is the need to improve on the ways of reducing the susceptibilities of human population to urban flooding. Within the present research, it is argued that linking the understanding and application of social vulnerability in the context of Lagos urban flooding, to other relevant concepts such as: cultural theory, environmental justice and resettlement will be relevant towards future expectation of flood risk management.

8.3.1 Cultural theory

Cultural theory explains individual differences in environmental risk perception and preference for particular risk management strategies (O'Riordan & Jordan, 1999; Steg & Sievers, 2000; O'Brien & Wolf, 2010). This is often because of the different 'myths of nature' which seems to remotely influence individual behaviours (Dake, 1992; Steg & Sievers, 2000). In chapter 2, the implication of cultural diversity in the management of Lagos urban flooding was presented. This section seeks to identify key specific issue(s) which is/are common within various views of cultural theory vis-à-vis vulnerability and risk assessment. Within such a framework, Adger *et al.,* (2009) argued that 'limits to adaptation' originate from communities and are therefore subject to, among other factors, individual attitudes to risk and culture. For the Lagos area, these factors point to the need for community-based approaches to risk management, since it appears individual differences and preferences are better perceived when such approaches are operationalised. Moreover, the question of corporate adaptation and resilience could arguably be addressed by analysing vulnerability along the line of cultural difference (Rosenzweig & Wilbanks, 2010).

8.3.2 Environmental justice

The question of equality and disproportion in terms of risk and opportunities for individuals within a given spatial location is the problem of environmental justice (Brulle & Pellow, 2006; Maantay & Maroko, 2009; Boone, 2010). There is a growing theory that flooding in recent times is an environmental justice issue (Dixon & Ramutsindela, 2006; Ueland & Warf, 2006; Bullard & Wright, 2009). Key evidence that underpins this assumption was provided by Walker & Burningham (2011) who used flooding experiences in the UK to show that patterns of exposure, social groups and impacts of flooding, development of flood management policy and adaptation to climate change predictions are key areas of injustice with regards to flooding in the UK. Although these findings were specific to flooding and management in the UK, they can be catalysts and yardsticks for research towards the sensitivities to environmental justice of various disaster risk concepts across other geographical locations. It then follows that social capacities, perception of risk, and participation levels, among other variables which vary among individual members of a community must be systematically investigated and used in the local definition of vulnerability (Schlosberg, 2007).

Within the Lagos context, considering the obvious inequality that prevails, framing the idea of environmental justice into vulnerability interpretation and analyses presents three critical issues of research. Firstly, it is expected that those unique factors which subject individuals to a disproportionate share of threats resulting from the hazard must be identified and integrated into vulnerability analyses. This presents challenging objectives for local researchers since readily available datasets, particularly the census data, have to be disaggregated to obtain more realistic information on demographic characteristics (Maantay & Maroko, 2009). Secondly, given that the question of equity, (from the point of view of giving everyone equal chance to participate in policy development), in FRM policy should be answered alongside technical and economic effectiveness under cost-benefit considerations (refer to: Johnson *et al.,* 2007), vulnerability should then be defined across various stages in FRM cycle. Simply put, at what stage of FRM were vulnerabilities discovered to be more critical? Following the 2007 flooding in the UK, Johnson *et al.*

(2007) identified gaps at the recovery and reconstruction stage. The lack of coordination and resources to support victims heightened the anxiety and pressure on recovery. This stimulated a challenging and slow process of recovery on individual basis which highlighted variations in coping capacities and vulnerabilities among social groups (Pitt, 2008). Finally, given that Lagos is a coastal area of the Atlantic Ocean, the effects of climate change in relation to sea level rise can imply that those places closest to the Atlantic and other major water bodies might be environmentally disadvantaged. Thus, the relative differences in the separation between various locations within Lagos and the major water bodies should be recognised (i.e. included in especially physical vulnerability variable), whilst conducting vulnerability analyses.

8.3.3 Resettlement

Framing vulnerability within Lagos context and thinking clearly about a seemingly last resort to increasing human vulnerability to urban flooding stir the idea of resettlement or mass relocation. Arguably, the increasing threats of climate change and related hazards, flooding for the purpose of this research, escalate the need for policy makers to consider mass resettlement as the last possible option (Barnet & Webber, 2010; Lopez-Carr & Marter-Kenyon, 2015). Such options have recently been acknowledged by the United Nations Framework Convention on Climate Change (UNFCCC, 2010). In Papua New Guinea, China and Vietnam, several communities, which were vulnerable to flooding, are being relocated to safer zones (de Sherbinin, *et al.,* 2011). McDowell (2013) reported at least a dozen DCs, including Uganda and Bhutan that recommended population resettlement in their national adaptation plans to the United Nations. Flooding threatens a nation's survival armamentarium, and whilst it is now logical to resettle communities, debatably, actualizing this objective, considering the different views of vulnerability, presents a clear research problem.

For the Lagos area, such problems will include identifying flood threats thresholds under which community resettlement can be recommended, and this should also be used in contextualizing vulnerability for the area. This will answer the question of scale of resettlement — individual, a whole community, or the entire region, and provide the basis for investigating the social, economic and psychological implications of resettlement. It follows that within this framework, the likelihoods of resettlement for communities can be used to explain the levels of vulnerabilities that exist within an area. Higher likelihood for communities to be resettled suggests higher vulnerability to flooding. Unfortunately, no study in Lagos has attempted resettlement despite many reports of flooding which suggest displacement of tens of thousands of people, a figure that is expected to increase by 2050 (Barnet & Wilmsen *et al.,* 2010; OCHA, 2012). To implement the idea of resettlement in Lagos, it will be recommended that socio-cultural, psychological and economic implications of resettlement are integrated into vulnerability research.

8.4 Further discussions on *GFSP-1*

Results of the two test cases demonstrate the capability of the new flood model to simulate a realistic flooding event, but it also underscores a number of issues that need to be addressed in relation to the efficient performance of the model for proper flood risk assessment. Although the simulated maximum water depths compared well with estimated maximum water depths in a number of flood inundation locations at Portsmouth and Lagos, there were significant variations at few locations. Figures 7-27 and 7-45 in chapter 7 (pages 207 and 226 respectively) show that Southsea, Landport and Old Portsmouth, in Portsmouth, as well as Balogun Street, Victoria Island and Lagos Island in Lagos respectively, simulated water depths were higher than actual water depth.

This raises the issue of uncertainty in the performance of the model. However, there are a number of possible explanations to this situation. Firstly, the presence of retention ponds, which were not taken into account in the LiDAR DEMs, given that all negative values in the applied DEM were regarded as NODAT, and the model does not compute water depth on NODATA cells. Secondly, the model is assumed to simulate the maximum water depth at those locations at the time when the maximum flood inundation was recorded, whereas the actual water depth was probably observed some time later when some water must have drained away oe even earlier prior to maximum flood depth was reached. This follows from the use of a single rainfall intensity value to simulate flooding, whilst assuming that rainfall lands uniformly on the case study terrain. We know that in reality, pluvial events do not retain same intensity from start to finish, but the means to represent in a flood model variations in rainfall intensity throughout the duration of the pluvial events is unrealistic within the context of Lagos. Finally, such situation could have also be due to errors that have arisen from the extrapolation of water depth from photographs and this highlight the need for a more accurate and quantitative flood validation dataset.

The simulated water depths and extents show that *GFSP-1* dynamically represents the physics of water flow. From the development framework, the new model incorporates friction, gravity, and slope as physical parameters which will enable the movement of water within cells representing an urban catchment. Within the model, gravity and slope ensures that water is not retained on higher elevation as long as there exist a space within lower cells. This is critical especially at the boundary cells in which conditions are applied, and thus help in the model performance. Reflective and absorptive boundary conditions used in the model ensures that water is neither created nor destroyed, and thus ensures the continuity principle in flood simulation. Coupling of CA and SIFDS in the new model made the simulation speed reasonably impressive. The couple mechanism provides a somewhat an adaptive time stepping scheme which chooses a time step for each iteration by comparing two time steps and choosing the minimum of the two, and this is important innovation of the present research.

GFSP-1 simulates flow on downslope direction, which means that water will continue to be transferred from the principal cell to any cell with lower elevation within the neighbourhood system. Although, representation of building shapes and sizes, both of which influence the movement of flood water was not considered in the model, water is transferred if a transition rule detects any available spaces within the intervening lower elevation cells in the neighbourhood system. From a computational point of view, the speed of *GFSP-1* is satisfactory, although the simulation duration is dependent on the DEM spatial resolution. For a 2-m DEM (which sampled 250000 cells), simulation of 11 hours (for Portsmouth) and 17 hour (for Lagos) spells of rain lasted 3.5 hours and 5 hours respectively on Intel(R) CPU 2.8GHz processor, 32 GB RAM and 1TB windows 10 computer. The time could be doubled if 1-m DEM used or halved by 5-m DEM. Scaling up the DEM's resolution would have obvious effects on the computation speed and the stability of the simulation output, but these would be recommended for investigation in the future research. Actually, higher resolution DEMs would require more sophisticated computer facilities to improve the simulation speed of the new model.

This synergistic application of CA principles with SIFDS in a flood modelling technique, which the present research proposes is an important contribution to the science of flood modeling. This new flood model has demonstrated two important things. Firstly, flood hazard can be analysed over a selected specific area in Lagos in terms of the flood water depth, extent and duration. Secondly, CA principles combined with SIFDS is capable of simulating convergent, unconditionally stable flood water depth and extent within reasonable computation cost. Since research in flood modelling is still looking at the means to address these issues, this new technique opens a new window of research towards addressing a number of other critical issues, especially the lack of flood data and limited technical capacity that relate to modelling of flooding in urban environment of DCs.

For the Lagos area, this new model will help to address a number of issues relating to flood risk assessment. For examples, financial constraints to acquire better validation data, production of flood hazard and risk maps, which may tackle the translational constraints in flood risk communication, poor awareness of flooding, lack of post-flood maps, poor institutional attitudes towards research needs, and the lack of openness of individuals to research issues. Most of these challenges were encountered during the reconnaissance survey, and these made getting realistic witnesses to the flooding event a difficult task. In relation to proper flood risk assessment in Lagos, using the simulated flood water depth, it is possible to link these to the social vulnerability indices. However, since the social vulnerability indices cover a large area, whilst the simulated flood hazard cover only a small proportion of a LGA, this operation has been constrained in the present research.

8.5 Bathtub modelling of urban flooding

The flood extents and depths simulated by *GFSP-1* schema prompt speculations about the possibility or otherwise that similar flood data would be obtained if the volume of water that fell in a given period is simply 'dropped' onto the DEM. This speculation apparently relates to how the performance of *GFSP-1* would be affected if the assumption of single value rainfall intensity and Manning's coefficient is ignored. These are critical issues which are likely to shape the future of flood modelling, especially with regards to the level of simplification or complexity needed to develop methodologies for the DPDCs. To investigate these issues, a number of test simulations has been carried out, using bathtub modelling technique implemented in ArcGIS 10.3 application.

Three individual tiles (542713; 543714 and 545713) of the Lagos LiDAR DEM, and the daily rainfall amount of 25.8mm, recorded for Tuesday 5th July 2011, shown in table 7-5 (refer to chapter 7 of the revised thesis: page 207) were used for this test simulations. The volume of water produced by *n* hours of rainfall was calculated using the equation 8-1 below, where Rf represents the recorded rainfall in cm. **V** is the volume of water in m^3 to be computed, n is the dimensionless index for the rainfall duration of interest, and A is the total Area of the DEM in m^2.

$$V_n = n\left({}^{Rf}/_{2400}\right) \times A$$

Equation 8-1: The volume of rainfall unto DEM cells.

In computing this volume, only water that dropped on the urban portion of the DEM is considered. Bathtub levels were not chosen arbitrarily, and this raises a key question with regards to how to know the actual bathtub level required to drop a given volume of water on the DEM. In the present research, the actual bathtub level for a given rainfall volume was identified after a repeated iteration using various assumed values. The entire bathtub modelling process is summarised as follows:

1. Create a *vector format* of the urbanised portion of the raster LiDAR DEM, and then extract the raster version of this area of interest (AOI) using the vector data and mask tool in ArcGIS 10.3.

2. Use the *zonal statistics and table* tool to estimate the number of cells within the extracted AOI of the DEM. This number of cells multiplied by 4 gives the total area that is used to compute the volume of water 'dropped' on the DEM.

3. Estimate *surface volume* of the AOI, and thus identify the bathtub levels, using the 3D Analyst toolbox. Repeat the process until the estimated volume corresponds to the volume computed using equation 8-1. The bathtub level that formed that volume is the actual bathtub level. Table 8-1 shows the computed volumes and the bathtub level for each of the LiDAR DEMs at particular rainfall periods of interest.

Table 8-1: Computed volumes for three periods of rainfall-
2 hours, five hours and eight hours.

S/No.	LiDAR DEM tile	Tile Area (m^2)	Rainfall duration (Hrs)	Volume (m^3)	Bathtub level (m)
1.	**542713**	**772932**	5	4154.510	*0.810*
2.			8	6647.215	*1.073*
3.			17	14125.332	*1.490*
4.	**545713**	**696304**	5	3742.634	*0.802*
5.			8	5988.214	*0.935*
6.			17	12724.956	*1.148*
7.	**543714**	**432468**	5	2324.516	*1.124*
8.			8	3719.225	*1.232*
9.			17	7903.353	*1.436*

4. Drop this volume of water on the DEM at the actual bathtub level using the *Raster calculator* within the Map Algebra of ArcGIS 10.3. Figure 8-1 shows the implementation of this bathtub approach using the raster calculator, requiring

only LiDAR DEM, and the rainfall volume plus bathtub level as input data. Raster calculator ignores NODATA and areas below zero elevation, simply performs a conditional evaluation on each of the DEM cells based on the actual bathtub level. The output is a new raster which represents the flood extent and depth.

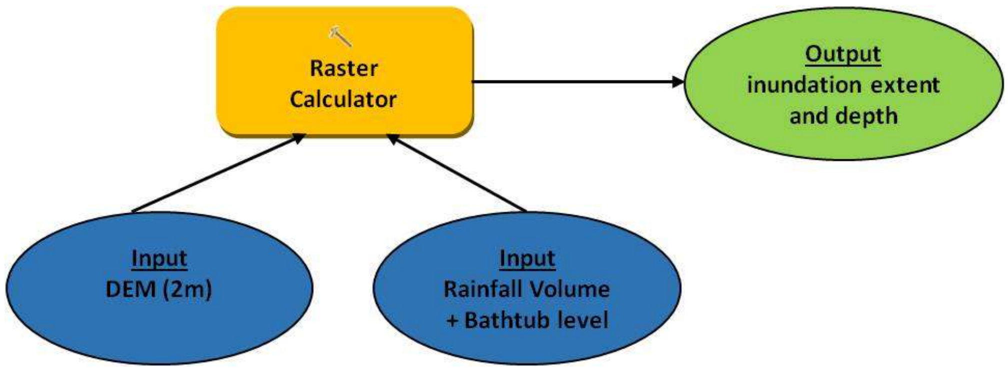


Figure 8-1: Schematics of the Raster Calculator for the Bathtub model

8.5.1 Simulated flood extents

Figures 8-2 to 8-4 show the resulting flood extent and depth for the three hour rainfall periods, five hours eight hours and seventeen hours, compared with those simulated by *GFSP-1*. From these figures, it can be shown that the volume of water, considered for the given period of rainfall, and 'dropped' onto the DEM cells, actually produces flood extent, which varies with the volume of water dropped. For the three LiDAR tiles evaluated, bathtub scheme simulates flood extent at locations not comparable to those of *GFSP-1*. The scheme appears to underestimate flood extent in most of the cells the LiDAR DEMs. This may due to the use of a fixed elevation threshold within the DEM, to determine floodable areas, unlike *GFSP-1*, and other hydraulic modelling tools, which apply hydrodynamic principles to simulate flooding. Bathtub scheme simulated limited flood extent, which appears to be restricted to small area of the LiDAR DEM or misses the particular location that was flooded.

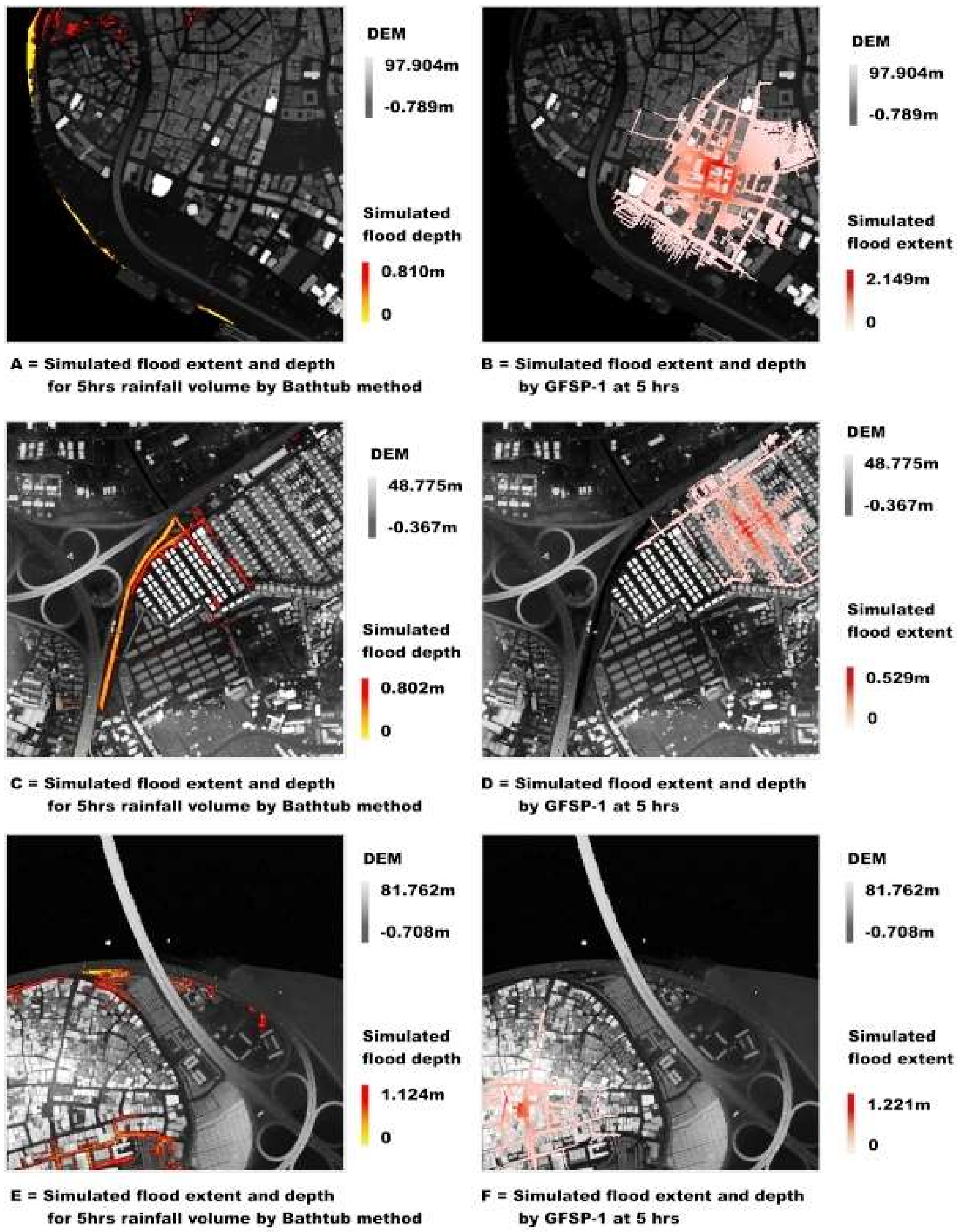


Figure 8-2: : Flood extent and depth for 5 hours volume of water, simulated by the Bathtub model, compared to flood extent and depth of the same period simulated by GFSP-1.

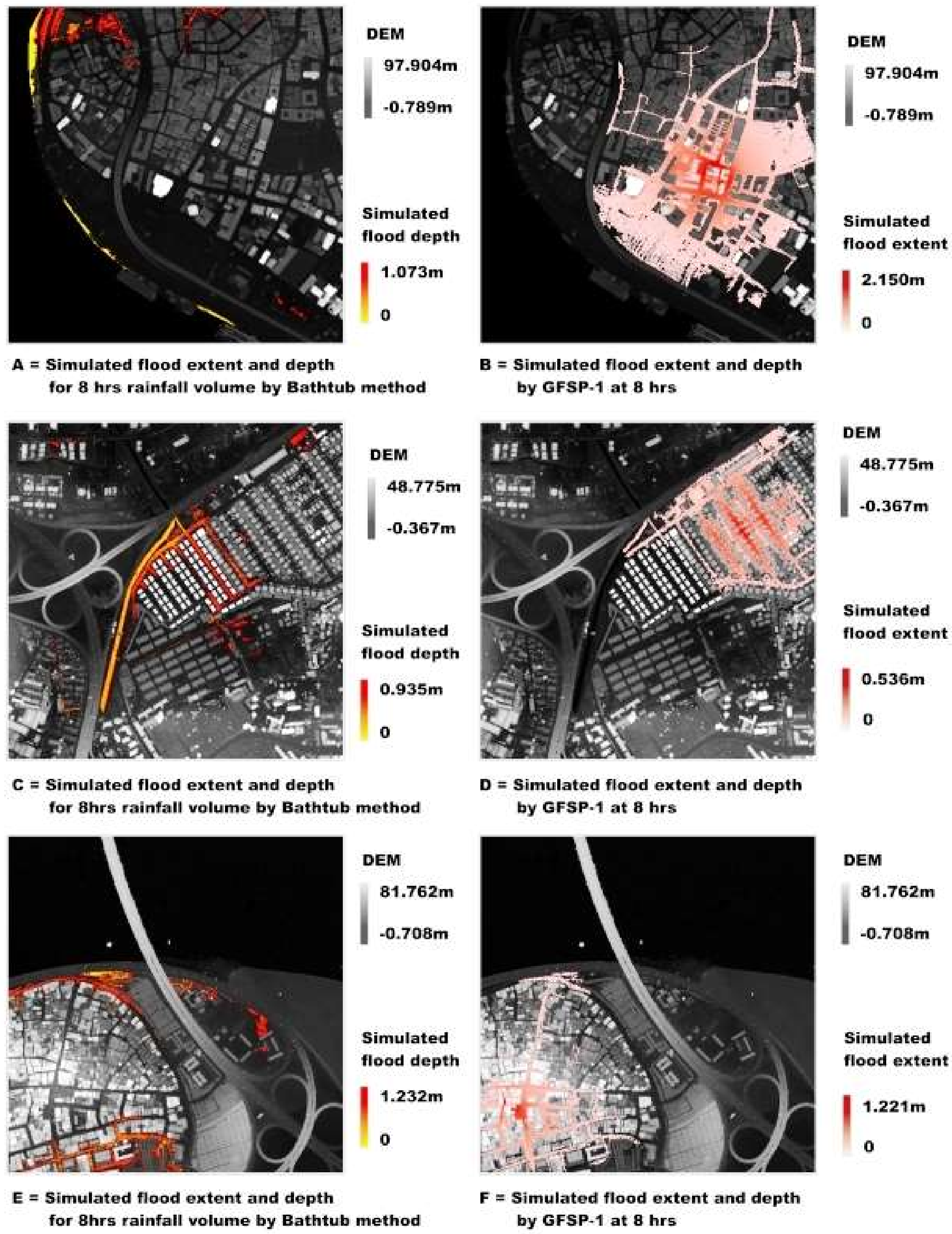


Figure 8-3: : Flood extent and depth for 8 hours volume of water, simulated by the Bathtub model, compared to flood extent and depth of the same period simulated by GFSP-1.

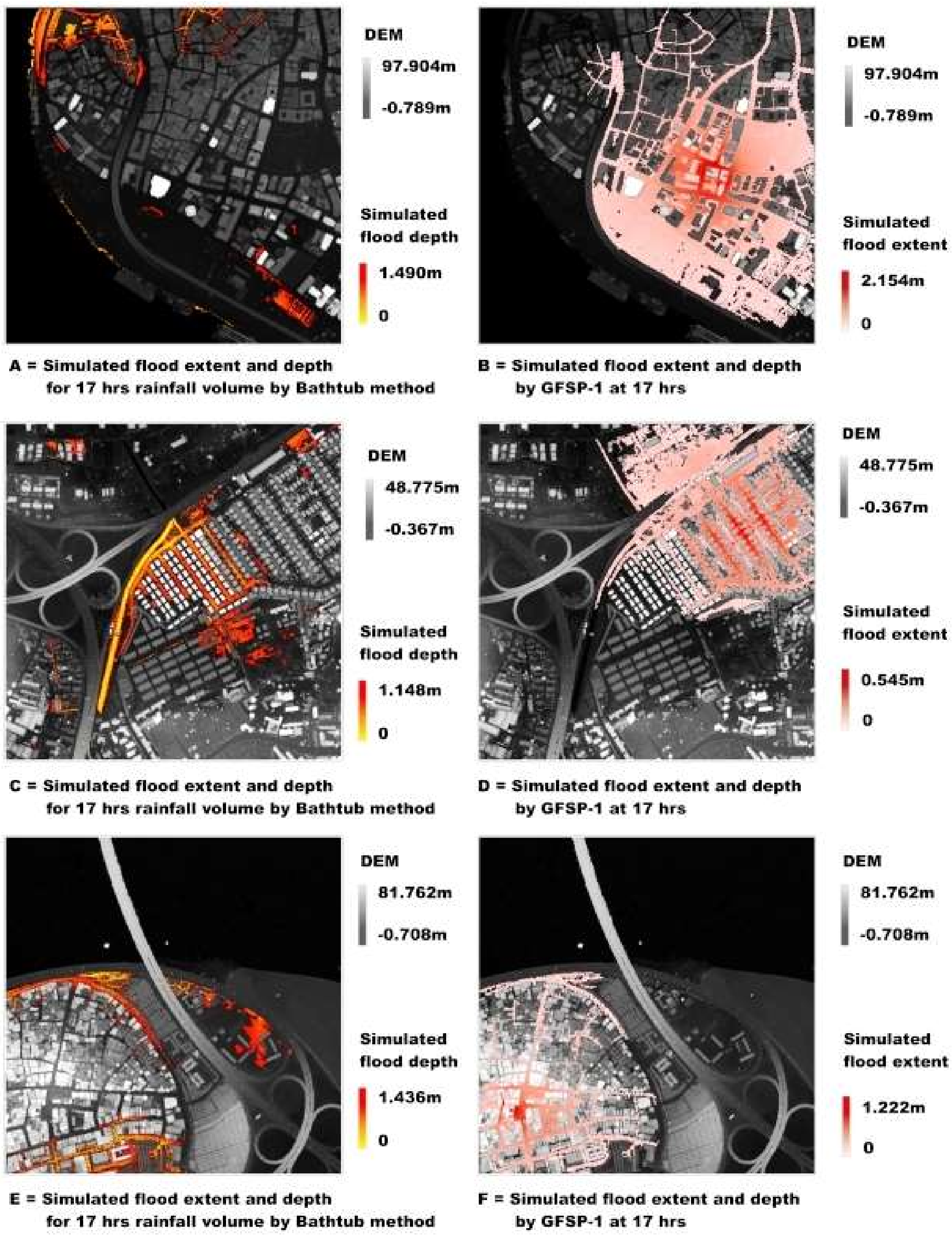


Figure 8-4: : Flood extent and depth for 17 hours volume of water, simulated by the Bathtub model, compared to flood extent and depth of the same period simulated by GFSP-1.

The figures above further demonstrate that when the volume of water 'dropped' onto the DEM cells is increased due to higher rainfall duration, bathtub scheme simulates flood extent that also increases correspondingly, although this is restricted to locations within a particular bathtub level. This suggests that whilst the 'dropped' volume has reached the fixed bathtub level, and the excess water is not evacuated by infiltration or storm drainage systems, flooding will take place only at locations within that bathtub level. This can be true theoretically and experimentally, but not necessarily in a realistic hydrodynamic flood modelling, where differences in elevation within a catchment area are also fundamental to identifying areas that are floodable or otherwise. In the *GFSP-1* model*, t*hese elevation differences or cellular hydraulic differences identified by rules within the CA framework are used to control excessive inflow of water into the DEM cells. Water is allowed only into cells that have more spaces than their neighbours', thus enabling the model to move water from cell to cell, rather than dump all available water volume into one cell which leads to uncertainty in simulating realistic flooding events.

On the subject of flood depth, bathtub scheme predicts flood inundation depth that primarily behaves in such a way that suggests only mass as a predominant factor, and therefore not controlled by other parameter, such as friction, slope, gravity, etc., which are often considered in a hydrodynamic modelling of flooding. Similar to *GFSP-1*, which simulated flood depths that compare well with flood depth estimated from social media resources (refer to chapter 7 of the revised thesis: pages 197 - 204; 220-223), the results of the present test modelling show bathtub scheme can simulate a realistic flood depth. However, the bathtub scheme requires trial and error with a repetition of the raster calculator to identify the bathtub level that can simulate a realistic flood depth. This is a significant point of disagreement between the two approaches, and also a major limitation in the bathtub modelling approach which increases uncertainties in the simulated output.

Considering its simplicity and utility of limited dataset, the bathtub scheme can be a useful tool for flood modelling towards meeting FRA challenges in the DPDCs. Critical issues, which may undermine its implementation lie largely on the simulation of limited flood extent which is likely to constitute significant uncertainties in flood modelling. However, this can be resolved if any other hydrodynamic parameters can be allied with the actual bathtub level to derive a more realistic flood extent.

Flood modelling by developed countries is a major research efforts towards addressing the challenges of urban flooding. However, FRA in the DPDCs presents the issue of lack of funds, insufficient quality data and weak technical capacity, all of which are crucial to research, and therefore suggest the need for bespoke flood models designed primarily for the level of publicly available datasets and resources accessible in those data poor areas. These are key factors, justifying the assumptions made in the present research to develop *GFSP-1.* Although *GFSP-1* is deemed capable of meeting the challenges of FRA in DPDCs, improvement in data availability which will go a long way to minimise the amount of assumptions often made to simulate a realistic flooding event within the context of DPDCs is still a critically lingering necessity. Where this necessity is not addressed, then more research is still needed towards developing flood models that can utilise available datasets without making excessive assumptions.

9 Conclusion and Recommendations

9.1 General conclusion

Widespread urban flooding and its increasing human and environmental impacts are issues of global significance. Crucial to the ongoing debates on flood hazard and flood risk is the widespread speculation that global and regional climate change effects, allied with upward trends in urbanisation and population growth, would worsen flood risk both now and in the future. Thus, flood management policies are being formulated to address flood risk at global, regional and local scales. These policies rely heavily on accurate flood risk assessment which can be broadly explained in terms of the procedure to identify and estimate flood hazard, as well as analyse and quantify its consequences on the basis of exposure and vulnerabilities of elements at risk. Various reports show that some progress has been made in flood risk assessment especially in the United States, UK and elsewhere in Europe, Australia and few places in Asia such as Vietnam, and China. However, in many developing countries (DCs) such as Nigeria and Bangladesh, limitations in flood risk assessment are significant issues which have drawn a wide range of discussion in the literature. These limitations which are generally attributed to lack of flood data, poor awareness of urban flooding and lack of political will-power have continued to create a gap in the literature between increasing urban flooding and the means of building the capacities of a wider human population to cope with floods.

Urban flooding and its management in the Lagos metropolis of Nigeria are issues of grave importance within the context of environmental management and sustainable urban development (Smit & Parnell, 2012). Available records indicate that flooding in the area, which appears to be an annual event, affects human population, destroys urban assets and disrupts economic activities. These floods and their consequences aggravate poverty levels among urban residents and in local communities. Previous studies which have attempted to look into these issues are limited in scope and application and have focused mainly on the general ideas of causes and impacts of flooding. Remedies, however, are discussed but on the general framework of institutional approaches and environmental management practices. A review of literature relating to management of flooding in the area was unable to identify a concrete method of flood risk assessment (FRA). More critical investigations involving flood hazard estimations are lacking. Exposure of social, economic and environmental systems to flooding can be identified from few studies which examined land use (LU) and land cover (LC) modifications in the area. However, these studies fail to provide the means of addressing increasing slum development in Lagos. The studies that have assessed vulnerabilities to flooding are insufficient to initiate any radical flood risk reduction measures. These limitations and insufficiencies in research apparently have significant effects on stakeholders' efforts at flood risk management which can at best be described as fragmented rather than integrated. Integrated flood risk management perceives flood risk as a complex system of physical, environmental, infrastructural, economic and managerial components, highlighting the importance of flood data and flood risk assessment.

The present research was a step forward towards finding solutions to these challenges. It was aimed to critically analyse current approaches to urban flood risk assessment in the Lagos area and to develop completely new models to address these inadequacies. Social vulnerability indices (SocVI) for the sixteen local government areas (LGAs) in the Lagos metropolis were computed using demographic data from notable repositories in Nigeria (NPC - National Population Census - and Lagos state digest of statistics) and political maps of the study area. To make the SocVI specific to flooding, topography from ASTER (Advanced Space-borne Thermal Emission and reflection Radiometers) global DEM was used as a source for elevation differences, to which flooding in the area is also associated. The demographic data were grouped into variables that are taken as proxies for susceptibility and lack of coping capacity. The UNDP Human Development Index approach has been adopted for normalization of the vulnerability variables. The method proposed by Patnaik & Narayanan (2009) was adopted for aggregating and ranking the indicators. GIS have been applied for finalizing and map completion of the social vulnerability indices (SocVI).

Using the knowledge of hydrology as a framework for gaining a better insight into flood propagation and generation of flood data, a new flood model, *GFSP-1*, was developed. This new flood model, which combines a semi implicit finite difference scheme (SIFDS) and a cellular automata (CA) mathematical principle, forms the novelty and innovation of the present research, as well as makes significant contribution to the science of flood modelling and flood risk assessment. SIFDS, which integrates the merits of explicit and implicit schemes, to achieve model unconditional stability and computation simplicity simulates flood velocity in a two-dimensional frame. The CA principle which utilises neighbourhood relationship, transition rules and boundary conditions on a mesh of cells computes the flood water depth and inundation extent. The link between the CA and SIFDS components is established in the model time step which is expected to provide the new model an ability to execute much faster than a conventional numerical flood model. The model was tested in Portsmouth UK, using the September 15th 2000 flooding event, and then validated against map of hotspot of surface water flooding in Portsmouth and social media-based dataset especially photographic images of the flooding event. The model was also used to simulate the July 11th 2011 flooding event in Lagos, showing various spatial and temporal scenarios.

The implications of limitations in FRA, critical evaluation of social vulnerability and SocVI construct, along with the performance test of *GFSP-1* are discussed. The critical implication of the current situation of flood risk management in Lagos, given the potential gaps in knowledge, is arguably indicative of a whole system failure, which suggests the need for holistic management approach including political, environmental and economic decision-making. The result of SocVI construct indicates three local government areas that are highly vulnerable to flood hazard as a result of susceptibility and lack of coping capacity caused mainly by gender variation, age distribution, family structure and housing condition. From the results, strengths and contributions of each indicator to overall SocVI are clarified with gender variation, poverty and socio-economic status contributing the most. The new model was able to simulate unconditionally stable solution of flood hydrodynamics using a minimum of input datasets, and within moderate computation cost. Moreover model outputs are easily accessible by means of a regular GIS program. While it is intended that these outputs will be utilized for future flood risk mapping of the area, it will also be useful for decision making and prioritizing plans and strategies with regards to flood risk mitigation activities especially towards building effective coping capacity in those areas with higher susceptibility to the flood hazard.

The major contributions of the present research have been the development of a new flood model on the basis of combined CA and SIFDS approach, provision of a critical review of flooding and flood risk management, as well as construction of SocVI for the local enumerations areas in Lagos metropolis of Nigeria. Despite these contributions, and the expectation that stakeholders and the research community will find the results of this research desirable for future flood risk mapping and flood management policy in the Lagos area, few limitations which suggest the needs for future research were identified.

9.2 Major limitations of research and recommendations for further studies

Primarily, an urban flood risk assessment was not undertaken in this research, given that the specific objectives are only limited to developing models towards addressing the challenges and urban flooding and limitations in its management in the Lagos area of Nigeria. Attention has not been given to policy issues, which are also relevant to improved urban flood risk management. However, discussions emerging from chapters 3, 4 and 8, provide key frameworks for formulating urban flood risk management policy. In addition to these issues, key limitations of the research, which relate primarily to the new flood model and the SocVI, are as follows:

1. The new flood model lacks of extensive validation. This had been due to lack of real data, coupled with time constraints to carry out such task. For this reason, a future study which will take advantage of high resolution radar-based satellite data (for example the ESA: European Satellite Agency) of flood depth and extent for further validation is recommend.

2. The performance of the new flood model has not been compared with existing models, whilst a flood risk map has not been prepared at this stage. For the purposes of giving end users an increased confidence in using the new model, future research is recommended to compare *GFSP-1* with such models as LISFLOOD-FP, GUFIN, JFlow, etc. Also, it is recommended for future research to test the suitability of 10-m DEMs, 30-m ASTER and 90-m SRTM DEMs for the new model. It is also imperative to investigate how the interaction between CA and SIFDS presented in this research potentially affect unconditional stability and computation cost of flood model designed for data poor urban areas.

3. Uncertainty analysis was not carried out. Future investigation is recommended towards identifying and analysing the various sources of uncertainties (such as epistemic, aleatory and parametric) and how they influence the integrity of the model.

4. With regards to the SocVI construct, a major limitation is the scale of data used. Such national and state demographic datasets are too coarse, and only give a generalised impression of social vulnerability to urban flooding at the level in which it was analysed. For a more comprehensive index of social vulnerability, a study which will utilize primary datasets at say individual and household level is recommended.

To improve FRM in the area, considering vulnerability, two important objectives should be addressed. Firstly, it is important that proper definition of flood vulnerability at local scale is articulated through more specific investigation into the exposure and sensitivities of various ecological systems to flooding. This should either be incorporated into or totally substitute the widely used LU/LC analyses which merely give generalised impression of exposure to flooding. Secondly, the recent SENDAI idea of public and private sector investment decisions needs rethinking and a systematic approach within Lagos framework developed. It is argued that this idea should be articulated and implemented by identifying those aspects of investment opportunities that have the greatest impacts on climate change. Poverty in Lagos appears to be the catalyst for various social and economic measures being undertaken by the residents to survive, and addressing such issue with regards to investment decisions towards actualising FRM goals in Lagos presents a significant gap in knowledge. Thus, a better understanding of vulnerability to urban flooding in Lagos should consider poverty alleviation as a logical pathway for corporate adaptation, adaptive capacity and community resilience.

Solutions to these gaps, drawn from behavioural and structural perspectives of vulnerability (refer to: Burton & Hewitt, 1974), will first and foremost necessitate evolving adaptation and resilience phenomena into the cultural identity of Lagos. Since adaptive capacity is context-specific (refer to: Smit & Wandel, 2006), the main purpose should be to identify pragmatic resilience and adaptation measures for the Lagos area. This will ensure that the adaptation portfolio combines a range of activities as opposed to concentrating on a single measure which is the present situation in Lagos. These activities should, as a matter of priority, include risk communication, which improves risk perception and consequently adaptive capacity to environmental hazards (Faulkner & Ball, 2007; McCarthy *et al.,* 2007).

Based on the concept of 'entitlement' (which basically explains food insecurity, civil strife and social disruption), vulnerability is often caused by lack of access to resources (Watts & Bohle, 1993; Turner *et al.,* 2003; Jeffers, 2013). Many hazard and vulnerability studies within Lagos context have identified the lack of resources as a major driver of vulnerability to flooding (Aderogba *et al.,* 2012; Nkwunonwo *et al.,* 2015). Nonetheless, resilience for Lagos urban residents on the basis of existing social, economic, environmental and political structures presents a new frontier of investigation. Such investigations will promote urban governance and how to effectively carry out specific roles, as opposed to general functions, which currently prevails within institutional framework in Lagos (Obeta, 2014; Nkwunonwo *et al.,* 2016). This will promote opportunities for collaboration and synergy towards corporate adaptation and resilience. Furthermore, it will strengthen the link in the understanding and application of social vulnerability in the context of Lagos urban flooding, to the concepts of cultural theory, environmental justice and resettlement.

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Appendixes

Appendix A: Evidence of ethical review

Faculty of Science
University of Portsmouth
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White Swan Road
PORTSMOUTH
PO1 2DT

Ugonna Nkwunonwo
ugonna.nkwunonwo@port.ac.uk
07/01/15

<u>Science Faculty Ethics Committee</u>

Protocol Title: SFEC 2015-046, Development of a simple flood model and social vulnerability indices (SocVI) for urban flood risk assessment in the Lagos metropolis of Nigeria.
Date application received: 22/06/15
Date Reviewed: 01/07/15

<u>CHAIR'S OPINION – SFEC 2015-046</u>

Dear Mr Nkwunonwo,

Thank you for your submission for ethical review. It appears that you have already undertaken much of this research and participants have already been recruited. University policy, in this situation, allows an Ethics Committee Chair to comment on the research regarding the likely outcome had the study been reviewed by the Committee. I can confirm that, in my opinion, your study would have been given a favourable opinion. You may use this letter as evidence of ethical review when requested at the time of submission of your thesis.

Please notify the Committee if you introduce any substantial amendments to the proposed procedures, and documents you recently submitted. Please send these to ethics-sci@port.ac.uk.

Thank you for your submission; I wish you well with your study.

Dr Chris Markham – Chair of SFEC

CC -
Holly Shawyer – Faculty Administrator

If you would like to offer any feedback on the Science Faculty Ethics Committee process please email ethics-sci@port.ac.uk, to be forwarded to the Chair

Appendix B: Form URP 16

FORM UPR16

Research Ethics Review Checklist

University of Portsmouth

Please include this completed form as an appendix to your thesis (see the Postgraduate Research Student Handbook for more information

Postgraduate Research Student (PGRS) Information			Student ID:	673233
PGRS Name:	NKWUNONWO, Ugonna Chimnonyerem			
Department:	SEES	First Supervisor:	WHITWORTH, Malcolm	
Start Date: (or progression date for Prof Doc students)		01 October 2012		

Study Mode and Route:						
	Part-time	☐	MPhil	☐	MD	☐
	Full-time	☒	PhD	☒	Professional Doctorate	☐

Title of Thesis:	Meeting the Challenges of Flood Risk Assessment in Data Poor Developing Countries, With Particular Reference to Flood Risk Management in Lagos, Nigeria.
Thesis Word Count: (excluding ancillary data)	56, 633 words

If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

UKRIO Finished Research Checklist:
(If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online version of the full checklist at: http://www.ukrio.org/what-we-do/code-of-practice-for-research/)

Question	YES	NO
a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame?	☐	☐
b) Have all contributions to knowledge been acknowledged?	☒	☐
c) Have you complied with all agreements relating to intellectual property, publication and authorship?	☒	☐
d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration?	☒	☐
e) Does your research comply with all legal, ethical, and contractual requirements?	☒	☐

Candidate Statement:

I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)

Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):	SFEC 2015 - 046

If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of questions a) to e), please explain below why this is so:

Signed (*PGRS*):		Date: 29/09/2016

UPR16 – August 2015

Appendix C: *GFSP-1* Flood Model code

```matlab
% This model, known as Geoinformation Flood Simulation Program 1 (GFSP-1)
% represents a code that integrates the (Cellular Automata) (CA) framework
% and Semi-Implicit Finite Difference Scheme (SIFDS) to simulate flood
% hydrodynamics. The model uses only rainfall intensity data and Manning's
% friction coefficients to compute flow on a DEM surface. It works on the
basis
% of uniform rainfall on the entire catchment (i.e. computation domain).The
% assumption is that flow is routed downslope and that available water is the
% rainfall intensity on a cell. This water is routed to the neighbouring
cells on
% the basis of slope differences. Maximum iteration here is 100000.

% Author:      Ugonna C., Nkwunonwo
% Date:        October 2015.

clear all
close all
clc

global IMAX JMAX dx dy dt g Hx Hy

g              = 9.81;              % gravity constant
flowRATE       = 0.1;               % assumed flow rate
rainFALL       = 0.0;               % source of water
initial_TIME   = 0;                 % initial time of simulation
Manning        = 0.00;              % Manning's friction value
eastBOUND      = double(0.0);       % east boundary condition
westBOUND      = double(0.0);       % west boundary condition
southBOUND     = double(0.0);       % south boundary condition
northBOUND     = double(0.0);       % north boundary condition

% read the DEM file
% load variables

filename1   = 'SZ6599_DSM_2M.asc';                 % specify the filename
fid         = fopen(filename1, 'r');               % obtain a file ID
A           = fscanf(fid,'%s',1);                  % column line string
ncols       = fscanf(fid,'%f',1);                  % read number of columns
A           = fscanf(fid,'%s',1);                  % row line string
nrow        = fscanf(fid,'%f',1);                  % read number of row
A           = fscanf(fid,'%s',1);                  % x-lower corner line string
xllcorner   = fscanf(fid,'%f',1);                  % read x - lower left corner
A           = fscanf(fid,'%s',1);                  % y-lower corner line string
yllcorner   = fscanf(fid,'%f',1);                  % read y - lower left corner
A           = fscanf(fid,'%s',1);                  % cell size line string
cellsize    = fscanf(fid,'%f',1);                  % read cell size
A           = fscanf(fid,'%s',1);                  % nodata line string
nodata      = fscanf(fid,'%f',1);                  % read nodata value
dem         = fscanf(fid,'%f',[ncols, nrow]);      % Open DEM as matrix A
dem         = dem';                                % transpose DEM
fclose('all');                                     % close all files

    row     = nrow;                     % row value
```

```
column  = ncols;                % column value
dx      = cellsize;             % spatial steps in row
dy      = cellsize;             % spatial steps in columns
xL      = xllcorner;            % x - lower left corner
yL      = yllcorner;            % y - lower left corner
NODATA  = nodata;               % NODATA value

%number of control volumes in each direction
IMAX = row;                     %maximum i - index
JMAX = column;                  %maximum j - index
xR = xL + dx*IMAX;              % value of upper x right corner
yR = yL + dy*JMAX;              % value of upper y right corner

%initial conditions
water_DEPTH(IMAX,JMAX) = 0;      % initial water depth
eta(IMAX,JMAX)         = 0;      % initial free water surface elevation
uVELOCITY(IMAX,JMAX)   = 0;      % velocity at x - locations
vVELOCITY(IMAX,JMAX)   = 0;      % velocity at y - locations

statusSET = fprintf('water flow simulation started at %d\n',
initial_TIME);

%initial conditions
for i = 1:IMAX
    for j = 1:JMAX
        % input rainfall source
        if i == 50 && j == 50
            Nwater_DEPTH(i,j)   = water_DEPTH(i,j) + rainFALL;
        else
            Nwater_DEPTH(i,j)   = water_DEPTH(i,j);
        end
        dem(i,j)                = dem(i,j);
        if dem(i,j) <= 0
            continue
        end
        all_DEPTH(i,j)  = dem(i,j) + Nwater_DEPTH(i,j);
    end
end

time = 0;         % initial time
tend = 180;       % final time (min)
CFL  = 0.9;       % CFL number
NMAX = 200000;  %max. number of time steps
u    = uVELOCITY;
v    = vVELOCITY;

for k = 1: NMAX

    umax = max(max(abs(u)));
    vmax = max(max(abs(v)));
    dt = min(0.01, CFL/( umax/dx + vmax/dy + 1e-14) );
    if(time+dt>tend)
        dt = tend-time;
```

```
end

 time = time + dt;

for i = 1: IMAX
    for j = 1: JMAX
        if i == 1
            all_DEPTH_N(i,j)      = 0;
            Nwater_DEPTH_N(i,j)  = 0;
        else
            all_DEPTH_N(i,j)      = all_DEPTH(i-1,j);
            Nwater_DEPTH_N(i,j)   = Nwater_DEPTH(i-1,j);
        end

        if i == IMAX
            all_DEPTH_S(i,j)      = 0;
            Nwater_DEPTH_S(i,j)   = 0;
        else
            all_DEPTH_S(i,j)      = all_DEPTH(i+1,j);
            Nwater_DEPTH_S(i,j)   = Nwater_DEPTH(i+1,j);
        end

        if j == 1
            all_DEPTH_W(i,j)      = 0;
            Nwater_DEPTH_W(i,j)   = 0;
        else
            all_DEPTH_W(i,j)       = all_DEPTH(i,j-1);
            Nwater_DEPTH_W(i,j)    = Nwater_DEPTH(i,j-1);
        end

        if j == JMAX
            all_DEPTH_E(i,j)      = 0;
            Nwater_DEPTH_E(i,j)   = 0;
        else
            all_DEPTH_E(i,j)      = all_DEPTH(i,j+1);
            Nwater_DEPTH_E(i,j)   = Nwater_DEPTH(i,j+1);
        end
    end
end

% use CA to transform the rainfall into streamflow
for i = 1:row
    for j = 1:column
        % calculate left flow rate
        grad = (all_DEPTH_W(i,j) - all_DEPTH(i,j));

        if grad > 0 && Nwater_DEPTH_W(i,j) > 0
            flow_LEFT = flowRATE * grad;
        elseif grad < 0 && Nwater_DEPTH(i,j) > 0
            flow_LEFT = flowRATE * grad;
        elseif grad == 0
            flow_LEFT = 0;
        else
```

```
    %                   fprintf('no water flows in or out\n');
    flow_LEFT = 0;
end
% CHECK BOUNDARY FLOW
if j == 2
    westBOUND = westBOUND + flow_LEFT;
end

% calculate right flow rate
grad = (all_DEPTH_E(i,j) - all_DEPTH(i,j));

if grad > 0 && Nwater_DEPTH_E(i,j) > 0
    flow_RIGHT = flowRATE * grad;
elseif grad < 0 && Nwater_DEPTH(i,j) > 0
    flow_RIGHT = flowRATE * grad;
elseif grad == 0
    flow_RIGHT = 0;
else
    %                   fprintf('no water flows in or out\n');
    flow_RIGHT = 0;
end
% CHECK BOUNDARY FLOW
if j == column
    eastBOUND = eastBOUND + flow_RIGHT;
end

% calculate upper flow rate
grad = (all_DEPTH_N(i,j) - all_DEPTH(i,j));

if grad > 0 && Nwater_DEPTH_N(i,j) > 0
    flow_UP = flowRATE * grad;
elseif grad < 0 && Nwater_DEPTH(i,j) > 0
    flow_UP = flowRATE * grad;
elseif  grad == 0
    flow_UP = 0;
else
    %                   fprintf('no water flows in or out\n');
    flow_UP = 0;
end
% CHECK BOUNDARY FLOW
if i == 2
    northBOUND = northBOUND + flow_UP;
end

% calculate lower flow rate
grad = (all_DEPTH_S(i,j) - all_DEPTH(i,j));

if grad > 0 && Nwater_DEPTH_S(i,j) > 0
    flow_DOWN = flowRATE * grad;
elseif grad < 0 && Nwater_DEPTH(i,j) > 0
    flow_DOWN = flowRATE * grad;
elseif grad == 0
    flow_DOWN = 0;
```

```
            else
                %                  fprintf('no water flows in or out\n');
                flow_DOWN = 0;
            end

            % CHECK BOUNDARY FLOW
            if i == row
                southBOUND = southBOUND + flow_DOWN;
            end

            Total = (flow_RIGHT + flow_LEFT + flow_UP + flow_DOWN);
            Finwater_DEPTH(i,j) = water_DEPTH(i,j) + Total;

            if Finwater_DEPTH(i,j) < 0
                Finwater_DEPTH(i,j) = 0;
            end

        end
    end

    % the semi implicit FDS begins here to compute water free surface
    % elevation, velocity and the water depths at velocity points
   % from Casulli (1990)
    for i = 1:IMAX
        for j = 1:JMAX
            % calculate the initial free water surface elevation using
the         % Zevernberger and Thorne's (1987) method
            eta(i,j) = (((all_DEPTH_S(i,j)- all_DEPTH_N(i,j))/(2*dx))^2
...             +((all_DEPTH_E(i,j)-all_DEPTH_W(i,j))/(2*dy))^2)^0.5;
            hb(i,j) = 0;                                    % bottom profile
        end
    end

%calculate the velocity points for further computation of the variables
    for i=1:IMAX+1
        for j=1:JMAX
            u(i,j) = 0;
            % define the bottom elevation at the u velocity points
            if(i==1)
                hx(i,j) = hb(i,j);          % piecewise constant
extrapolation
            elseif(i==IMAX+1)
                hx(i,j) = hb(i-1,j);        % piecewise constant
extrapolation
            else
                hx(i,j) = 0.5*(hb(i-1,j)+hb(i,j));  % average left and
right bottom
            end
        end
    end
    for i=1:IMAX
        for j=1:JMAX+1
            v(i,j) = 0;
            % define the bottom elevation at the v velocity points
            if(j==1)
```

```
                hy(i,j) = hb(i,j);          % piecewise constant extrapolation
            elseif(j==JMAX+1)
                hy(i,j) = hb(i,j-1);        % piecewise constant extrapolation
            else
                hy(i,j) = 0.5*(hb(i,j-1)+hb(i,j));  % average from above and below
            end
        end
    end

    % neglect the nonlinear convective terms
    Fu = u;
    Fv = v;
    %      [Fu,Fv]=Upwind2Dxy(u,v);

    % compute the total depth H at the u velocity points
    for i=1:IMAX+1
        for j=1:JMAX
            if(i==1)
                Hx(i,j) = max(0, hx(i,j)+eta(i,j) );
            elseif(i==IMAX+1)
                Hx(i,j) = max(0, hx(i,j)+eta(i-1,j) );
            else
                Hx(i,j) = max(0, hx(i,j)+max(eta(i,j),eta(i-1,j)) );
            end
        end
    end

    % compute the total depth H at the v velocity points
    for i=1:IMAX
        for j=1:JMAX+1
            if(j==1)
                Hy(i,j) = max(0, hy(i,j)+eta(i,j) );
            elseif(j==JMAX+1)
                Hy(i,j) = max(0, hy(i,j)+eta(i,j-1) );
            else
                Hy(i,j) = max(0, hy(i,j)+max(eta(i,j),eta(i,j-1)) );
            end
        end
    end

    % compute the total depth H for grid points
    for i=1:IMAX
        for j=1:JMAX
            H(i,j) = max(0, hb(i,j)+eta(i,j) );
        end
    end

    % assemble the right hand side
    QL = 0; % left discharge boundary condition
    QR = 0; % right ...
    QT = 0; % top ...
    QB = 0; % bottom ...
```

```
    for i=1:IMAX
        for j=1:JMAX
            rhs(i,j) = eta(i,j);   % old free surface
            % x - fluxes
            if(i==1)
                rhs(i,j) = rhs(i,j) - dt/dx*(Hx(i+1,j)*Fu(i+1,j)-QL);
            elseif(i==IMAX)
                rhs(i,j) = rhs(i,j) - dt/dx*(QR-Hx(i,j)*Fu(i,j));
            else
                rhs(i,j) = rhs(i,j) - dt/dx*(Hx(i+1,j)*Fu(i+1,j)-
Hx(i,j)*Fu(i,j));
            end
            % y - fluxes
            if(j==1)
                rhs(i,j) = rhs(i,j) - dt/dy*(Hy(i,j+1)*Fv(i,j+1)-QB);
            elseif(j==JMAX)
                rhs(i,j) = rhs(i,j) - dt/dy*(QT-Hy(i,j)*Fv(i,j));
            else
                rhs(i,j) = rhs(i,j) - dt/dy*(Hy(i,j+1)*Fv(i,j+1)-
Hy(i,j)*Fv(i,j));
            end
        end
    end

    % solve the linear system for the free surface (linear version of
(5.10));
    eta = CG2Dxy(rhs);
    % update the velocities (5.16) and (5.17)
    for i=1:IMAX+1
        for j=1:JMAX
            if(i==1)
                u(i,j) = QL/Hx(i,j);
            elseif(i==IMAX+1)
                u(i,j) = QR/Hx(i,j);
            else
                u(i,j) = Fu(i,j) - g*dt/dx*( eta(i,j) - eta(i-1,j) );
            end
        end
    end
    for i=1:IMAX
        for j=1:JMAX+1
            if(j==1)
                v(i,j) = QB/Hy(i,j);
            elseif(j==JMAX+1)
                v(i,j) = QT/Hy(i,j);
            else
                v(i,j) = Fv(i,j) - g*dt/dy*( eta(i,j) - eta(i,j-1) );
            end
        end
    end

   % Reset the cells to start again
    for i = 1: row
        for j = 1: column
```

```
            if i == 50 && j == 50
                Nwater_DEPTH(i,j) = Finwater_DEPTH(i,j) + rainFALL;
            else
                Nwater_DEPTH(i,j) = Finwater_DEPTH(i,j);
            end

        end
    end

  % update the total water depth
    for i = 1:row
        for j = 1:column
            water_DEPTH(i,j)  = Finwater_DEPTH(i,j);

            if dem(i,j) <= 0
                continue
            end
            all_DEPTH(i,j)  = dem(i,j) + Nwater_DEPTH(i,j);
        end
    end

    % advance time and plot the result
    time = time + dt;

    %  advance time and plot the result
     if time == 1800
        header              = [column;row;xL;yL;dx;NODATA];
        filename            =
'C:\Users\user\Desktop\SZ6399_DSM_myfile001.asc';
        fid1                = fopen(filename, 'w+');
        writeASCII(water_DEPTH, header, filename);
    end
    if time == 7200
        header              = [column;row;xL;yL;dx;NODATA];
        filename            =
'C:\Users\user\Desktop\SZ6399_DSM_myfile002.asc';
        fid2                = fopen(filename, 'w+');
        writeASCII(water_DEPTH, header, filename);
    end
    if time == 18000
        header              = [column;row;xL;yL;dx;NODATA];
        filename            =
'C:\Users\user\Desktop\SZ6399_DSM_myfile003.asc';
        fid3                = fopen(filename, 'w+');
        writeASCII(water_DEPTH, header, filename);
    end
    if time == 28800
        header              = [column;row;xL;yL;dx;NODATA];
        filename            =
'C:\Users\user\Desktop\SZ6399_DSM_myfile004.asc';
        fid4                = fopen(filename, 'w+');
        writeASCII(water_DEPTH, header, filename);
    end
```

```
    if time == 39600
        header              = [column;row;xL;yL;dx;NODATA];
        filename            =
'C:\Users\user\Desktop\SZ6399_DSM_myfile005.asc';
        fid5                = fopen(filename, 'w+');
        writeASCII(water_DEPTH, header, filename);
    end
    if time == 50400
        header              = [column;row;xL;yL;dx;NODATA];
        filename            =
'C:\Users\user\Desktop\542713_myfile006.asc';
        fid6                = fopen(filename, 'w+');
        writeASCII(water_DEPTH, header, filename);
    end
    if time == 61200
        header              = [column;row;xL;yL;dx;NODATA];
        filename            =
'C:\Users\user\Desktop\542713_myfile007.asc';
        fid7                = fopen(filename, 'w+');
        writeASCII(water_DEPTH, header, filename);
    end

     if time == final_TIME
        break
    end
end
toc;

%Function (CG) that solves the non linear system of equations
%Conjugate gradient method to solve
% the linear system
%   A*x = b
% (A must be symmetric and positive definite)
%using a matrix-free implementation.
%The product A*x is given by the function "matop"
% Input:
%  b = known right hand side
%Output:
%  x = solution of the problem
function x=CG2Dxy(b)
N = length(b); % get the number of unknowns
x = b;       % initial guess
v = matop2Dxy(x); %matrix-vector product
r = b-v;     % initial residual = steepest descent direction
alpha = sum(sum(r.*r)); % square of the norm of r
tol = 1e-14;         % user defined tolerance
p = r;               % initial search direction is the initial residual
for k=1:N
    if(sqrt(alpha)<tol)
        % If the norm of the residual is
        % below the tolerance, the system
        % is considered as solved
        return
    end
    v = matop2Dxy(p);
```

```
    lambda = alpha/sum(sum(p.*v));
    x = x + lambda*p;
    r = r - lambda*v;
    alphaold = alpha;
    alpha = sum(sum(r.*r));
    p = r + alpha/alphaold*p;
end

%Function (matop) Matrix operator

% left hand side for the 2D xy model
function Ae=matop2Dxy(eta)
global dx dy IMAX JMAX g dt Hx Hy
for i=1:IMAX
    for j=1:JMAX
       Ae(i,j) = eta(i,j);
       % x-fluxes
       if(i==1)
           Ae(i,j) = Ae(i,j) - g*dt^2/dx^2*( Hx(i+1,j)*(eta(i+1,j)-
                eta(i,j)) - ...
                                                  0 );
       elseif(i==IMAX)
           Ae(i,j) = Ae(i,j) - g*dt^2/dx^2*( 0 - ...
                                                  Hx(i  ,j)*(eta(i,j)-
                eta(i-1,j)) );
       else
           Ae(i,j) = Ae(i,j) - g*dt^2/dx^2*( Hx(i+1,j)*(eta(i+1,j)-
                eta(i,j)) - ...
                                                  Hx(i  ,j)*(eta(i,j)-
                eta(i-1,j)) );
       end

       % y-fluxes
       if(j==1)
           Ae(i,j) = Ae(i,j) - g*dt^2/dy^2*( Hy(i,j+1)*(eta(i,j+1)-
                eta(i,j)) - ...
                                                  0 );
       elseif(j==JMAX)
           Ae(i,j) = Ae(i,j) - g*dt^2/dy^2*( 0 - ...
                                                  Hy(i,j  )*(eta(i,j)-
                eta(i,j-1)) );
       else
           Ae(i,j) = Ae(i,j) - g*dt^2/dy^2*( Hy(i,j+1)*(eta(i,j+1)-
                eta(i,j)) - ...
                                                  Hy(i,j  )*(eta(i,j)-
                eta(i,j-1)) );
       end
    end
end



% function for writing the outputs as ascii files
```

```
function writeASCII( z, title, filename )
% This function writes the results of the simulations as ascii
% raster files that can be viewed easily in GIS applications
   % Input:
% a filename with associated path
% a 2-D file that results from computation of flood hydrodynamics
   % Output:
% a rater ascii grid files
% Nkwunonwo Ugonna C. (2015)

fid          = fopen(filename, 'w+');
z            = z./10;

%WRITE title
fprintf(fid,'%s','ncols         '); %1
fprintf(fid,'%12.0f\n', title(1,1));
fprintf(fid,'%s','nrows         '); %2
fprintf(fid,'%12.0f\n', title(2,1));
fprintf(fid,'%s','xllcorner     '); %3
fprintf(fid,'%f\n', title(3,1));
fprintf(fid,'%s','yllcorner     '); %4
fprintf(fid,'%f\n', title(4,1));
fprintf(fid,'%s','cellsize      '); %5
fprintf(fid,'%f\n', title(5,1));
fprintf(fid,'%s','NODATA_value '); %6
fprintf(fid,'%f\n', title(6,1));

%WRITE MATRIX
%substitute to NaN the NODATA_value written in title
z(find(isnan(z))) = title(6,1);
%start loop
column = title(1,1);
row = title(2,1);
handle = waitbar(0, mfilename);
for i = 1:row;
    waitbar(i/row);
    % if varname is a vector instead of a 2-D array
     if size(z,2) == 1;
         fprintf(fid,'% f ',z( ((i-1)*column + 1) : (i*column) )' );
         fprintf(fid,'%s\n', ' ');
        % if varname is a 2-D array
    else
         fprintf(fid,'%f ',z(i,:));
         fprintf(fid,'%s\n', ' ');
    end
end
fclose(fid);
fclose('all');

waitbar(i/row, handle, 'Done!');
close(handle)
end
```

Appendix D: Pictures of flooding impacts

Impacts of 2015 Accra floods with urban infrastructure severely affected. Source: Google online images of Accra flooding

Impacts of 2010 Pakistan floods showing displaced human populations and damaged urban infrastructure. Source: Google online images of Pakistan flooding

Impacts of 2007 UK floods in Herefordshire and Worcestershire
Source: Google online images of UK flooding

Impacts of 2010 Tennessee floods with urban infrastructure severely affected. Source: Google online images of Tennessee flooding

Impacts of 2015 Chennai floods with urban infrastructure severely affected. Source: Google online images of Chennai flooding

Appendix E: Pictures of flooding for model validation in Portsmouth

Photograph of September 15th flooding at Landport area. Source: PCC.
Estimated water depth (0.8m – 1.0m).

Photograph of September 15th flooding at Northend area. Source: PCC.
Estimated water depth (0.08m – 0.1m).

Photograph of September 15th flooding at Southsea area. Source: PCC.
Estimated water depth (0.5m – 0.7m).

Photograph of September 15th flooding at Tipner area. Source: PCC.
Estimated water depth (0.5m – 0.7m).

Photograph of September 15th flooding at Bradford junction. Source: PCC.
Estimated water depth (0.6m – 0.8m).

Photograph of September 15th flooding at Central Southsea. Source: PCC.
Estimated water depth (0.5m – 0.7m).

Photograph of September 15th flooding at Fratton area.
Source: Online (www.portsmouthseptember152000flooding).
Estimated water depth (0.4m – 0.6m).

Photograph of September 15th flooding at Old Portsmouth. Source: PCC.
Estimated water depth (0.7m – 0.9m).

Photograph of September 15th flooding at Portsea. Source: PCC.
Estimated water depth (0.5m – 0.7m).

Photograph of September 15th flooding at Hilsea.
Source: Online (www.portsmouthseptember152000flooding).
Estimated water depth (0.2m – 0.4m).

Appendix F: Pictures of flooding for model validation in Lagos

Photograph of July 11th flooding at Dolphin Estate.
Estimated water depth (0.4m – 0.6m).

Photograph of July 11th flooding at Castle Road.
Estimated water depth (0.1m – 0.3m).

Photograph of July 11th flooding at Broad and Balogun Street.
Estimated water depth (1.8m – 2.0m).

Photograph of July 11th flooding at Lagos Island.
Estimated water depth (1.0m – 1.2m).

Photograph of July 11th flooding at Victoria Island_2.
Estimated water depth (0.5m – 0.7m).

Photograph of July 11th flooding at Victoria Island.
Estimated water depth (1.5m – 1.7m).

Appendix G: Explanation of Table 4-1 and 4-3

The table 4-1 (page 101) contained a summary of the data used to construct the social vulnerability index. These data representing LGAs and LCDA were merged from the 2007 national census and Lagos state digest of statistics, and analysed. The overall data are herein organised in the following headings:

1. Land Area (Sqkm)
2. Population Density (PD)
3. Gender population
    - i. Population (Male)
    - ii. Population (Female)
4. Age Populations
    - i. Population (0-14 years)
    - ii. Population (15-69 years)
    - iii. Population (70-80+ years)
5. Development projects (not specified)
6. Professionals (generalised)
7. Gainfully employed
8. Average annual tenements
9. Primary health care
10. Number of births
11. Annual revenues
12. Housing condition
    - i. House on separate stand or yard
    - ii. Traditional structure made of traditional materials
    - iii. Flat in blocks of flat
    - iv. Semi-Detached House
    - v. Rooms/Let in House
    - vi. Earth / and Wood material for floor
    - vii. Earth / and Wood material for wall
    - viii. Thatched, Earth / and Wood material for Roof
13. House ownership and type of dwelling unit
    - i. Informal improvised dwelling & Others
    - ii. Absence of regular sleeping Room
    - iii. House owned by occupiers
    - iv. House Rented by occupiers
    - v. Squatters and free occupiers and others
    - vi. House owned by Head of Household
    - vii. House owned by Spouse to head of household
    - viii. House owned by Other household member
    - ix. House owned by Relative but not household member
    - x. House owned by Privately owned (Landlord)

xi. House owned by Private employer
xii. House owned by Other private agency
xiii. Public/Government ownership
xiv. Others

14. Source of water supply
    i. water supplied by Pipe-borne inside dwelling
    ii. Water supplied by pipe-borne outside dwelling
    iii. Water supplied by Tanker supply/water vendor
    iv. Water supplied by well
    v. water supplied by Borehole
    vi. Water supplied by Rainwater
    vii. River/Stream/Springs
    viii. Dugout/Pond/Lake/Dam/Pool
    ix. Others

15. Type of sanitation facility
    i. Sanitation by Water Closet
    ii. Sanitation by Pit Latrine
    iii. Sanitation by Bucket/Pan
    iv. Sanitation by Toilet facility in another (different) dwelling
    v. Sanitation by Public toilet
    vi. Sanitation by Nearby bush/beach/field
    vii. Others

16. Type of cooking energy
    i. Cooking by Electricity
    ii. Cooking by Gas
    iii. Cooking by Kerosene
    iv. Cooking by Firewood
    v. Cooking by Coal
    vi. Cooking by Animal dung/Saw dust/Coconut husk
    vii. Cooking by Solar
    viii. Others

17. Type of lightning energy
    i. Lightning by Electricity
    ii. Lightning by Kerosene
    iii. Lightning by Candle
    iv. Lightning by Solar
    v. Others
18. Method of solid waste disposal
    i. Solid waste Collected
    ii. Solid waste Buried by household
    iii. Solid waste by Public approved dumpsite
    iv. Solid waste by Unapproved dumpsite
    v. Solid waste Burnt by household

vi. Others

19. Access to telephone
20. Access to TV
21. Literacy
    i. Below SSCE & None education
    ii. Graduate
    iii. Postgraduate

22. Type of household
    i. Regular household
    ii. Institutional household
    iii. Homeless Household
    iv. Homeless Person
    v. Nomadic Household
    vi. Transient person household
    vii. Fishing and Hunting person household

23. Marital status
    i. Never Married
    ii. Unmarried
    iii. Separated
    iv. Divorced
    v. Widowed

24. Number of people occupying a house
    i. 1 Person in a house
    ii. 2 People in a house
    iii. 3 People in a house
    iv. 4People in a house
    v. 5 People in a house
    vi. 6 People in a house
    vii. 7 People in a house
    viii. 8 People in a house

25. relationship to the house owner
    i. Head of household
    ii. Spouse
    iii. Child
    iv. Parent
    v. Brother / Sister
    vi. Other blood relations
    vii. Non-blood relation
    viii. Institutional Household

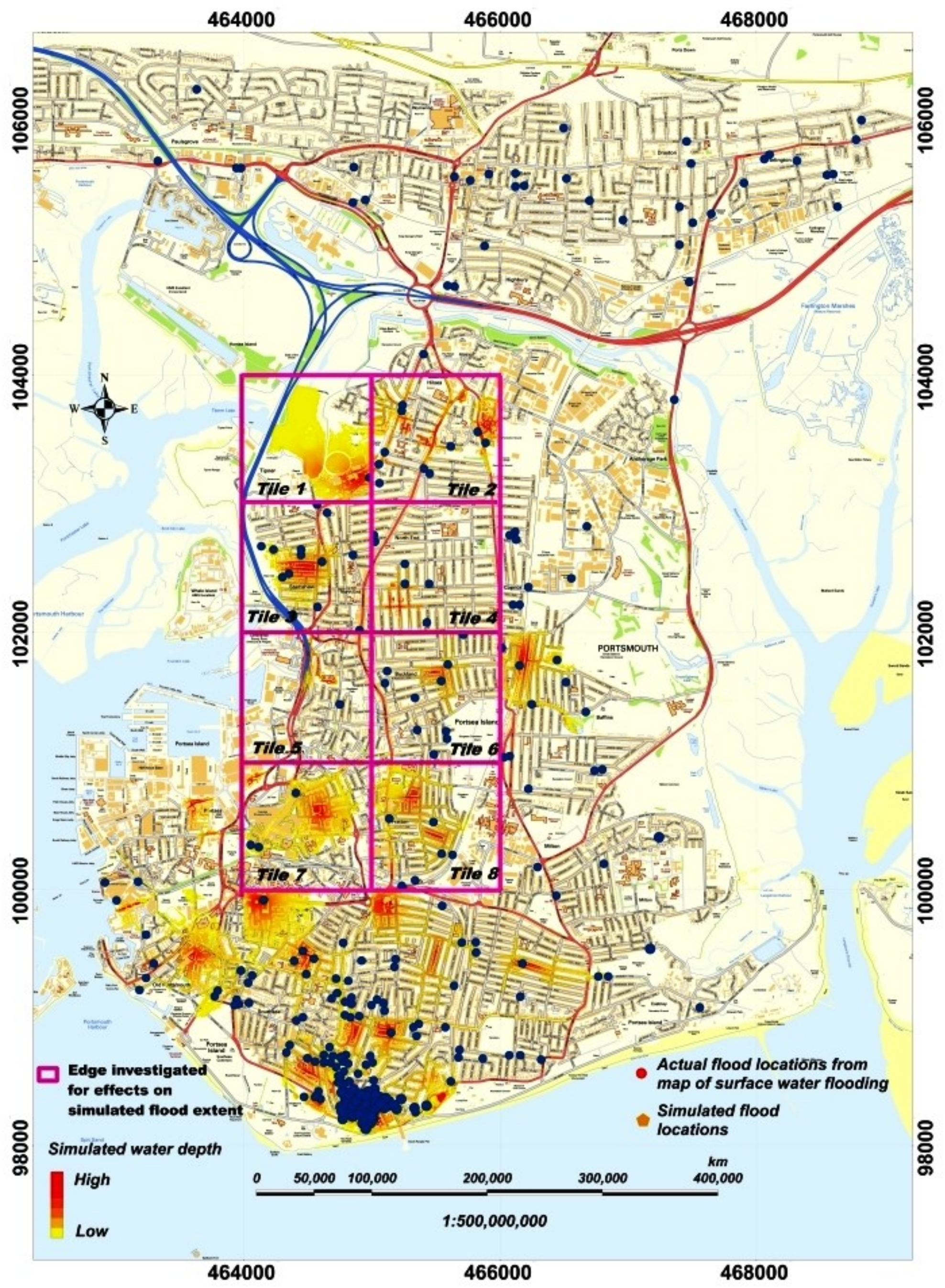
26. Disability

Table 4-3 (page 105) contained the social vulnerability indices arranged according to the LGAs consisting the Lagos metropolis. This table within this appendix clarifies the indices by adding some metadata such as population, population density, and the land area of the LGAs in relation to the indices computed for Lagos area.

S/No.	LGAs	Land Area (Sqkm)	Population (Male)	Population (Female)	Total Population (TP)	Population Density (PD)	Gender vulnerability	Age Vulnerability	Marital status Vulnerability	Disability Vulnerability	Housing condition Vulnerability	Family structure Vulnerability	Socio-economic status vulnerability	Poverty Vulnerability	Topography Vulnerability
1	AGEGE	11.263	238456	223287	461743	40996.45	0.5	0.48	*1.9*	0.22	0.48	0.38	*0.75*	0.41	0.1
2	AJEROMI-IFELODUN	12.395	352273	335043	687316	55451.07	0.49	0.55	0.43	0.43	0.69	0.58	0.5	0.49	0.61
3	ALIMOSHO	186.195	665750	653821	1319571	7087.04	0.5	*0.75*	1	*1.01*	0.39	*0.71*	0.35	0.52	0.42
4	AMUWO-ODOFIN	135.240	173742	155233	328975	2432.53	0.49	0.38	0.1	0.1	0.42	0.31	0.62	0.58	0.9
5	APAPA	26.798	123163	99823	222986	8320.99	0.49	0.35	0.01	0	0.5	0.29	0.52	0.5	0.92
6	ETI-OSA	193.460	158858	124933	283791	1466.92	0.48	0.35	0.06	0.05	0.63	0.32	0.36	0.6	0.97
7	IFAKO-IJAYE	26.769	219109	208628	427737	15978.82	0.5	0.42	0.19	0.19	0.31	0.36	0.48	0.44	0
8	IKEJA	46.427	171782	145832	317614	6841.15	0.49	0.37	0.09	0.08	0.27	0.33	0.73	0.43	0.35
9	KOSOFE	81.889	358935	323837	682772	8337.77	0.48	0.5	0.42	0.42	0.61	0.56	0.6	0.49	0.96
10	LOGOS-ISLAND	8.707	110042	102658	212700	24428.62	0.5	0.44	0	0	0.4	0.29	0.48	0.47	0.9
11	LAGOS-MAINLAND	19.572	170568	156132	326700	16692.21	0.5	0.42	0.1	0.09	*0.79*	0.35	0.66	0.51	0.54
12	MUSHIN	17.576	326873	304984	631857	35949.99	0.49	0.6	0.38	0.37	0.53	0.52	0.47	0.4	0.35
13	OJO	158.884	315401	293772	609173	3834.07	0.49	0.44	0.36	0.35	0.37	0.45	0.61	*0.67*	0.85
14	OSHODI-ISOLO	44.999	325207	303854	629061	13979.44	0.49	0.5	0.38	0.37	0.49	0.5	0.62	0.43	0.95
15	SHOMOLU	11.615	207519	196050	403569	34745.50	0.5	0.47	0.17	0.16	0.48	0.38	0.6	0.44	0.51
16	SURULERE	23.122	260509	242356	502865	21748.33	0.49	0.52	0.26	0.25	0.47	0.43	0.74	0.42	*1*

Appendix H: Edge effects on the simulated flood extent

This issue was investigated using the edges of eight tiles of the Portsmouth LiDAR DEM. The map diagram below delineates the hotspot locations vis-avis the edges of the investigated cells used to simulate the water extent.



Flow across the edges is only suggestive of the type of boundary condition used in the new model. Every model that operates on gridded cells conceived a way to deal with what happens at the edges of the cells that do not have a complete neighbourhood. Ghimire *et al.* (2013) applied a similar idea in which no flow was allowed at the edges. The model in the present research uses absorptive and reflective boundary conditions (refer to section 6.14: page 160), and these seem to suggest that water does not go beyond the edges. This situation can raise critical issues in relation to modelling flooding over a small section of a larger area. The only way to explore this situation is to mosaic the DEMS and run simulation which could take several weeks or even months to complete. However, from the figure above, the majority of hotspot locations not simulated by *GFSP-1*, were found inside the DEM cells used to simulate the flood extent, and not at the edges. Hotspots location at the edges of the cells were simulated by an adjoining DEM cell. This suggest that the edge assumptions has no significant impact on the simulated flood extent.