Accepted Manuscript

Urban flood modelling combining cellular automata framework with semi-implicit finite difference numerical formulation

U.C. Nkwunonwo, Malcolm Whitworth, Brian Baily

PII: S1464-343X(18)30339-X

DOI: https://doi.org/10.1016/j.jafrearsci.2018.10.016

Reference: AES 3353

To appear in: *Journal of African Earth Sciences*

Received Date: 2 November 2016

Revised Date: 17 September 2018

Accepted Date: 30 October 2018

Please cite this article as: U.C. Nkwunonwo, Malcolm Whitworth, Brian Baily, Urban flood modelling combining cellular automata framework with semi-implicit finite difference numerical formulation, *Journal of African Earth Sciences* (2018), doi: 10.1016/j.jafrearsci.2018.10.016

Urban flood modelling combining cellular automata framework with semi-implicit finite difference numerical formulation

Nkwunonwo, U.C. [1, 2,] Whitworth, Malcolm[2], Baily, Brian[3]

[1]Department of Geoinformatics and Surveying, University of Nigeria, Enugu Campus.
[2]School of Earth and Environmental Sciences, University of Portsmouth, UK.
[3]Department of Geography, University of Portsmouth, UK.

Abstract

Urban flooding is increasingly pervasive, with dreadful impacts on people and development assets. Whilst the frequency of occurrence of this hazard, mainly from pluvial events, is of fundamental importance in climate change and earth sciences research, the severity of its impacts motivates major debates within the context of flood risk management and sustainable urban development. The present study focuses on the development of a novel flood model, as a contribution to meeting the challenges of flood risk assessment within data poor urban areas such as in Nigeria. The new model combines the full functionality of cellular automata (CA) framework with a semi-implicit finite difference numerical scheme (SIFDS), whilst the resulting algorithms were programmed within MATLAB*TM* programming platform. In this study, computation complexity and distributed topographic data requirement, both which are associated with flood modelling, and which tend to present a major limitation to flood modelling in the developing countries (DCs) are being addressed. A highly urbanized area within the Lagos metropolis of Nigeria was chosen as a case study to validate the model and to simulate the July 10th 2011 flooding event. A 2-m horizontal resolution LiDAR DEM, published Manning's friction coefficients and rainfall intensity, were used as data inputs into the new flood model. Simulated results compared well with actual flooding inundations, reported by urban residents, and detailed in some literature and by the media. The Pearson correlation coefficient (r) between predicted flood depth and estimated values is 0.968. It is expected that the challenges of urban flooding in Lagos particularly and in the DCs generally will be better addressed if robust, but low-cost flood models are developed and utilized in the assessment of flood damage.

Keywords: Urban flooding, Flood modelling, Flood risk assessment, Cellular automata, Semi-implicit finite difference scheme.

1. Introduction

Concerns about widespread urban flooding have increased in recent times, whilst it remains an emerging theme in various research relating to climate change, natural hazards, earth sciences and flood risk management (Cherqui *et al.,* 2015, Anees *et al.,* 2016). During urban flooding, surface water inundates large areas with severe impacts whereby human life is threatened and large sections of the population are displaced from homes and traumatized. At the same time critical infrastructure is destroyed, whilst a myriad of economic activities are disrupted (Kaźmierczak & Cavan, 2011). Climate change with its potential to increase the magnitude and frequency of heavy rainstorms is largely implicated in urban flooding (Djordjević *et al.,* 2011). Poor urban drainage facilities which are easily overwhelmed by excess rainfall and infiltration process which is attenuated by widespread use of impervious surfaces in cities escalate these floods (Zevenbergen *et al.,* 2008; Perales-Momparler *et al.,* 2017). Recent flood disasters across the globe show that the severe impacts of urban flooding frequently correlate with high concentrations of human population and associated developments in urban areas. This means that with the rapid growth in global population and the amount of wealth being amassed comes increased human exposure with more and more personal and corporate wealth being placed at risk (Smith, 2013).

Issues arising from extant discussions in flood risk research suggest the need to identify the various human and environmental agencies of urban flooding and their interactions, as well as to develop robust and more realistic methodologies for assessing and managing flood risk within the context of urban areas. This highlights the importance of flood modelling, to characterize or predict a flooding event in terms of the flood water depth, extent and water flow velocity and produce flood risk maps (Teng *et al.,* 2017). With the growing application of depth-damage functions for economic assessment of flood risk, flood modelling has become a primary research concern, for which significant progress has been made over the years especially in modelling of fluvial and coastal flooding (Costabile & Macchione, 2015). Modelling of urban flooding has arguably not received sufficient attention. There have been several research initiatives towards urban flood modelling, although it seems the increased availability of urban flood models have unrealistic corresponding effects on the growing challenges of urban flooding, especially in developing countries (DCs) (Nkwunonwo *et al.,* 2015). Within urban flood modelling research, specific objectives such as representation of urban geomorphology, LiDAR (Light Detection and Ranging) processing tailored to urban flood modelling, paucity of high resolution topographic data, computation effectiveness and model uncertainty are still ongoing debates (Chen *et al.,* 2012; Kim *et al.,* 2018).

The main aim of the present research is to advance the availability of models for simulating urban flooding. Within this research two specific objectives are being addressed which are computation simplicity and minimum data requirement. Thus, a new flood model, named *GFSP-1 (Geoinformation Flood Simulation Program-1)*, which combines the capability of a semi-implicit finite difference scheme (SIFDS) and cellular automata (CA) framework is being proposed. The model is coded using MATLAB™ programming language, and used to simulate the July 10th 2011 flooding of the urban areas of Lagos Nigeria, West Africa. Only digital elevation models (DEM), rainfall intensity and Manning's friction coefficient were used as variables to simulate urban flooding inundation. The authors hypothesize that whilst fragility functions are being widely utilized for economic assessment of flood damage, the development of bespoke models to simulate urban flooding will greatly enhance the use of such functions especially in the DCs.

2. Methodology

The technical design of *GFSP-1* consists of CA framework and the SIFDS formulation. CA signifies a set of mathematical procedures that solve complex systems on cellular spaces in which time is discrete and a set of universal laws apply (Engelen *et al.,* 1995; Wahle *et al.,* 2001). It represents one of the most recent efforts to address the gaps in the science of flood modelling (Cirbus & Podhoranyi, 2013; Liu *et al.,* 2015). The popularity of CA in the physical sciences is linked to the work of Von Newman and Stanislav Ulam in the 1940s and has since gained significant attention in many research areas to dynamically model systems whose states evolve with respect to time and space (von Neumann, 1951). The relative advantage of CA over other techniques for simulating physical systems is its ability for spatial and temporal discretization (Ghimire *et al.,* 2013). In the context of flood modelling, this advantage is expected to scale down the computation burden associated with physically based numerical models. The CA framework proposed in this research encompasses the four essential features of an ideal CA system. These include; the mesh of cellular space, neighbourhood, transition rules and boundary conditions. CA formulation presented in Ghimire *et al.* (2013) has two additional elements, system state and time step. Time step is an important factor not only for CA framework, to determine the pace at which the model operations progress, but also in the simulation of dynamic systems elsewhere.

- The mesh of cellular space provides the simulation domain. It is made up of a framework of grids, which define a discrete representation of the geometry involved in the physical phenomenon. Any of the LiDAR data types – digital terrain model (DTM), digital surface model (DSM) and DEM can provide the two-dimensional cellular space for the present CA system. A *2-m* horizontal resolution LiDAR DEM was used in the test case presented later on, although *3-m* and *5-m* resolutions are also applicable.

- The neighbourhood defines the distance from a given origin of a set of objects or points, within a cellular space. The von Neumann type of neighbourhood was considered in the present CA framework. It consists 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). Yamamoto *et al.* (2007) argued that simplicity is a key merit of von Neumann neighbourhood in comparison to Hexagonal and Moore neighbourhood systems.

- Transition rule(s) consist of a set of principles based on mathematical expressions that direct the CA procedure. 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. In the present CA formation, a set of four transition rules were implemented. They include: rule for adding rainfall into the individual cells and excluding losses especially through infiltration and evapotranspiration, rule - based on Manning's formula (*equation 1*) - to determine the length of time water stays in the cells before distribution, rule - based on *equation 2* - to compute the amount of water to be transferred as flux from the principal cell into neighbouring cell. In actual fact, the hydraulic differences between the principal cell and the neighbouring cells drive water movement. This is the routing scheme for *GFSP-1*, by which water is transferred from the principal cell into whichever neighbouring cell has the lowest elevation. This scheme has the effect of reducing the computation time of the model and allowing water to flow over a variable urban terrain without causing much computation errors to the predicted values. The final rule controls the minimum water level which each cell can retain. 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.

$$V = \frac{h^{\frac{2}{3}} * \sqrt{S_f}}{n} \quad (1)$$

$$flux(i,j) = \frac{(principal\ cell(i,j) - neighbour\ cell(i,j))}{neighbour\ cell(i,j)} * water\ in\ principal\ cell \quad (2)$$

Where V (LT^{-1}) is the velocity, (L) is the water depth, *flux* is the rate of change of discharge across a unit area (LT^{-3}) and S_f (-) is the water surface slope, computed using the method proposed in Zevenbergen and Thorne (1987).

- The boundary condition applies 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 Dirichilet boundary condition in a regular numerical modelling, refer to: Bazilevs & Hughes, 2007) were used (see figure 1). 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.

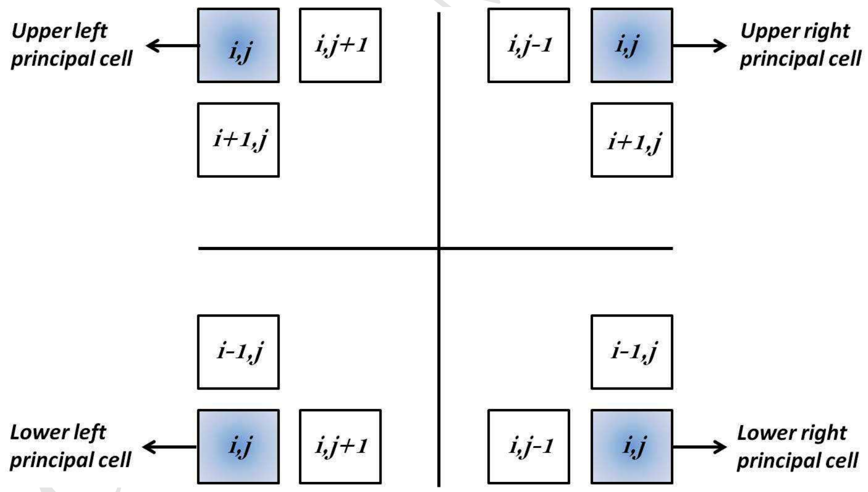

Figure 1: Boundary Condition- the blue-dyed boxes represent the boundary cells, whilst the hollow boxes are the remaining members of the neighbourhood. There are only three cells, which imply an incomplete von Newman neighbourhood at the boundaries.

The SIFDS that couples with CA in the present model is based on the original work of Casulli (1990). It is an attempt to provide a realistic flow solution at a reduced computation cost within the framework of unconditional model stability. Casulli (1990) derived the SIFDS on a staggered grid using a combination of explicit and implicit numerical schemes. The free water surface slope in the momentum equations and the velocity in the continuity equations with friction terms were discretised implicitly. This removes the stability of the model from wave celerity. The other terms in the shallow water equations (SWEs) were discretised explicitly. This method of discretization incorporates the relative advantages of the explicit and implicit schemes (which are computation cheapness and unconditional stability respectively) into a single flood simulation model. The resulting SIFDS equations are shown in Casulli (1990), Casulli and Stelling (2013), Dumbser and Casulli (2013), Dumbser *et al.* (2015).

The combination of CA and SIFDS in the present research introduced a dynamic interaction between two model components to enhance model performance in simulating a typical urban flooding event. From figure 2, the link between 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, leading to evolution of water depth.

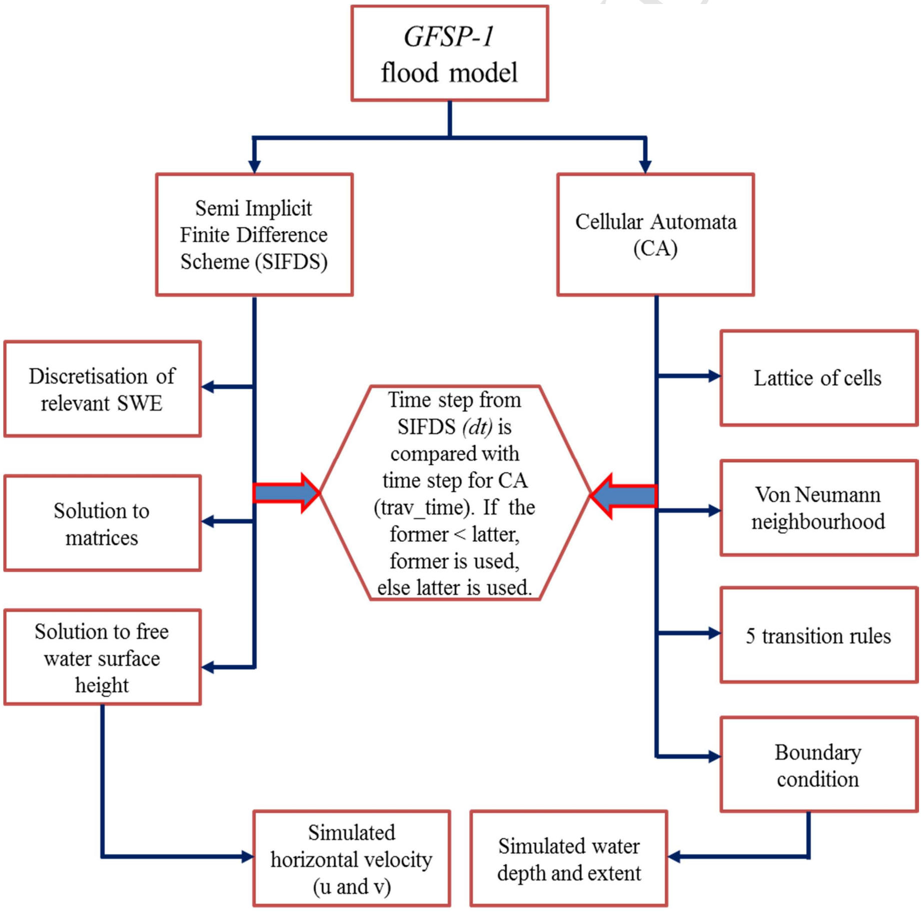

Figure 2: Schematics showing the dynamic link between the CA and the SIFDS in the *GFSP-1* model.

Evolution of water depth 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 3*. 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 4*. 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. 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.

$$Total\ flux(i,j) = \sum\{influx(i-1,j), influx(i+1,j), influx(i,j-1), influx(i,j+1)\} \quad (3)$$

$$Water\ depth(i,j) = water\ depth(i,j) + \frac{Totalflux(i,j)}{(dx*dy)} * \Delta t \quad (4)$$

Where Δt (T) is the model time step

The present model is coded and implemented in MATLAB™ which is a powerful, easy to implement object oriented programming (OOP) language. MATLAB™ has several in-built functions, with capability for modularity and for handling and manipulating matrices (which are the building block of DEMs). This choice of MATLAB™ in this research is an attempt to advance research towards using the potentials and capabilities of MATLAB™ to improve flood modelling techniques. Programming flood simulation models using MATLAB™ is still an emerging procedure with only few flood models essentially programmed in MATLAB™ (see MOD2-Flow model: Martin & Gorelick, 2005; Kulkarni *et al.,* 2014). As a commercial programming language, access to end-users in low income societies can be limited. However, MATLAB™ codes can easily be exported and adapted to freely accessible windows integrated program development environments (IDEs).

3. Model testing and validation using the Lagos case study

3.1. Study area description

Lagos is the largest city in Nigeria, and the second largest in Africa. Its most functional part, the 'Lagos metropolis', is made up of sixteen local government areas (LGAs) of varying enumeration sizes. The Lagos metropolis is located in the south western part of Nigeria from latitude 6° 24′ N to 6° 48'N and longitude 3° 10′ E to 3° 24'E, enclosing a relatively small land mass, just about 1100 km^2 (see figure 3). The metropolis is a densely populated urban area with an estimated population of over 21 million people (LSG, 2012). The city is annually threatened by flooding from excess rainfall, which was not infiltrated due to much impervious surfaces, nor evacuated by available drainage facilities. The July 2011 event which was triggered by heavy rainfall that lasted two days remains historic in terms of its large scale impacts on human population and development assets. The meteorological data for the event suggests that approximately 463 mm of rainfall was recorded for the month, although most of the rain fell within 17 hours of the 10th day (IFRC, 2011; Adelekan, 2015). Losses estimated at millions of USD were incurred from the event. Unfortunately, the lack of data relating to flood depth and extent was a major constraint to *GFSP-1* model validation. Although, there have been major flood management efforts, flooding and its threats are still important problems, especially among the poor urban communities who lack the capacity to cope and the means to adapt with the challenges (Adelekan, 2010, Nkwunonwo *et al.,* 2016).

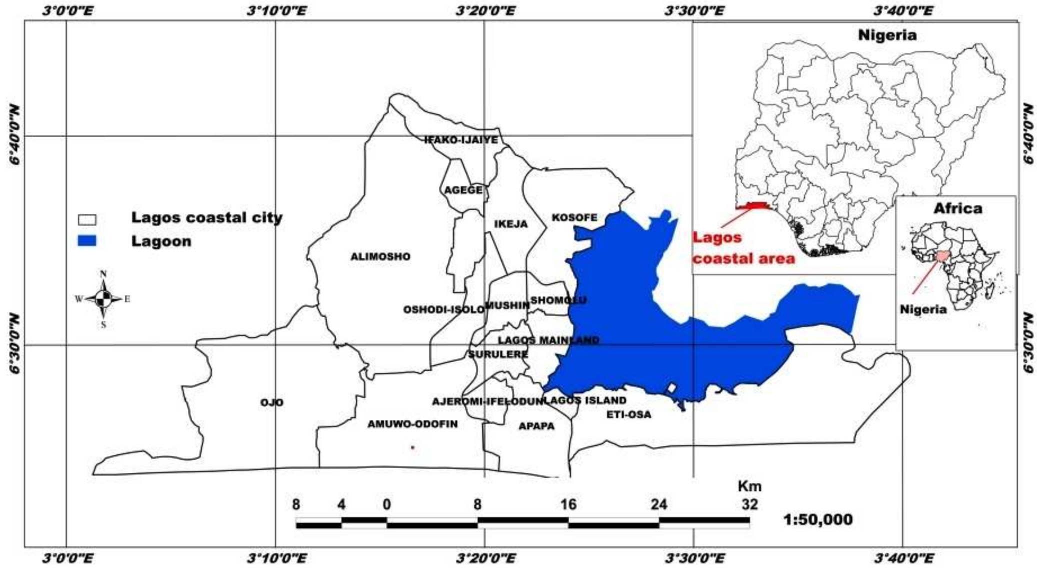

Figure 3: The Lagos metropolis of Nigeria (Inset showing Africa and Nigeria).

3.2. Model validation datasets

The key data used in validating *GFSP-1* is the LiDAR DEM, which within the present test case, covers some places within Eti-Osa and Lagos Island LGAs. The Lagos LiDAR data which comes in the original (*.las*) format was acquired from GIS section of the Lagos state office of Lands and Survey. Lagos is the only region in Nigeria that has acquired such a dataset. Each tile forms a regular polygon dense of DSM, measuring 500 meters by 500 meters (see figure 4). The horizontal and vertical resolutions are 1m respectively (although each tile was subsequently resampled to a 2-m horizontal resolution to ease the computation burden of *GFSP-1*). Each tile cost about twenty thousand Nigerian naira (i.e. £90 using the 2013 exchange rate). It was reported by Nkwunonwo *et al.* (2016) that the cost of acquiring these datasets remains a significant constraint to flood modelling in Lagos. However, in the present research, 32 tiles were acquired for this research, to delineate flood hazard on a relatively wider spatial extent.

These 32 tiles are unable to facilitate a nuanced understanding of the elevation differences of the study area, and how they affect the simulation results. Thus, a 35-meter elevation map of Lagos, which displays range of elevation with different colours, shown in figure 4a, will be superimposed on the simulated results. The map was generated using elevation data from NASA's 90m horizontal resolution SRTM data.

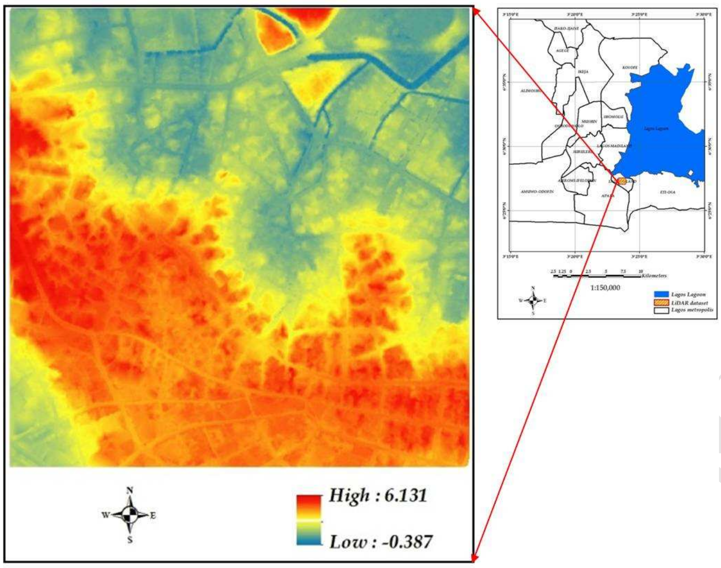

Figure 4: one tile of the 1-m horizontally-spaced point clod LiDAR DSM of the study area.

The rainfall datasets were acquired from NIMET. Two months rainfall data at a daily amount sampling rate were acquired (see table 1). To obtain effective rainfall intensity for the simulation, average of respective intensities was taken (a solution that is being proposed in the literature) (for example Chen, 1983). For the present model, it is assumed that effective rainfall intensity disaggregates the daily rainfall amounts to hourly measures, so that simulated flood inundation can be characterised over the recorded duration of the rainfall (Wójcik & Buishand, 2003). Using this approach, the effective rainfall amount was calculated to be 0.65 mm/hr. Abstractions and other loses were not considered in the present simulation due to lack of data relating to them. A roughness coefficient of 0.02 was adopted from published values in Chow *et al.* (1988).

Table 1: 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**

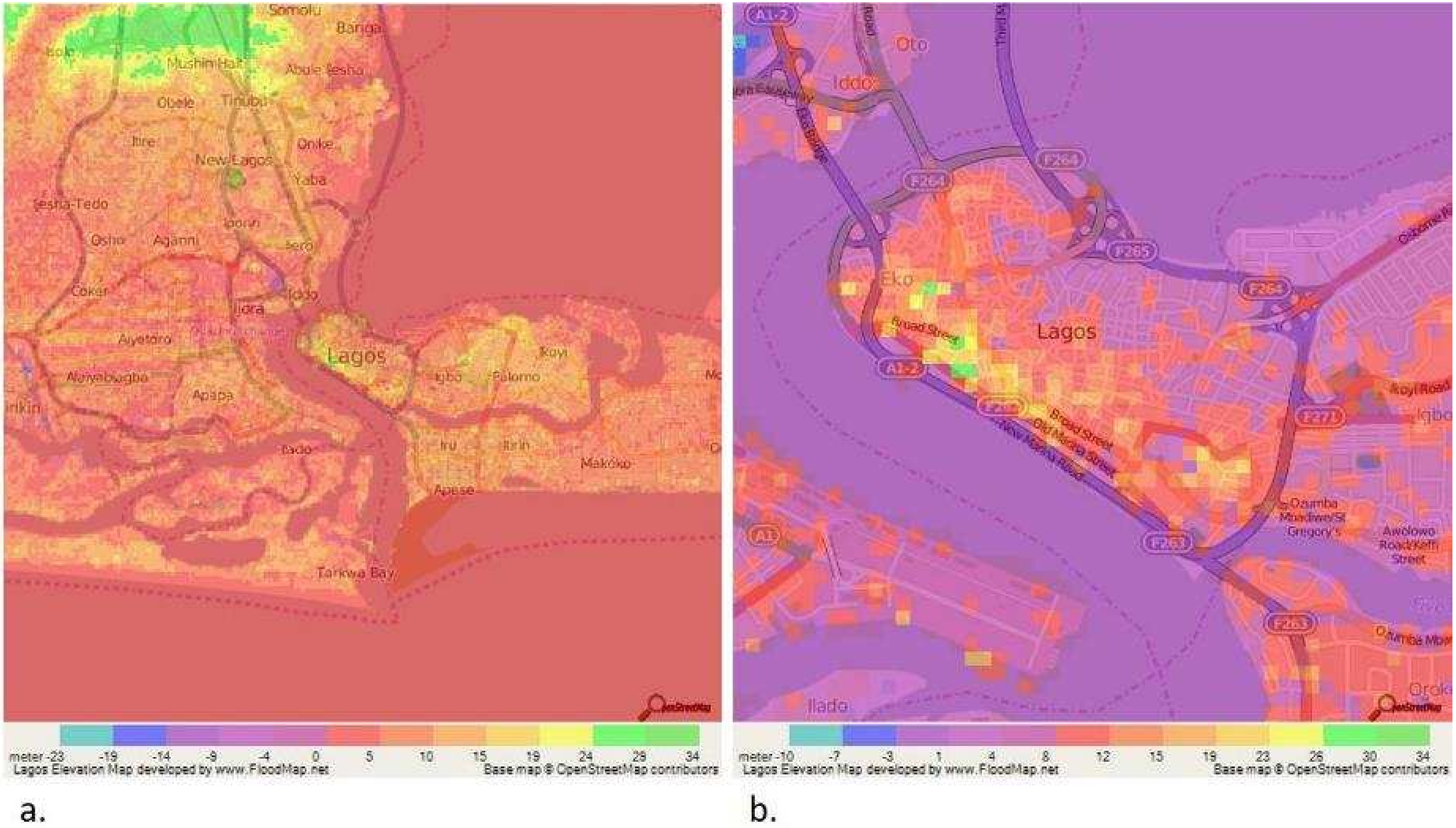

Figure 4a: 35-meter elevation map of Lagos, which displays range of elevation with different colours. The map was generated using elevation data from NASA's 90m resolution SRTM data (www.floodmap.net). (a) Elevation map for Lagos area. (b) Elevation map for part of the study area.

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 (thirty of which has been used in model validation), and this provided detailed eye witnesses' testimonies of the flooding event (see table 2). 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.

3.3. Model validation procedure

In the present research, quantitative information extracted from photographs has been used to validate *GFSP-1.* This is due to the lack of measured flood water, coupled with lack of funds to acquire synthetic aperture radar (SAR) satellite data which can be analyzed to extract water levels for the historical flooding being simulated. There is ample evidence to show the increasing utility of social media data such as Flickr, twitter, newspaper reports, online photographs, etc., to validate flood model in situations where authoritative and field-based datasets are lacking (Latonero & Shklovski, 2011; Alexander, 2014; de Albuquerque *et al.,* 2015; Smith *et al.,* 2015). 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. 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 overrule 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.

Social media data such as photographs show contextual information and situational relationship between water level and some parts of the environment such as buildings, submerged cards, 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.

Table 2: 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)

In applying this technique to the present research, six photographic images (figure 5) of July 10th 2011 Lagos flooding, carefully selected from online sources, were used to estimate ranges of flood water depth. 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 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 different markedly from that estimated outside the building compound. In the present research, only the outside flood water is considered. With the knowledge that many houses measure up to 1m from the floor to the window, water depth can be estimated to lie 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 5: Photographic images of July 11th 2011 Lagos flooding. *GFSP-1* model was validated against water depth values estimated from these photographs.

GFSP-1 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, rainfall intensity, and the assumed Manning's Coefficient value. Initial and final times of simulation are also entered in the input file. The model requires MATLAB^{TM} program to be pre-installed and running on computer system. To enhance the computation speed the model, a minimum processing speed of 2.0GHz along with a minimum RAM of 2GB will be desirable.

Once the model begins to run, effective rainfall is assumed to land uniformly on the domain. Hydrological losses entered into the input file are accounted for. The water depth is outputted at the interval based on the user's specification. This is to enable the end-user to have a closer idea of the time-variant flood water depth and extent. In the test cases reported later, water depth is output at 30 minutes, 2 hours, 5 hours, 8 hours, 11 hours, 14 and 17 hours epochs. Some models such as the LISFLOOD-FP specifies a regular interval, for example 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.

4. Results and Discussion

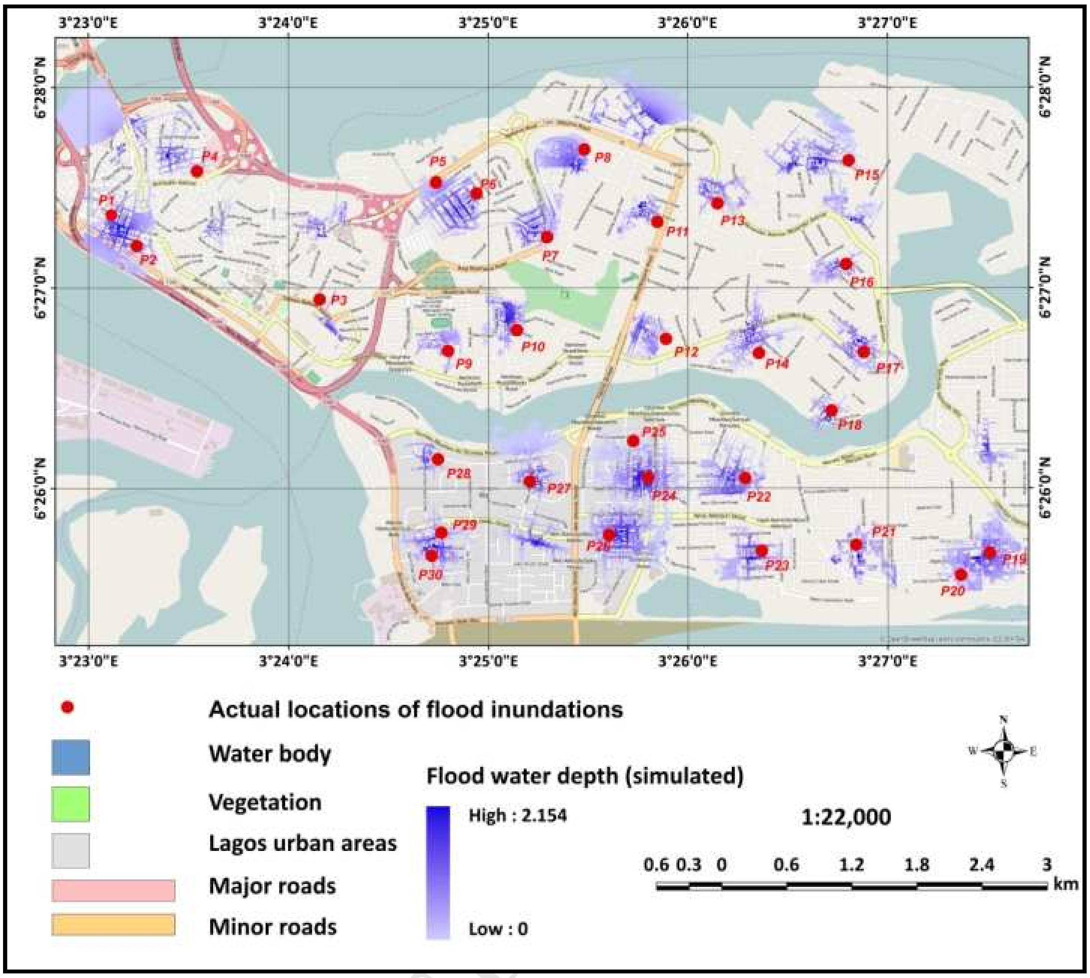

Figure 6: Simulated flooding inundation mapped against actual inundation locations based on secondary sources and eye witness evidence of the July 2011 flooding in Lagos.

From figure 6 above, it can be seen that within the chosen area, *GFSP-1* simulated flood inundations in locations that matched the actual locations of inundation, following the 2011 flooding event. Only *P3*, an area known as Onikan within Lagos-Island was wrongly predicted, as there was no evidence of flood inundation there. To critically assess the performance of *GFSP-1,* and to understand the true impact of the 2011 in terms of spatial and temporal flow variability within the case study, 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 7-12.

This figure was intersected with the section of the elevation map showing the Lagos Island part of the study area. The resulting map (figure 6a) indicates that *GFSP-1* simulated flooding at locations having lower elevations within the study area. This follows the routing scheme which transfers water to a neighbouring cell with elevation value lower that the rest of the cells within a specified neighbourghood system.

figure 6a

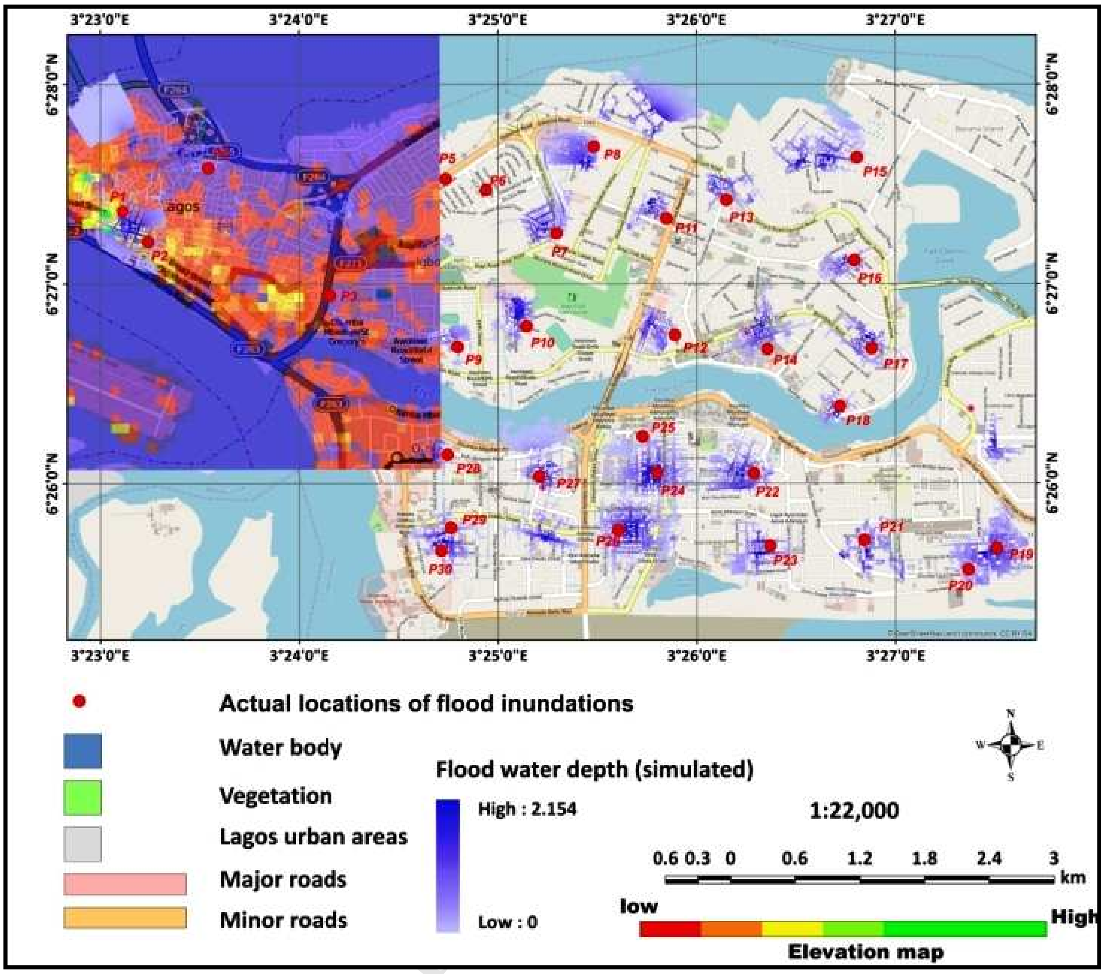

Figure 6a: Simulated flooding inundation intersected with a part of the SRTM elevation map.

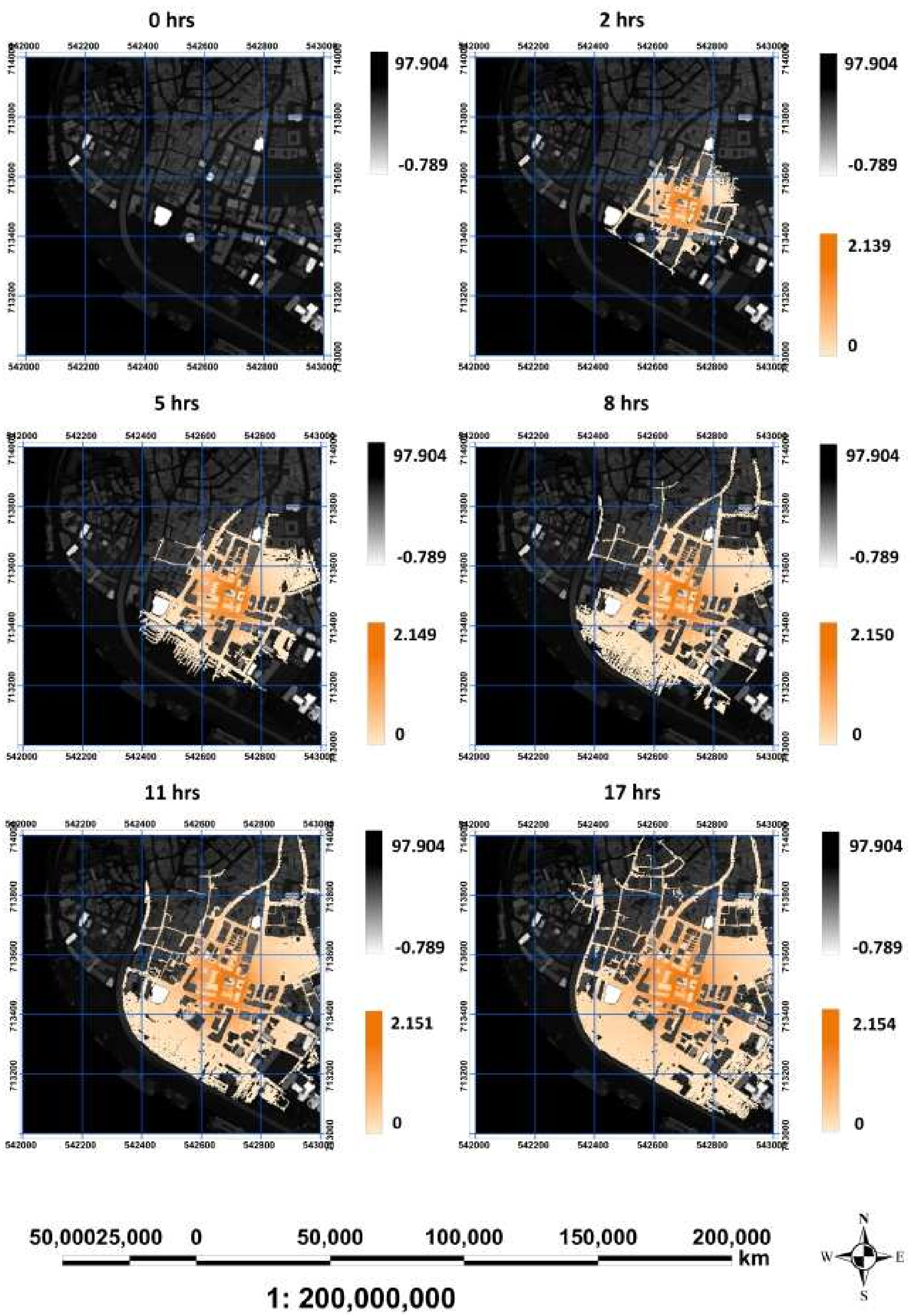

Figure 7: Simulated water depth at Broad and Balogun Street areas, Lagos Island

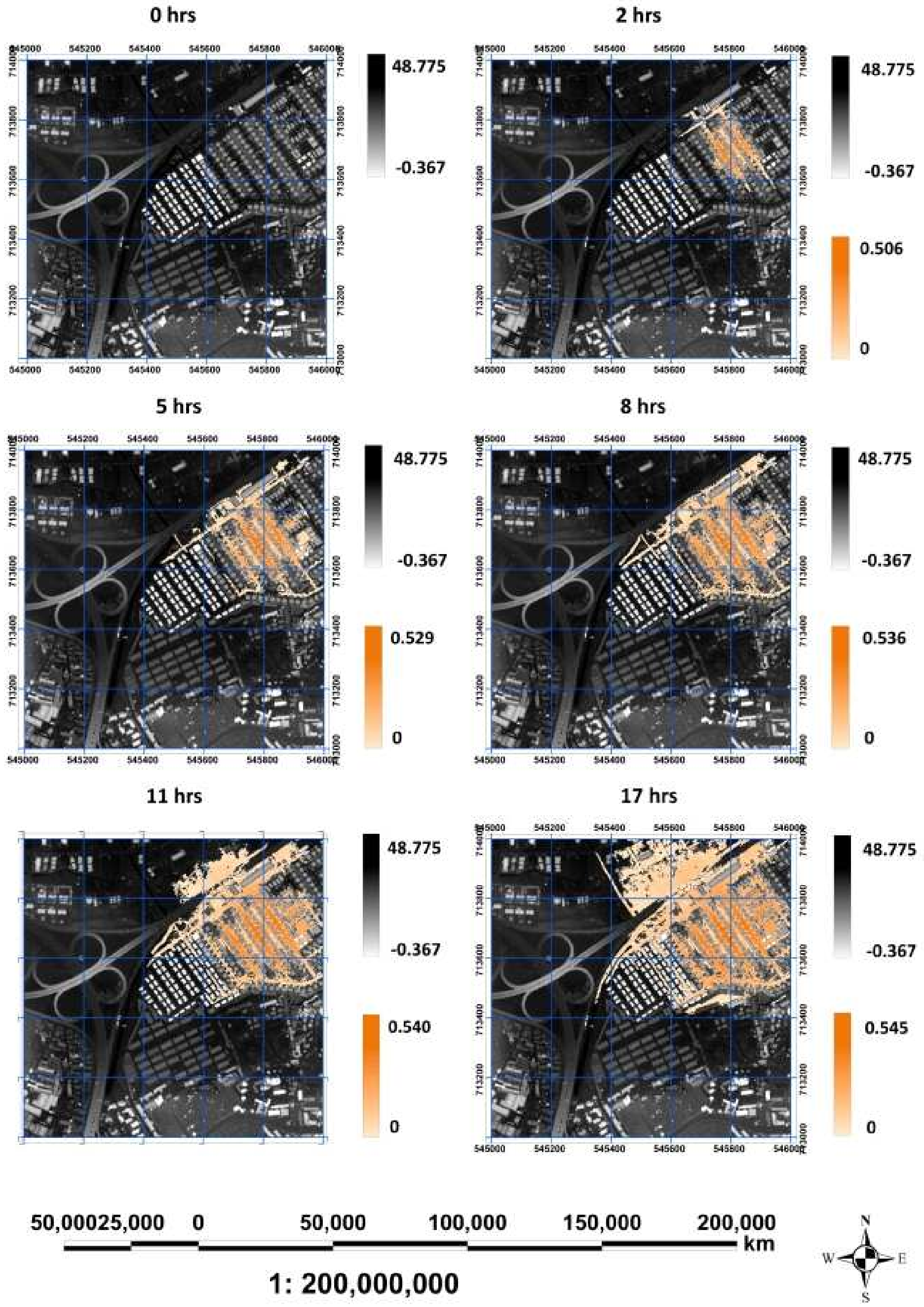

Figure 8: Simulated water depth at Dolphin estate

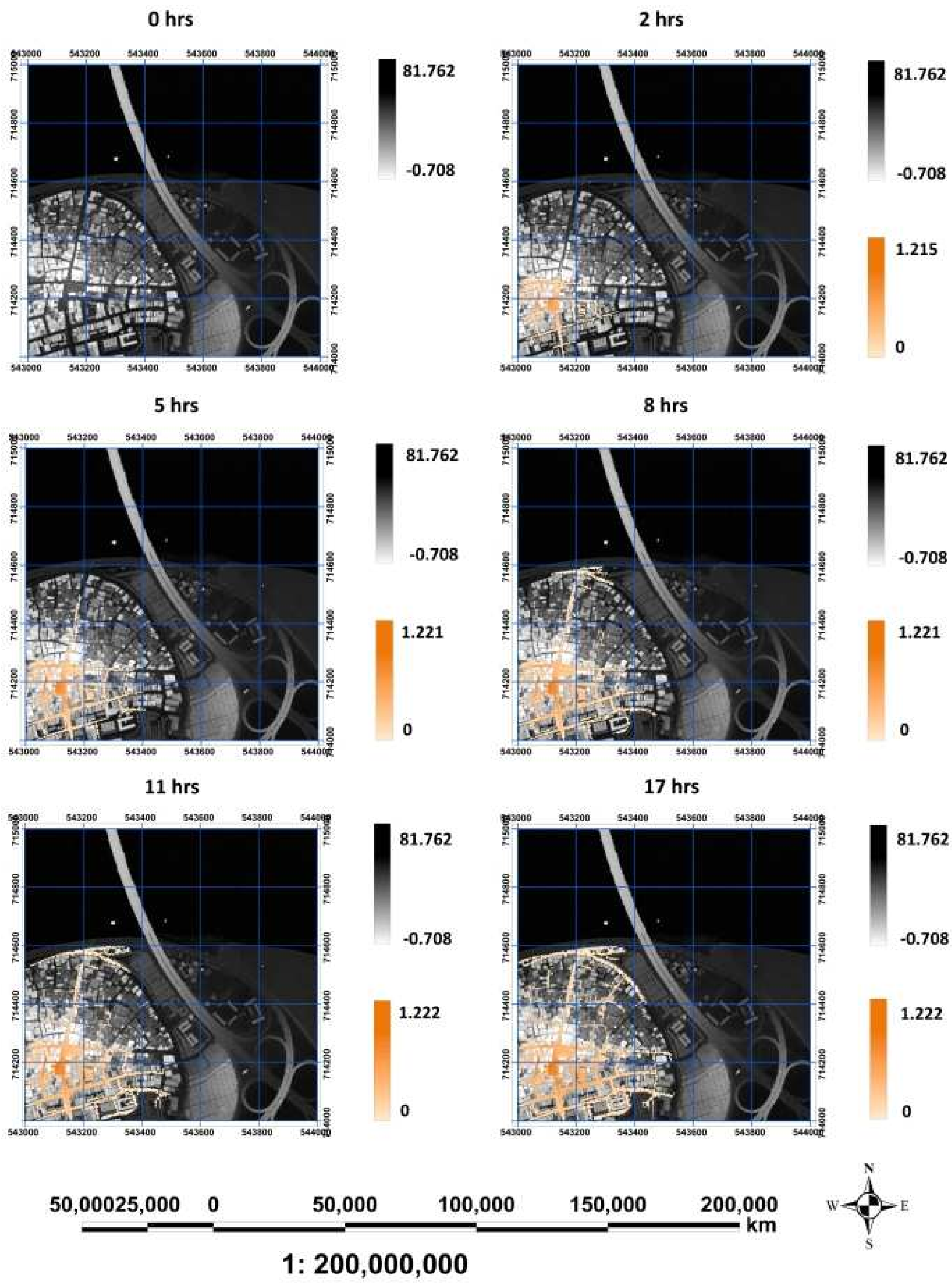

Figure 9: Simulated water depth at Lagos Island

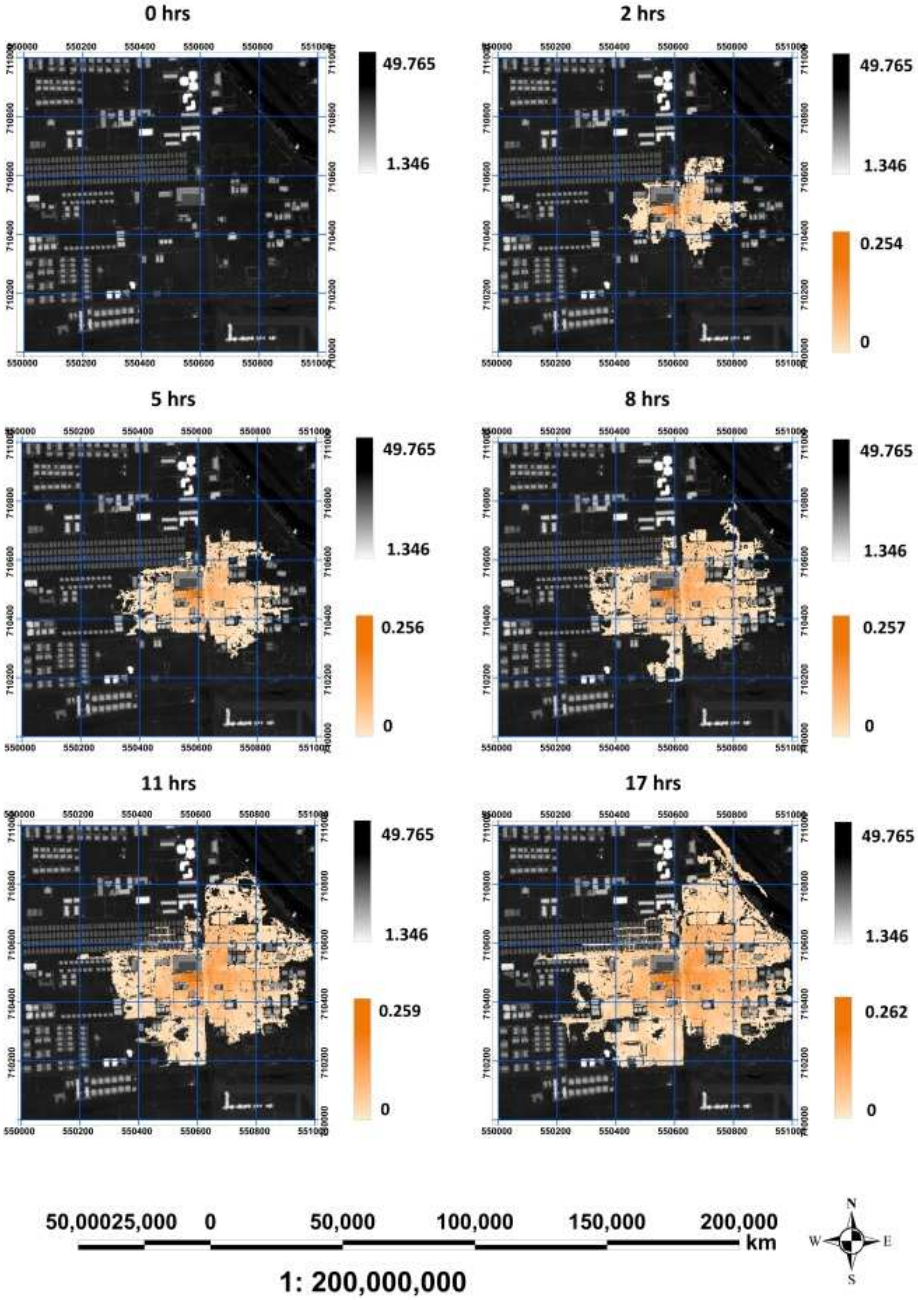

Figure 10: Simulated water depth at Castle estate

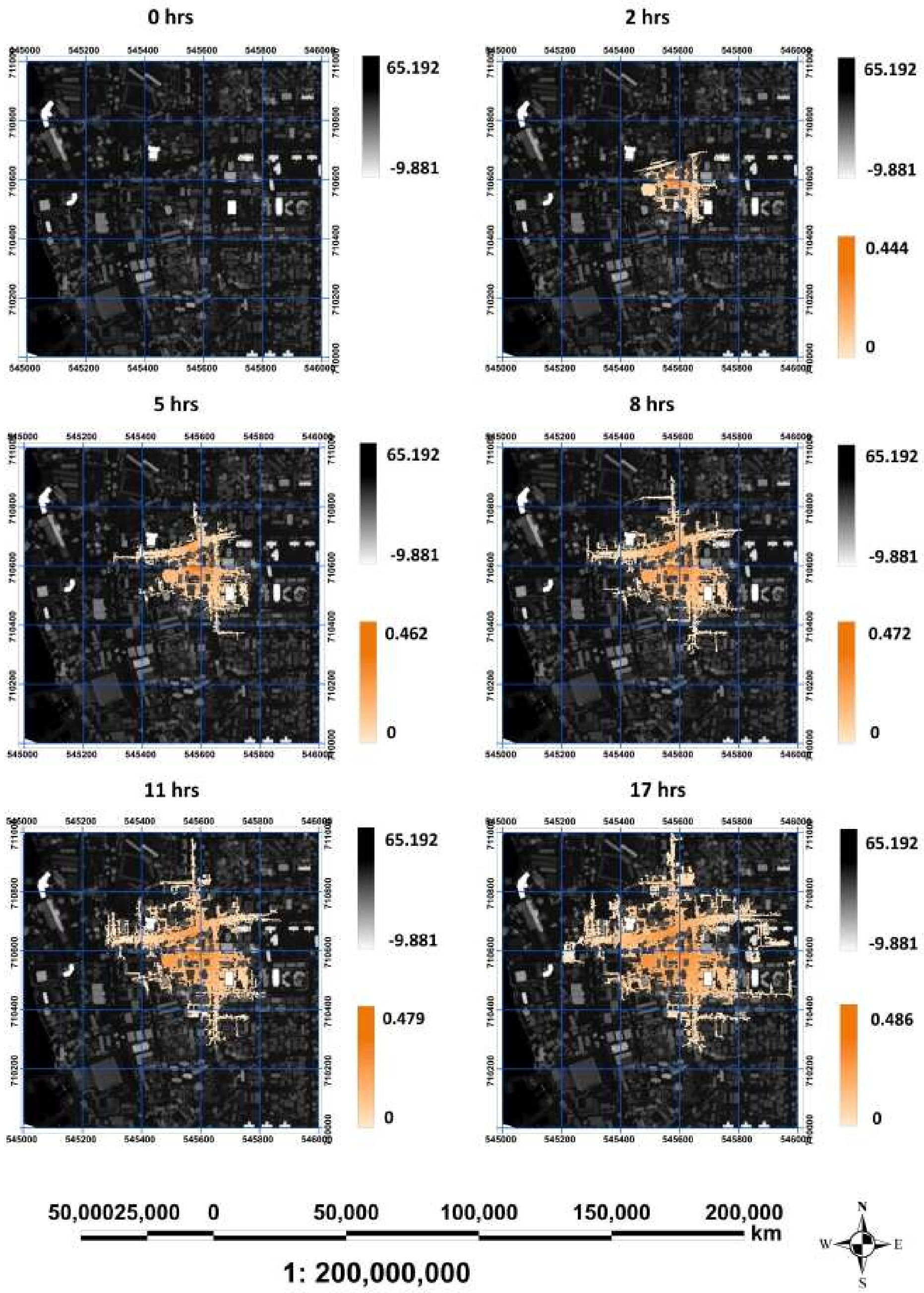

Figure 11: Simulated water depth at Victoria Island

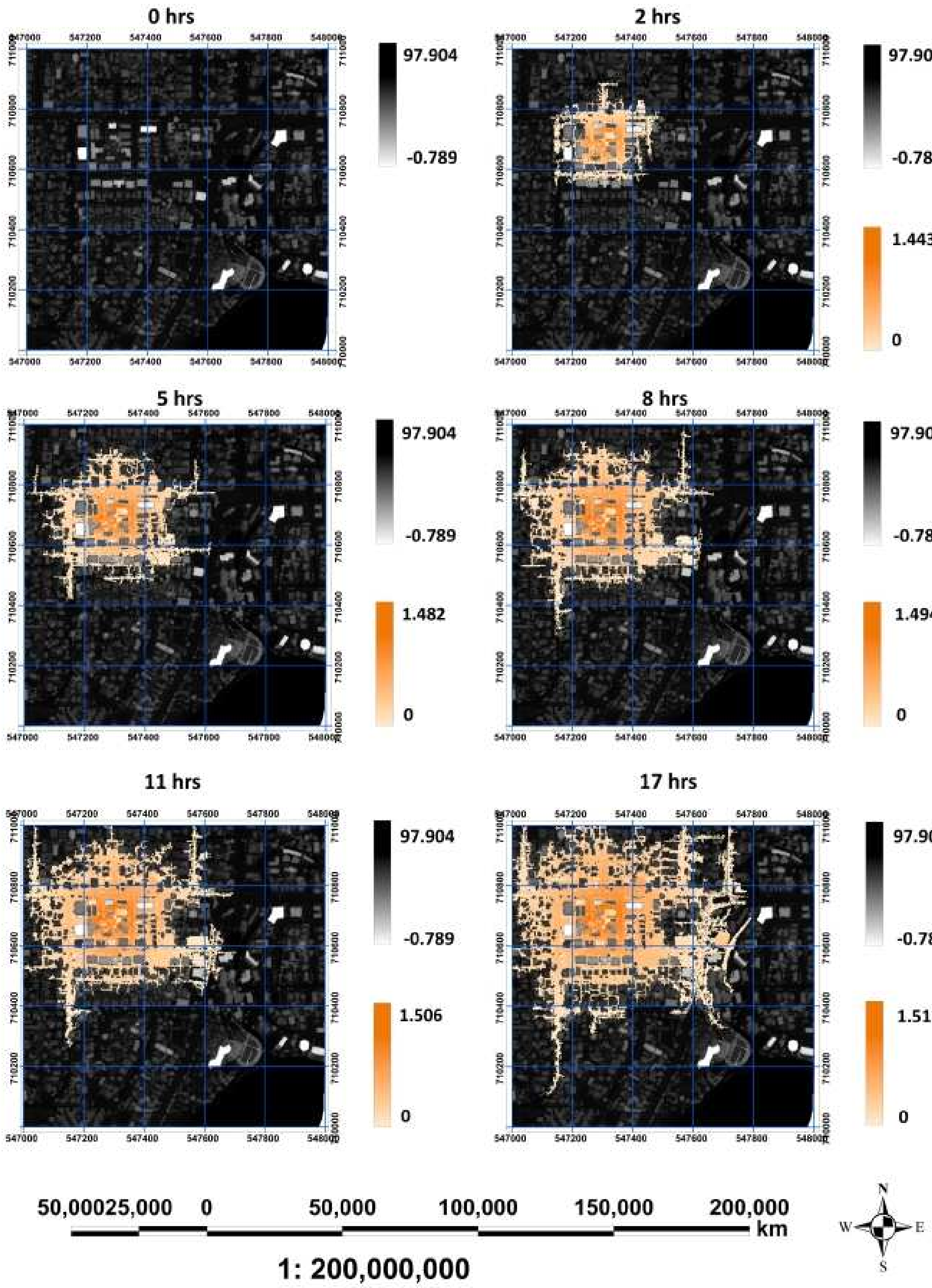

Figure 1: Adetokumbo Ademola road in Transit area, Victoria Island

The plots of water depth vs. time (figure 13) indicate that the simulated results are relatively stable solutions of flood hydrodynamics with respect to flood water depth and extent. Higher inundation depths were simulated around Balogun and Broad Street (2.154m), Adeyinka Oyekan Avenue (1.222m) in Lagos Island, and the area around Adetokumbo Ademola road (1.511m) 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 elation 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 0.545m and 0.486m 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 (0.262m) 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.

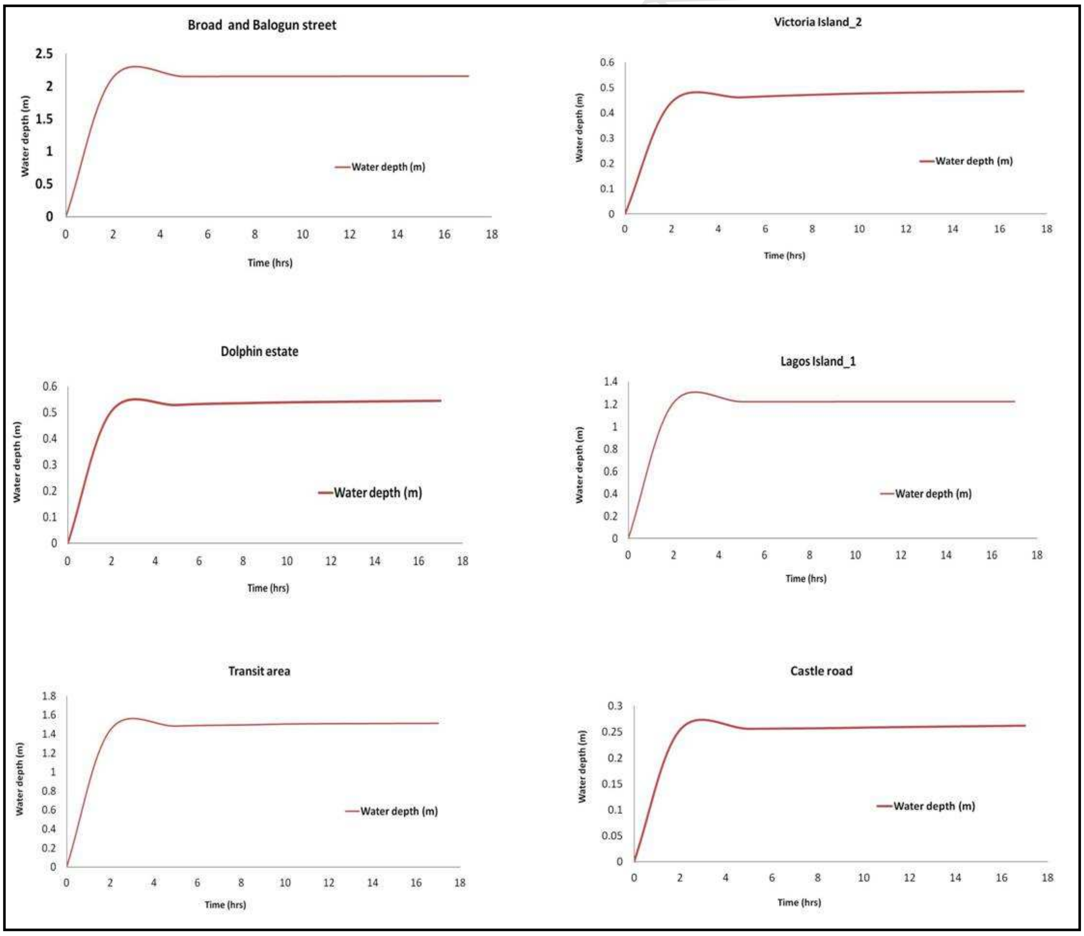

Figure 2: Plots of simulated water depth vs. time for the six selected locations in the study area

From the temporal variations of inundation depth at the chosen locations shown in figure 13 above, 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).

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. Water is also transferred if a transition rule detects any available spaces within the intervening lower elevation cells in the neighbourhood system. The smooth curve in figure 13 shows that the model simulation output 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.

To complete the validation of the *GFSP-1* model against the social media-based data, flood water depths were estimated from the six photographic, which were hotlinked to their appropriate flooded locations within the case study areas on the Lagos basemap (figure 14).

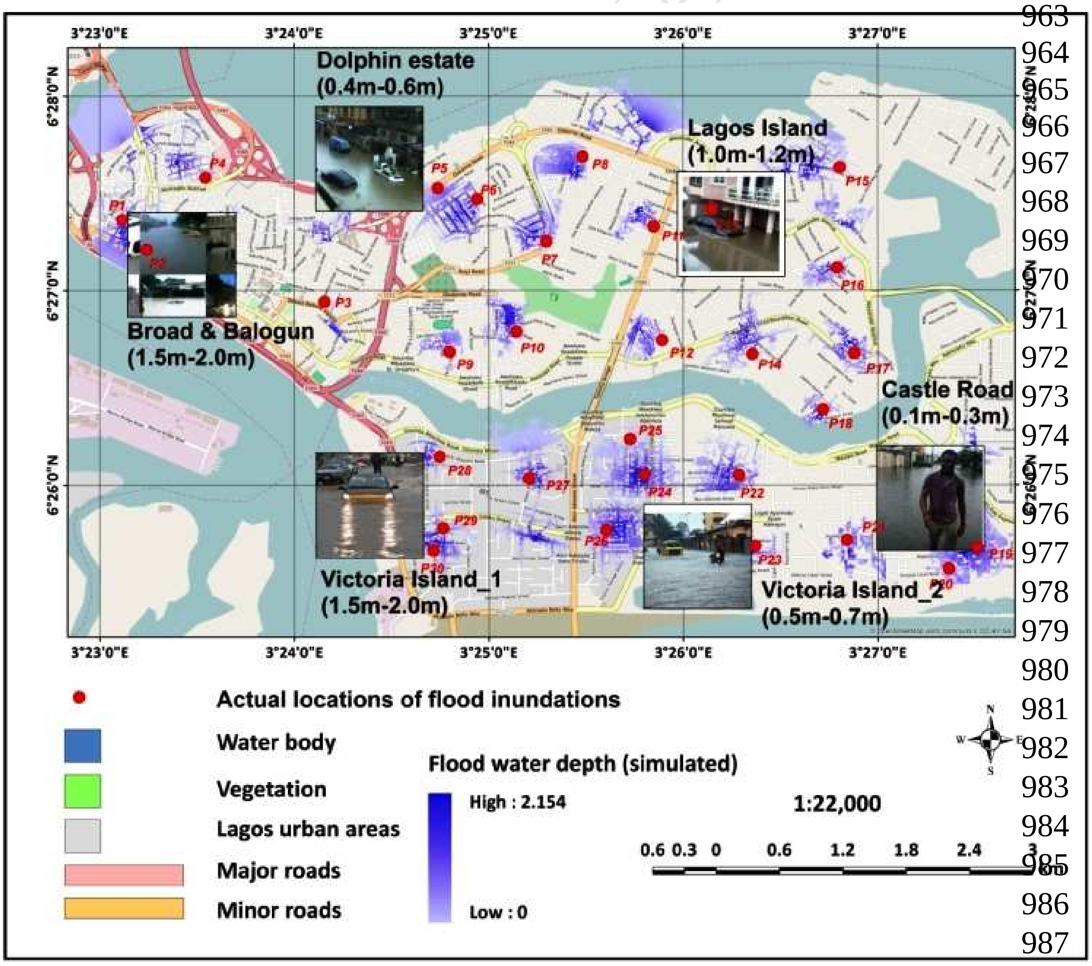

Figure 3: Thumbnails of selected photographs hotlinked to appropriate flooded locations on the Lagos basemap

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 3). These values were outlined as bar charts (figure 15) and scatter plots (figure 16), 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 (that is values simulated within seventeen hours flood duration) 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. Further analyses were carried out to determine the correlation.

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

Table 3: Estimated maximum water depths, and their respective averages compared with the maximum water depths values simulated by GFSP-1 for Lagos.

Coupling of CA and SIFDS in the new model made the simulation speed reasonably impressive. This is somewhat an adaptive time stepping scheme which chooses a time step for a complete iteration by comparing two time steps and choosing the minimum of the two. On the whole, the simulation duration for *GFSP-1* is dependent of the DEM spatial resolution. For a 2-m DEM 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 using a 5-m DEM. Unfortunately, scaling up the spatial grid of the DEM compromises the simulation output. However, to restrict modelling on the basis of higher resolution DEMs, more sophisticated computer facilities can largely improve the simulation speed of the new model.

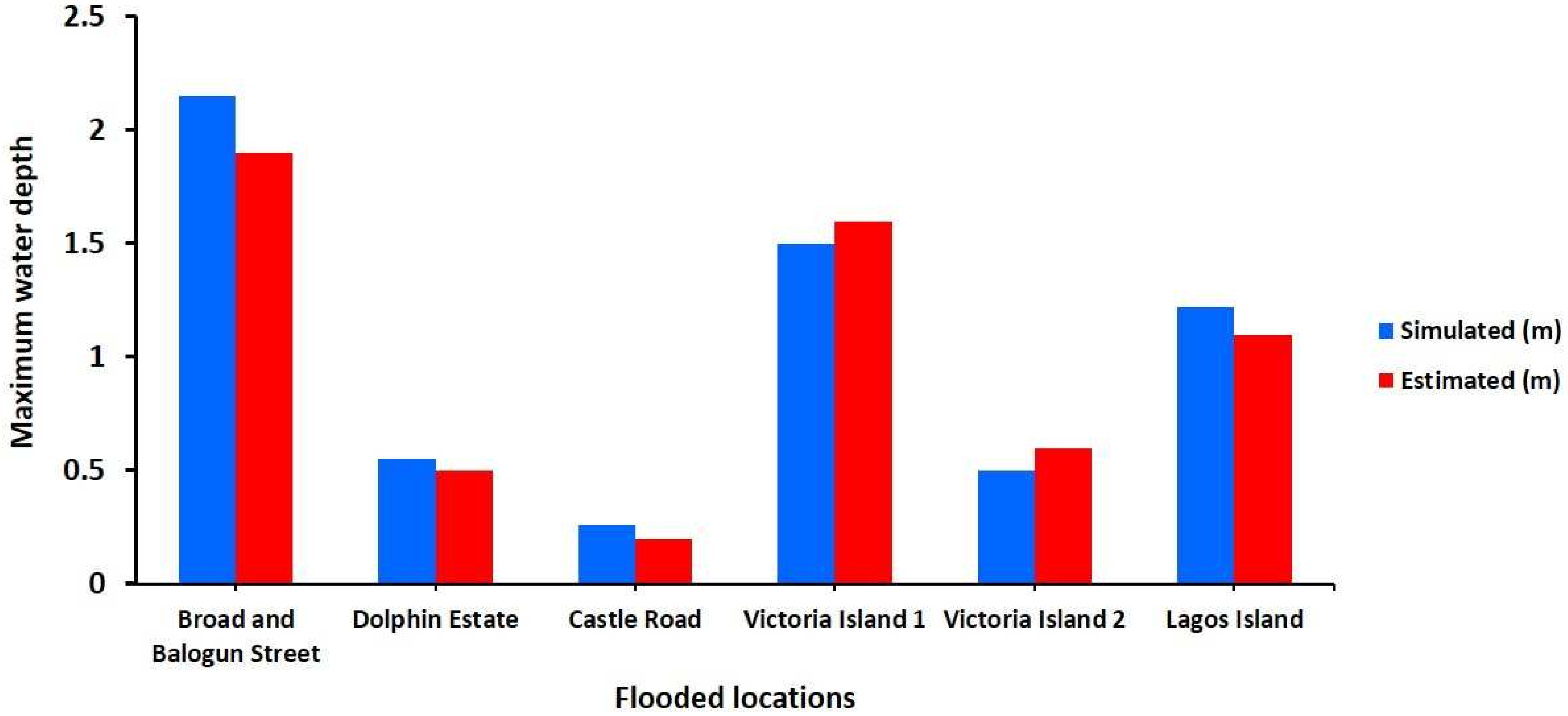

Figure 15: Bar charts showing the relationship between maximum flood water depths simulated using *GFSP-1*, compared with average water depths estimated from photographs of flooding in Lagos.

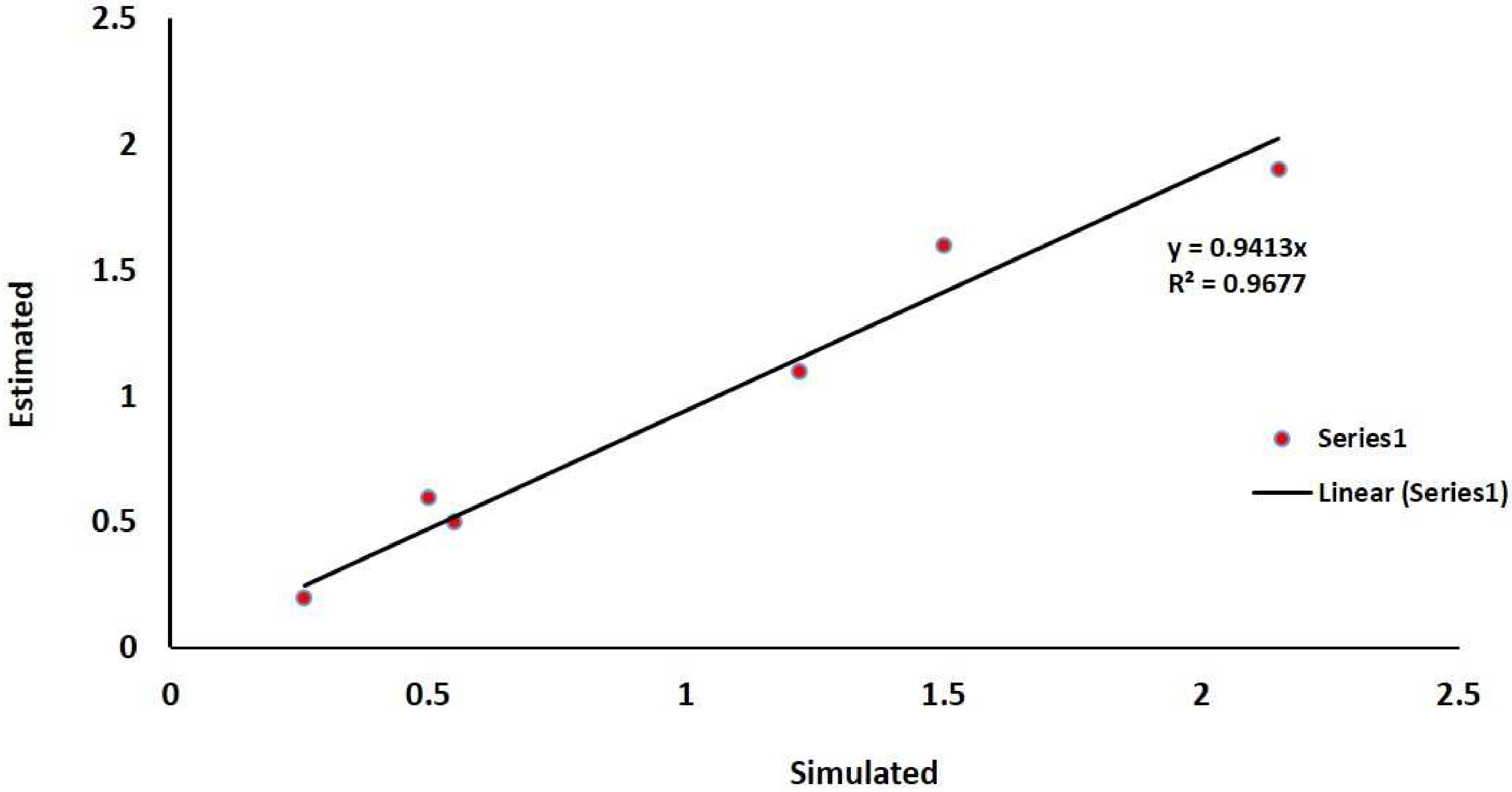

Figure 16: Scatter plots relationship between maximum flood water depths simulated using *GFSP-1*, compared with average water depths estimated from photographs of flooding in Lagos. Computed correlation coefficient is 0.968.

5. Conclusion

This study has developed an effective and efficient flood model, *GFSP-1,* to simulate urban flooding inundation for urban flood risk management. The model combines cellular automata (CA) framework and a semi-implicit finite difference scheme (SIFDS), based on the original work of Casulli (1990). Within the CA framework, a von Neumann neighborhood system defines the discrete space, whilst a set of transition rules are shown to govern the introduction of water and its movement in and out of the cell. The SIFDS is an attempt to combine the merits of explicit and implicit numerical scheme within a single numerical formulation. It is shown that the dynamic link between the CA and the SIFDS improves on the model time step. This link enables the model to maintain unconditional stability within a convenient simulation time.

This model is used to simulate the July 10th 2011 flooding in the Lagos areas of Nigeria. Using a LiDAR (Light Detection and Ranging) digital elevation model (DEM), which horizontal resolution is 2-m, rainfall amount measured during the event was input into the model, and allowed to simulate flooding within the rainfall duration which is seventeen hours. Two local government areas (LGAs) – Eti-Osa and Lagos-Island, were selected, based on the availability of the LiDAR DEM. Altogether thirty two DEMs were acquired for the simulation, and each of them measured 500m * 500m, enclosing 250, 000 cells. With such a large number of cells, the model computing time on MATLAB^{TM} platform for simulating the 17 hours rainfall event was about 4 hours, using a 6GB RAM, 500 HDD, 2.3 GHz Intel Core processing machine. This suggest a fast simulation of flooding, although this speed is subject to improvement by applying the object-oriented programming of MATLAB^{TM}, parallel computing, and by using higher processing machines.

Simulated flood inundation outputs are comparable to those recorded by the media and witnessed by local residents. These results suggest that the new model is capable of generating reliable predictions of the July 2011 urban flooding event, and this provides useful information for flood risk management in the Lagos area of Nigeria. Major innovations in the new model are: (1) the integration of SIFDS and CA, (2) the ability to run with a minimum of input data, a suitable DEM and rainfall intensity or amount and (3) outputs format that can be accessed easily using any available GIS program. Outputs from the model are written as arc grid files that can be opened easily in any GIS program.

This research is the first ever attempt to publish flood modelling procedure for the Lagos area, and this will have a significant impact in the understanding of urban flooding and flood risk management in this city. Additionally, coupling SIFDS and CA within a flood model framework is innovative in flood modelling research, and is expected to make significant contribution to the science of flood risk assessment. However, there are few uncertainties, which are being recommended for future studies. Firstly, the suitability of global DEMs to accurate prediction of flooding within the new model framework is still unknown. More testing and validation of the model using other urban inundation flood models need to be undertaken. Representation of complex urban features which influence the movement of flood water may be a major source of uncertainty to the performance of the model. This also has to be investigated in future research.

Acknowledgements

This publication is the key result of a PhD research, which has been funded by the Tertiary Institutions Education Trust Fund (TETFund), a FGN/UNN academic staff intervention scheme. The Surveyors Council of Nigeria (SURCON) is being acknowledged for providing some supplementary grants. Data relating to the July 2011 flooding were obtained mainly from previously published research and courtesy of responses from eye witnesses. The anonymity of these eye witnesses has been protected in line with the ethical proviso of this research. The Center for Research in Epidemiology of Disasters (CRED), Nigeria's Ministry of the Environment and the Nigeria Environmental Study Action/Team (NEST) are also acknowledged. Previous works in the area of flood modelling, especially the original work of Professor Vincenzo Casulli, are equally acknowledged, and so are the anonymous reviewers, and the editor of this journal.

References

Adelekan, O. (2010). Vulnerability of poor urban coastal communities to flooding in Lagos, Nigeria. *Environment and Urbanization,* 22, 433-450.

Adelekan, I. O. (2015). Flood risk management in the coastal city of Lagos, Nigeria. *Journal of Flood Risk Management.* DOI: 10.1111/jfr3.12179.

Aderogba, K. A. (2012). Global warming and challenges of floods in Lagos metropolis, Nigeria. *Academic Research International,* 2(1), 448-468.

Akanni, O., & Bilesanmi, L. (2011, July 20). Flood: Lagos residents forced to relocate …. Drowning teenager rescued in Vanguard: Towards a Better Life for the People. *Lagos: Vanguard Media Limited*, p. 20.

Ajibade, I., McBean, G., & Bezner-Kerr, R. (2013). Urban flooding in Lagos, Nigeria: Patterns of vulnerability and resilience among women. *Global Environmental Change, 23,* 1714-1725.

Alexander, D. E. (2014). Social media in disaster risk reduction and crisis management. *Science and Engineering Ethics*, *20*(3), 717-733.

Anees, M. T., Abdullah, K., Nawawi, M. N. M., Ab Rahman, N. N. N., Piah, A. R. M., Zakaria, N. A., Syakir, M.I., & Omar, A. M. (2016). Numerical modeling techniques for flood analysis. *Journal of African Earth Sciences*, *124*, 478-486.

Bazilevs, Y., & Hughes, T. J. (2007). Weak imposition of Dirichlet boundary conditions in fluid mechanics. *Computers & Fluids*, *36*(1), 12-26.

Casulli, V. (1990). Semi-implicit finite difference methods for the two-dimensional shallow water equations. *Journal of Computational Physics, 86(1),* 56-74.

Casulli, V., & Stelling, G. S. (2013). A semi-implicit numerical model for urban drainage systems. *International Journal for Numerical Methods in Fluids*, *73*(6), 600-614.

Chen, A. S., Evans, B., Djordjević, S., & Savić, D. A. (2012). Multi-layered coarse grid modelling in 2D urban flood simulations. *Journal of Hydrology*, *470*, 1-11.

Chen, C. L. (1983). Rainfall intensity-duration-frequency formulas. *Journal of Hydraulic Engineering*, *109*(12), 1603-1621.

Cherqui, F., Belmeziti, A., Granger, D., Sourdril, A., & Le Gauffre, P. (2015). Assessing urban potential flooding risk and identifying effective risk-reduction measures. *Science of the Total Environment*, *514*, 418-425.

Chow, V.T., Maidment, D.R., & Mays, L.W. (1988). *Applied Hydrology*. New York: McGraw-Hill.

Cirbus, J., & Podhoranyi, M. (2013). Cellular automata for the flow simulations on the earth surface, optimization computation process. *Applied Mathematics & Information Sciences*, *7*(6), 2149.

Costabile, P., & Macchione, F. (2015). Enhancing river model set-up for 2-D dynamic flood modelling. *Environmental Modelling & Software*, *67*, 89-107.

de Albuquerque, J. P., Herfort, B., Brenning, A., & Zipf, A. (2015). A geographic approach for combining social media and authoritative data towards identifying useful information for disaster management. *International Journal of Geographical Information Science*, *29*(4), 667-689.

Djordjević, S., Butler, D., Gourbesville, P., Mark, O., & Pasche, E. (2011). New policies to deal with climate change and other drivers impacting on resilience to flooding in urban areas: the CORFU approach. *Environmental Science & Policy*, *14*(7), 864-873.

Dumbser, M., & Casulli, V. (2013). A staggered semi-implicit spectral discontinous Galerkin scheme for the shallow water equations. *Applied Mathematics and Computations, 219,* 8057-8077.

Dumbser, M., Iben, U., & Ioriatti, M. (2015). An efficient semi-implicit finite volume method for axially symmetric compressible flows in compliant tubes. *Applied Numerical Mathematics*, *89*, 24-44.

Engelen, G., White, R., Uljee, I., & Drazan, P. (1995). Using cellular automata for integrated modelling of socio-environmental systems. *Environmental Monitoring and Assessment*, *34*(2), 203-214.

Etuonovbe A. K. (2011). The devastating effect of flooding in Nigeria. In FIG Working Week. 2011, May. Accessed 10 March 2015; Available at: http://www.fig.net/pub/fig2011/papers/ts06j/ts06j_etuonovbe_5002.pdf

Fohringer, J., Dransch, D., Kreibich, H., & Schröter, K. (2015). Social media as an information source for rapid flood inundation mapping. *Natural Hazards and Earth System Sciences*, *15*(12), 2725-2738.

Ghimire, B., Chen, A. S., Guidolin, M., Keedwell, E. C., Djordjević, S., & Savić, D. A. (2013). Formulation of a fast 2D urban pluvial flood model using a cellular automata approach. *Journal of Hydroinformatics*, *15*(3), 676-686.

IFRC (International Federation of Red Cross and Red Crescent) (2011): Nigeria: Floods – July, available at: http://reliefweb.int/disaster/ fl-2012-000138-nga (last access: 10 March 2015).

Kaźmierczak, A., & Cavan, G. (2011). Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure. *Landscape and Urban Planning*, *103*(2), 185-197.

Kim, D., Sun, Y., Wendi, D., Jiang, Z., Liong, S. Y., & Gourbesville, P. (2018). Flood Modelling Framework for Kuching City, Malaysia: Overcoming the Lack of Data. In *Advances in Hydroinformatics* (pp. 559-568). Springer, Singapore.

Kulkarni, A. T., Mohanty, J., Eldho, T. I., Rao, E. P., & Mohan, B. K. (2014). A web GIS based integrated flood assessment modeling tool for coastal urban watersheds. Computers & Geosciences, 64, 7-14.

Lagos State Government (LSG). (2012). Abstract of Local Government Statistics, Lagos: Lagos Bureau of Statistics, Ministry of Economic Planning and Budget Secretariat, Alausa, Ikeja.

Latonero, M., & Shklovski, I. (2011). Emergency management, Twitter, and social media evangelism. *International Journal of Information Systems for Crisis Response and Management*, *3*(4), 67-86.

Liu, L., Liu, Y., Wang, X., Yu, D., Liu, K., Huang, H., & Hu, G. (2015). Developing an effective 2-D urban flood inundation model for city emergency management based on cellular automata. *Natural Hazards and Earth System Sciences 15,* 381–391.

Martin, N., & Gorelick, S. M. (2005). MOD_FreeSurf2D: A MATLAB surface fluid flow model for rivers and streams. *Computers and Geosciences, 31(7),* 929-946.

Nkwunonwo, U. C., Malcolm, W., & Brian, B. (2015). Flooding and Flood Risk Reduction in Nigeria: Cardinal Gaps. *Journal of Geography & Natural Disasters, 5(1),* 1-12.

Nkwunonwo, U. C., Whitworth, M., & Baily, B. (2016). Review article: 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*(2), 349-369.

Oyinloye, M., Olamiju, I., & Adekemi, O. (2013). Environmental impacts of flooding on Kosofe local government area of Lagos state, Nigeria: A GIS perspective. *Journal of Environmental and Earth Science* 3(5), 57-66.

Perales-Momparler, S., Andrés-Doménech, I., Hernández-Crespo, C., Vallés-Morán, F., Martín, M., Escuder-Bueno, I., & Andreu, J. (2017). The role of monitoring sustainable drainage systems for promoting transition towards regenerative urban built environments: A case study in the Valencian region, Spain. *Journal of Cleaner Production*, *163*, S113-S124.

Smith, K. (2013). *Environmental hazards: assessing risk and reducing disaster.* Routledge.

Smith, L., Liang, Q., James, P., & Lin, W. (2015). Assessing the utility of social media as a data source for flood risk management using a real-time modelling framework. *Journal of Flood Risk Management*.

Teng, J., Jakeman, A. J., Vaze, J., Croke, B. F., Dutta, D., & Kim, S. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*, *90*, 201-216.

Von Neumann, J. (1951). The general and logical theory of automata. *Cerebral Mechanisms in Behaviour*, *1*(41), 1-2.

Wahle, J., Neubert, L., Esser, J., & Schreckenberg, M. (2001). A cellular automaton traffic flow model for online simulation of traffic. *Parallel Computing*, *27*(5), 719-735.

Wójcik, R., & Buishand, T. A. (2003). Simulation of 6-hourly rainfall and temperature by two resampling schemes. *Journal of Hydrology*, *273*(1-4), 69-80.

Yamamoto, K., Kokubo, S., & Nishinari, K. (2007). Simulation for pedestrian dynamics by real-coded cellular automata (RCA). *Physica A: Statistical Mechanics and its Applications, 379(2),* 654-660.

Zevenbergen, C., Veerbeek, W., Gersonius, B., & Van Herk, S. (2008). Challenges in urban flood management: travelling across spatial and temporal scales. *Journal of Flood Risk Management*, *1*(2), 81-88.

Zevenbergen, L.W., & Throne, C.R. (1987). Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms*, *12*, 47-56.