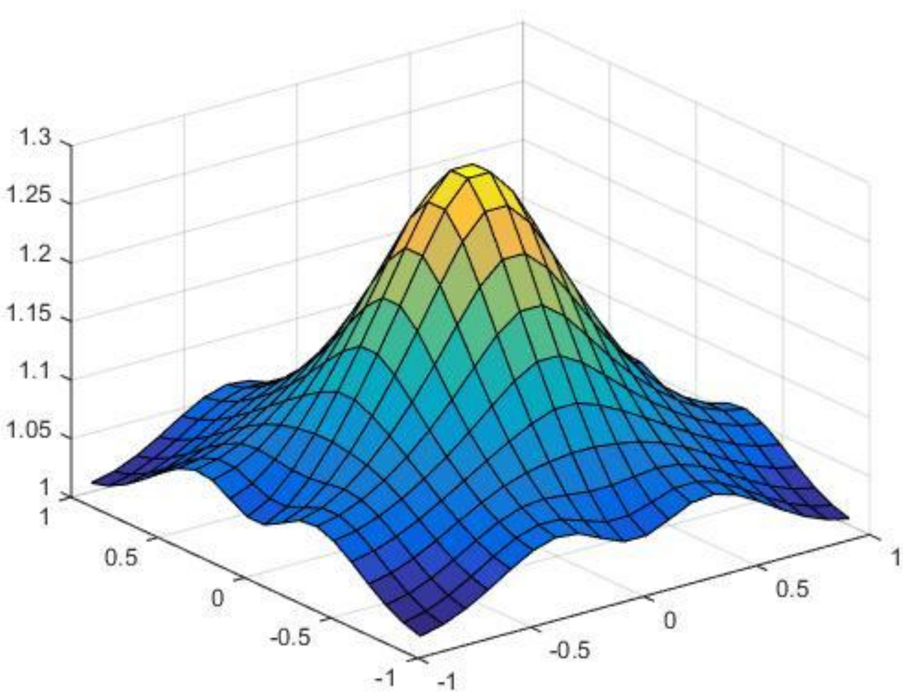
The design and development of Geoinformation Flood Simulation Program 1 (GFSP-1) flood hydrodynamic model



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Preface

Flood risk management (FRM) is the science that is motivated by the inexorability of flooding. Following this notion, the idea of "living with floods rather than fighting them" was contrived – all credits to the United Nations International Strategy on Disaster Reduction (UNISDR). Interestingly, much knowledge has evolved constantly over the years in this area of scientific enquiry. Previous topical and thematic debates are no sooner proposed than they are superseded. This demonstrates the unparalleled significance of meeting the challenges of flooding within the human societies. Despite the critical objectives of FRM and the much achievement recorded over the years, the level of awareness of flooding in especially the developing countries (DCs) has been considerably poor. The issue of data paucity to address flooding on the basis of best practices still lingers. More scientific procedures, such as flood modelling is lacking. This is the critical foundation for the research which is being described here.

This monograph describes the design and development of a novel flood model, *GFSP-1*, (Geoinformation Flood Simulation Program-1) designed to meet the challenges of flood modelling in the DCs and data poor urban localities. This is the key aspect of a PhD research conducted at the university of Portsmouth, United Kingdom. *GFSP-1* combined two conceptual parts – Cellular Automata (CA) and Semi-Implicit Finite Difference Scheme (SIFDS), and required only a 2-m horizontal resolution airborne Light Detection and Ranging Digital Elevation Model (LiDAR DEM), Manning's friction coefficient, and a rainfall intensity value to simulate urban flood hydrodynamics. This is a significant contribution to the science of flood modelling, whist GFSP-1 attempts to complement existing flood models and thus addressed some key limitation such as requirement of elaborate datasets, limited model external calibration, copyright restrictions and model extensive computation cost which often prescribes high end computers.

GFSP-1 was tested and validated in Portsmouth, United Kingdom, using a severe flooding event that occurred on September 15th 2000. Simulation of various spatial and temporal scenarios for the July 11th 2011 flooding in Lagos Nigeria was also carried out. These events were chosen since map of hotspots of surface water flooding and social media-based information, especially photographic images of the events, were available to enable a rigorous validation of the new model. In both of the test cases, 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 DCs 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 DCs outweigh considerations for uncertainty and standardisation in FRM. These new measures will consider the critical understanding of the dynamics of flooding, and the factors that influence increasing vulnerability to the hazard in the DCs. While such understanding is underpinned by provision of data and mapping of flood hazard and risk, considering climate change scenarios, how to maximise the potentials within presently available datasets in the DCs should be explored as a major research opportunity. The research presented in this monograph 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 flooding in the DCs and data poor urban centers. It is fundamental to innovative FRM policy and practice within these areas, as well as to strengthen existing flood risk adaptation efforts.

In preparing this monograph, which presents a key aspect of the doctoral research conducted at the university of Portsmouth United Kingdom, the author feels strongly overwhelmed by a litany of assistance and kind gestures from all and sundry. Of course the thesis which reports a whole spectrum of the doctoral research contains a full section of acknowledgements for agencies, organisations, and countless individuals, most of whom are friends, families and academics of global reputation, to whom the doctoral thesis in particular, and by extension this monograph owe their existence. However, there has never been any overindulgence in repeating 'Thank you'. Therefore, I would like to acknowledge again the doctoral supervisory team - Dr. Malcolm Whitworth, Dr. Brian Baily, and Dr. Robert Inkpen. The Tertiary Education Trust Fund (TETFUND) deserves a special acknowledgement for funding the doctoral study. Professor Vincenzo Casulli, whose seminal work on Semi Implicit Finite Difference Scheme (*SIFDS*) has been very useful to the completion of the flood modelling aspect of the doctoral study is acknowledged. I thank the two Vice-chancellors, Professors Bartho Okolo and Benjamin Ozumba, of the University of Nigeria Nsukka (UNN). The former approved my application for study leave with pay while the latter granted extensions on the original approval. I thank all my colleagues at the department of Geoinformatics and Surveying UNEC, for their camaraderie and cooperation. Thanks to Dr. Elijah Ebinne, the current HOD, whose permission and candid suggestion led to the actualization of the monograph.

Whilst it is hard to accommodate an endless list of acknowledgements within a lone page, a quick “THANK YOU” to all whose jokes, personal interest and valuable hints were instrumental to the writing of this monograph. While this effort could not have been possible without the stunning support of many, any shortcomings, mistakes or omissions are all mine.

Novelty, contribution to knowledge and possible research impacts

This monograph documents the flood modelling aspect of the doctoral research conducted at the school of earth and environmental sciences (SEES), University of Portsmouth, United Kingdom. Facts and figures have been presented in as much concise manner as possible without missing out on the nuances of the entire research effort. Readers are referred to the whole thesis or several publications that have emerged from the doctoral research. The thesis is archived in the online library of the University of Portsmouth. Some of the publications which readers might find interesting to digest the whole spectrum of work undertaken within the context of the PhD can be accessed in Nkwunonwo *et al.* (2014), Nkwunonwo *et al.* (2015a), Nkwunonwo *et al.* (2015b), Nkwunonwo *et al.* (2016a), Nkwunonwo *et al.* (2019), etcetera.

The flood modelling aspect of the doctoral research refers to the development of a new open source application (research code), *GFSP-1 (Geoinformation Flood Simulation Program -1),* for flood modelling in urban areas. This model combined the CA (Cellular Automata) principles and a SIFDS (Semi-implicit Finite Difference numerical Scheme), and was tested using a real flooding event that occurred in year 2000 in Portsmouth United Kingdom. Then simulation of various spatial and temporal scenarios for the July 11^{th} 2011 flooding in the Lagos area of Nigeria was also carried out. Whilst flood modelling has never been attempted in any study prior to the present research 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.

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 a wide range of applications of *GFSP-1* flood model for urban flood risk management in Lagos, and this is the possible impact of the present research.

Copyright and Trademarks

Author

Dr. Ugonna Nkwunonwo holds a B.Sc and Master's degrees in Geoinformatics and Surveying, from the University of Nigeria, and PhD, which is in earth and environmental sciences, from the University of Portsmouth, United Kingdom (UK). His PhD, part of which is reported in this monograph explored the means to meet the challenges of flood risk assessment in data poor localities, with particular reference to flood risk management in Lagos, Nigeria. Within this momentous study, a new flood simulation schema, *GFSP-1*, was developed and validated. GIS tools and techniques were sufficiently used to analyse and process air-borne samples of large-scale LiDAR (Light Detection and Ranging) topographic datasets, produce maps of social vulnerability to pluvial flooding in Lagos, and maps of flood hazard respectively for Lagos and Portsmouth, United Kingdom. Ugonna has lectured in various universities in the United Kingdom, and is currently with the department of Geoinformatics and Surveying, University of Nigeria. His present research interests encompass a range of themes within the fields of African scientific studies, geosciences, earth and environmental studies. He is also researching multi-hazard assessment and modelling, vulnerability assessment, urban heat, renewable energy, tourism and the application of risk assessment techniques, sustainable urban drainage system (SUDS), remote sensing, geographical information system (GIS), cinema, films and social media data for natural hazard assessment, and application of geospatial data infrastructure in the study of contemporary environmental issues.

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INTRODUCTION

Flooding is the most common of all naturally-occurring hazards, accounts for more than 40% of all global economic losses, affects both rural and urban settlements, and threatens human lives and properties (Ohl &Tapsell, 2000; Ahern *et al.,* 2005; Di Baldassarre *et al.,* 2010). Over the last two decades, flooding has caused severe damage in the United States, Europe, Asia, Australia, Africa and the Caribbean (CRED/EM-DAT database). The flooding of 2007 that affected many cities within England and Wales, the 2010 flooding in Pakistan, the 2012 flooding that affected more than three quarters of the Nigerian states, and the 2015 flooding in Chennai and Ghana some recent notable examples. In addition to exclusive media contents, journalistic reports and anecdotal records, all of which are remarkable with strong emotive narratives, the ubiquitous and pervasive nature of flooding as well as the vulnerabilities of social systems, have been sufficiently expressed in a number of scientific and empirical documentation (for examples Lane *et al.,* 2013; Levy *et al.,* 2016; Fanta *et al.,* 2019).

Much of the discussions about flooding also include the typology and attribution of flooding as well as its management (Dawson *et al.,* 2008). From the point of view of flooding typology and attribution, coastal flash and fluvial and flooding types are well known, although pluvial flooding which literally affects urban areas has become unprecedented in recent times (Nkwunonwo *et al.,* 2019). These urban floods generally results from heavy storms, but also from flash floods, extensive fluvial and coastal flooding. 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). Recent predictions in global climate change and rapid urbanisation and population growth seem to have globalised the concept of urban flooding, although discussion are more vigorous for the developing countries (DCs) due to a number of critical issues including limitations in research and lack of institutional capacity for effective disaster and risk management (Environment Agency (EA), 2000; CEA, 2007; Lumbroso & Vinet, 2011). More recent reviews of flood hazard such as those of Merz *et al.* (2010), Kellens *et al.* (2013), Kundzewicz *et al.* (2014) and Teng *et al.* (2017) indicate that urban flooding has probably not received the attention it deserves in the literature.

These are critical issues which exacerbate the general limitation in flood risk management (FRM) efforts especially within the DCs and thus underline the significance of flood modelling (Merz *et al.,* 2010; Dasgupta *et al.,* 2015; Koks *et al.,* 2015; Nkwunonwo *et al.,* 2016). Primarily, the aim of flood modelling is to recreate those hydrodynamic properties upon which the threats of urban flooding are based. Although those properties which include varying depths and spatial extent of flood water and the velocity with which it flows are often difficult to measure directly during flooding events, they are used for constructing fragility functions and flood risk maps, all of which are inalienable from FRM (Dawson *et al.,* 2008; Jha *et al.,* 2012). Despite the merits of flood modelling procedures, and the particular implications and gaps which they can fill in FRM within a variety of contexts, such procedures are largely lacking in many flood management policies and efforts within the DCs (van de Sande *et al.,* 2012; Nkwunonwo *et al.,* 2014).

The lack of flood modelling can be associated with some of the limitations in the existing flood modelling procedure which make them unsuitable for a external applications. These include; lack of calibration data, high computation cost of existing models which often stipulates high-end computer systems, and copyright restriction which is a major handicap to accessing these models' licenses and their technical supports (Maksimović *et al.*, 2009). Several studies have focused on finding ways of addressing these limitations, especially as it applies to the means of reducing computation time while deriving stable solution of flow over a spatial domain (Almeida *et al.*, 2012). Two popular key strategies are being adopted. The first one involve modification of existing models which is well discussed in the current literature (refer to: Nkwunonwo, 2016). The second strategy is the development of a new flood model which the research described in the monograph has attempted to accomplish.

The development of a new model in the present research demonstrate the extent to which novelty and innovation in flood modelling procedures can make contributions to the science of flood modelling in the DCs. This addresses the question of how it would be 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 DCs. Thus, this aspect of the research was undertaken on the basis of two crucial objectives – to develop a new deterministic flood inundation model and to carry out rigorous tests to establish the model's performance. The new model, *GFSP-1* (*Geoinformation Flood Simulation Program -1*) developed in the present research combines Semi Implicit Finite difference Scheme (SIFDS) with Cellular Automata (CA) principle to simulate pluvial urban flooding. The model was tested using Portsmouth flooding of September 15th 2000, and then 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 topographic data was also carried out.

LITERATURE REVIEW

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 *et al.,* 2005). The procedure is an essential prerequisite for flood risk and flood hazard assessment and mapping (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 (Sampson *et al.,* 2013; Yan *et al.,* 2015). Despite these merits, only few research has considered modelling urban flooding from pluvial events (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 of sufficient flexibility for application to external case studies (Hunter *et al.,* 2007). 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 the introduction, the lack of large scale calibration datasets, high computation cost and copyright restrictions are major issues with existing flood models (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. This thesis (Nkwunonwo, 2016b), Nkwunonwo *et al.* (2014) and Nkwunonwo *et al.* (2019) highlight 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, 2006; 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, 2006; Yu, 2010). These are complex procedures which often do not accomplish expected goals, thus leaving FRM objectives in the DCs with the sole option of developing new bespoke flood models.

The new flood model reported in this monograph combines the capabilities of SIFDS and CA. 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 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 (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.

METHODOLOGY

The CA framework involved in developing *GFSP-1* 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. Refer to the full thesis, Parsons & Fonstad (2007), Ghimire *et al.* (2013), Nkwunonwo *et al.* (2019) for a comprehensive discussions on these features, and the major assumptions which were made to actualize the new model. In particular, the mesh of cellular space was provided by a *2-m* horizontal resolution airborne LiDAR DEM. The von Neumann type of neighbourhood was considered. Absorptive and reflective boundary conditions were applied. A set of four transition rules were used. Rule (4) was the most important and used Manning's formula (*equation 1*) to calculate the velocity and then used this velocity to determine the time it will take the water to leave the cell.

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

where 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 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 & Stelling, 2013). 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 fit in 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, Tavelli & Dumbser, 2014; 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 governing equations for the formulation of SIFDS are the shallow water equations (SWEs) which are described by *equations* 2, 3 and 4 (continuity, U-momentum and V-momentum equations respectively).

$$\frac{\partial H}{\partial t} + \frac{\partial (HU_x)}{\partial x} + \frac{\partial (HV_y)}{\partial y} = 0 \qquad (2)$$

$$\frac{\partial (HU)}{\partial t} + \frac{\partial (HUU)}{\partial x} + \frac{\partial (HUV)}{\partial y} + gH\frac{\partial \eta_x}{\partial x} + gHS_f = 0 \qquad (3)$$

$$\frac{\partial(HV)}{\partial t} + \frac{\partial(HUV)}{\partial x} + \frac{\partial(HVV)}{\partial y} + gH\frac{\partial \eta_y}{\partial y} + gHS_f = 0 \quad (4)$$

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 S_f(-) is the friction slope.

In the design and development of *GFSP-1*, four important steps are crucial. They include (1) the computation of flow at the principal cell using the Von Newman type of neighbourhood, (2) the global evolution of water depth and extent, (3) the dynamic link between the CA and SIFDS and how they interact to advance the simulation of flood hydrodynamics, and (4) the development of the model algorithm. These steps are well discussed in the thesis, and Nkwunonwo *et al.* (2019). However, this monograph will only present a summary of what takes place in the model.

1. The computation of flow at the principal cell is on the basis of a simple mathematical proportions implemented on the program conditionals to determine the amount of water transferrable from the principal cell to the neighbouring cells. *Equation* 5 guides the amount of water to be transferred as flux from the principal cell into neighbouring cells In actual fact, the differences in water depth between the principal cell and the neighbouring cells drive water movement.

$$flux(i,j) = \frac{(DPC(i,j) - DNC(i,j))}{DNC(i,j)} * water\ in\ principal\ cell \quad (5)$$

where DPC (L) and DNC (L) are the depth of water in the principal cell and the neighbouring cell respectively, i, j are the indices in the vertical and horizontal directions of the cells respectively.

2. The global evolution of water explains what happens in the model especially within the CA framework, in which the final water depth and extent for each time step is updated. In *GFSP-1*, the fluxes into the cells are first summed up for each time step using *equation* 6. 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* 7.

$$Total\ flux(i,j) = \sum\{influx(i-1,j), influx(i+1,j), influx(i,j-1), influx(i,j+1)\} \quad (6)$$
$$Water\ depth(i,j) = water\ depth(i,j) + \frac{Totalflux(i,j)}{(dx*dy)} * \Delta t \quad (7)$$

3. CA and SIFDS interact at a strategic point within the *GFSP-1*, to simulate a typical urban flooding event. The link between these components 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.

4. *GFSP-1* 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 is usually measured millimeters over a period of spell, but this is converted into rainfall intensity using in the model, and read into the code as a single variable, assuming a uniform rainfall over the study area.

RESULTS

Model *GFSP-1* was run over a 2-m horizontal resolution LiDAR DEM covering the whole city of Portsmouth, acquired from Environment Agency (EA) Geomatics archive data team. *Figure 1* 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.

Figure 1: Sample of LiDAR DEM for the Portsmouth study area.

To simulate the temporal and spatial variations of the July 2011 flooding in Lagos, *GFSP-1* was run over the LiDAR DEM for this test case was acquired from GIS section of Lagos state office of Lands and Survey. 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 2*). However, the Lagos LiDAR data was 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 of the thesis (Nkwunonwo, 2016b) 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.

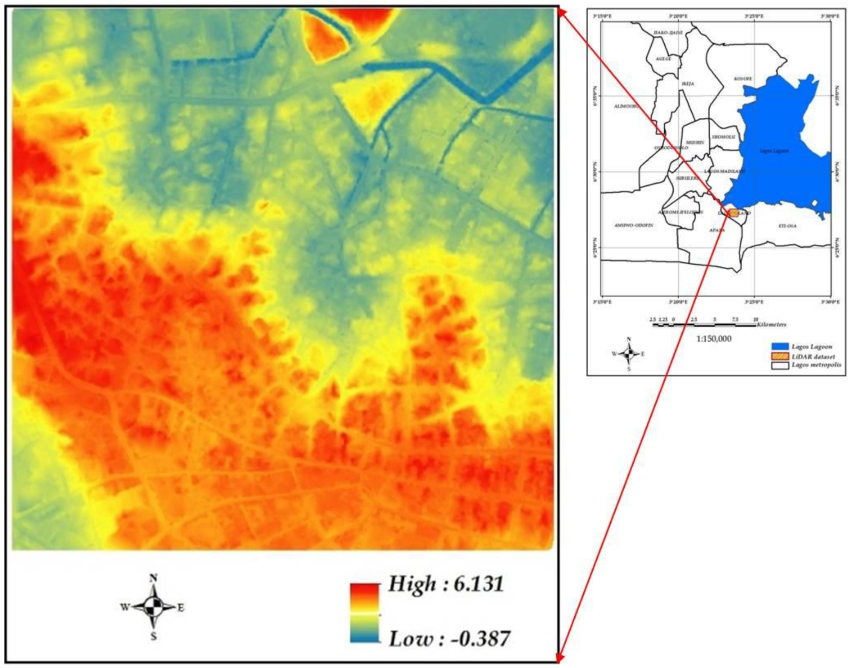

Figure 2: Sample of Lagos LiDAR DEM produced from point clod LiDAR dataset. The author converted the traditional (.las) files into readable 'ascii' format and then applied the natural neighbour interpolation resampling technique to generate a 2-m horizontal resolution DEM.

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 3* shows locations in which *GFSP-1* simulated flood inundation, and these are comparable to the hotspots of surface water flooding. From the figure, 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 $=\frac{67}{93} * 100\%$) (see *figure 4*). Ten locations delineated in the surface water flooding hotspots map were selected. 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. Results identified from these locations and the water extent and depth simulated independently were reported in the full thesis and Nkwunonwo *et al*. (2019).

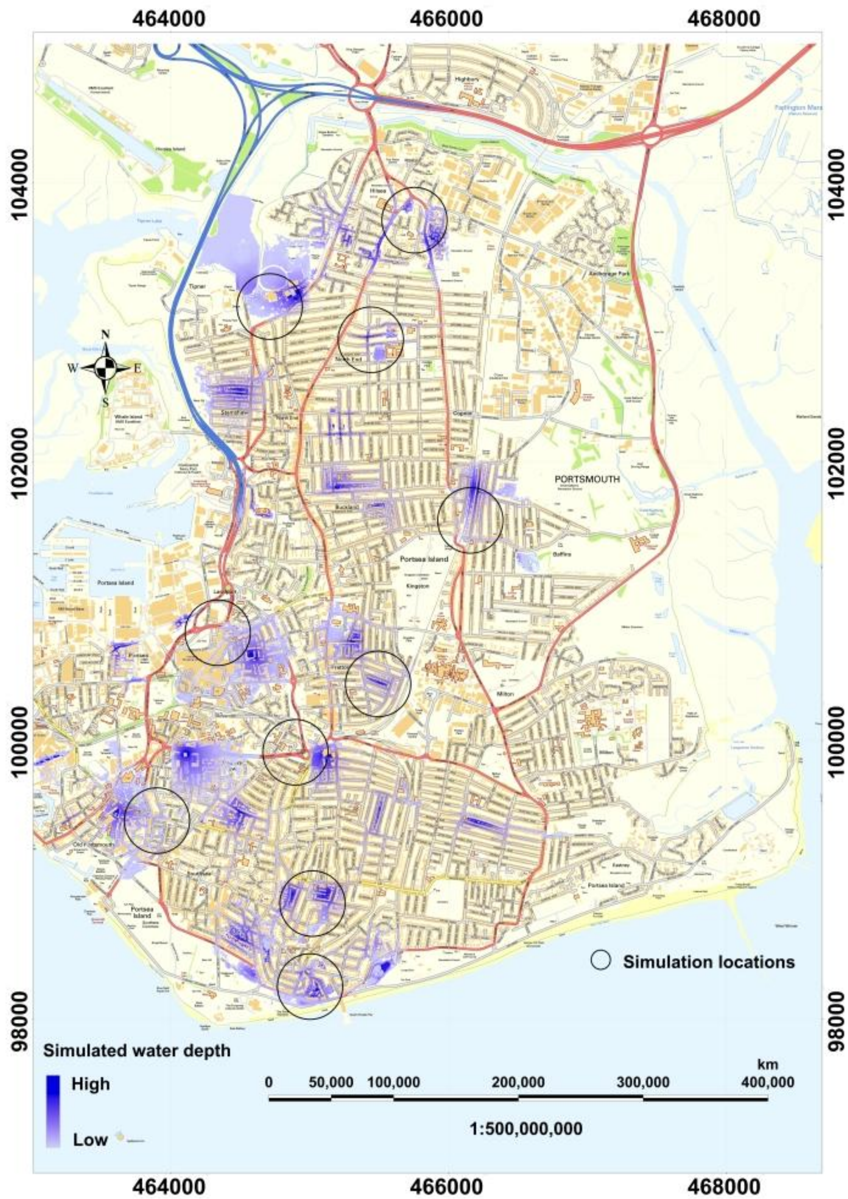

Figure 3: Locations where flooding inundation were simulated using the GFSP-1. When compared to the map of surface water flooding hotspots, this model accurately simulated ten locations of flood inundation in Portsmouth area.

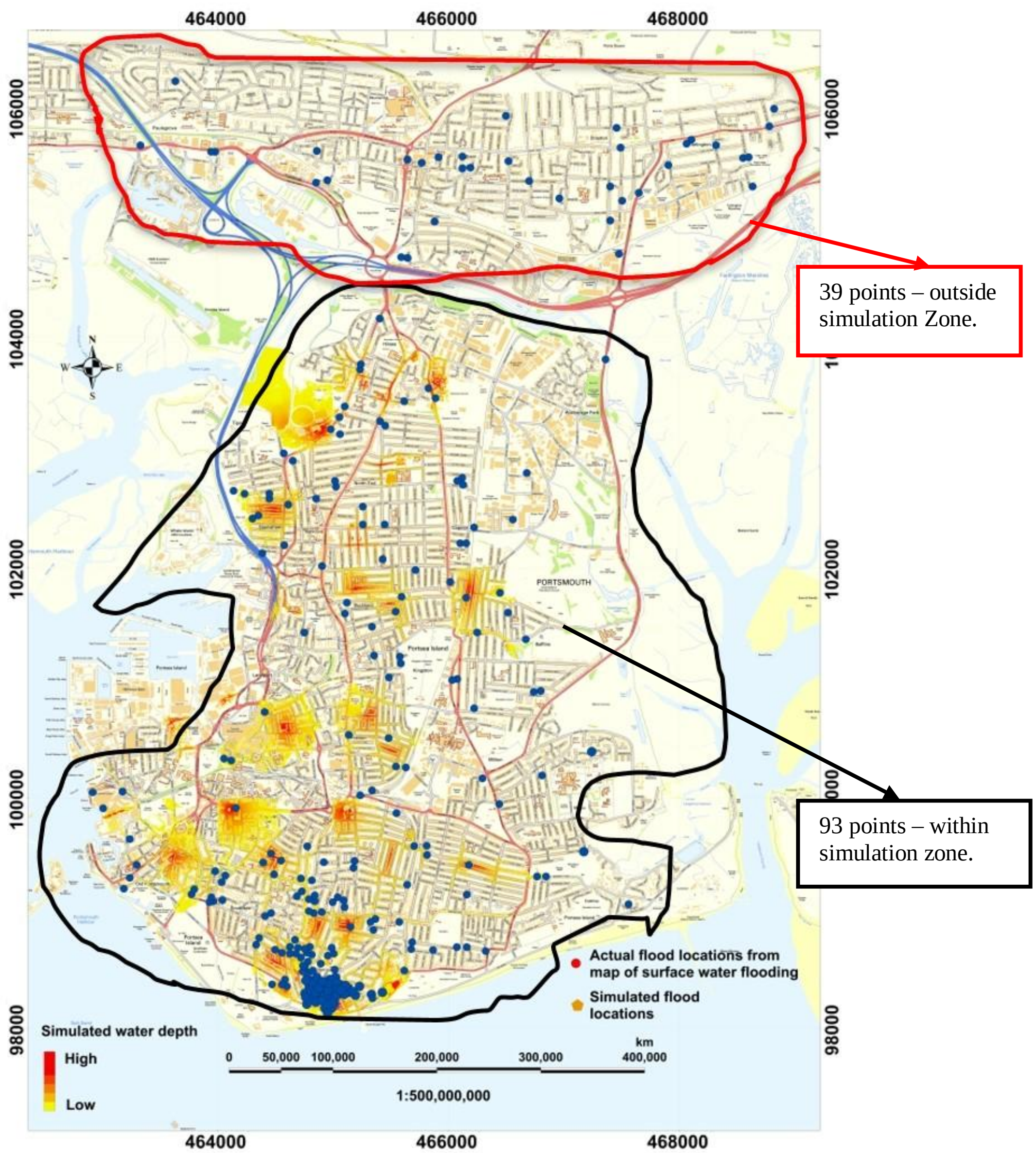

Figure 4: Simulated flood locations compared to surface water flooding hotspots

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. *Figure 5* shows a major location in Lagos, where *GFSP-1* simulated the spatial and temporal components of July 2011 flooding. For the July 11th flooding event, *GFSP-1* simulated flood inundation locations that matched the actual locations, identified during the on-site survey (*figure 6*).

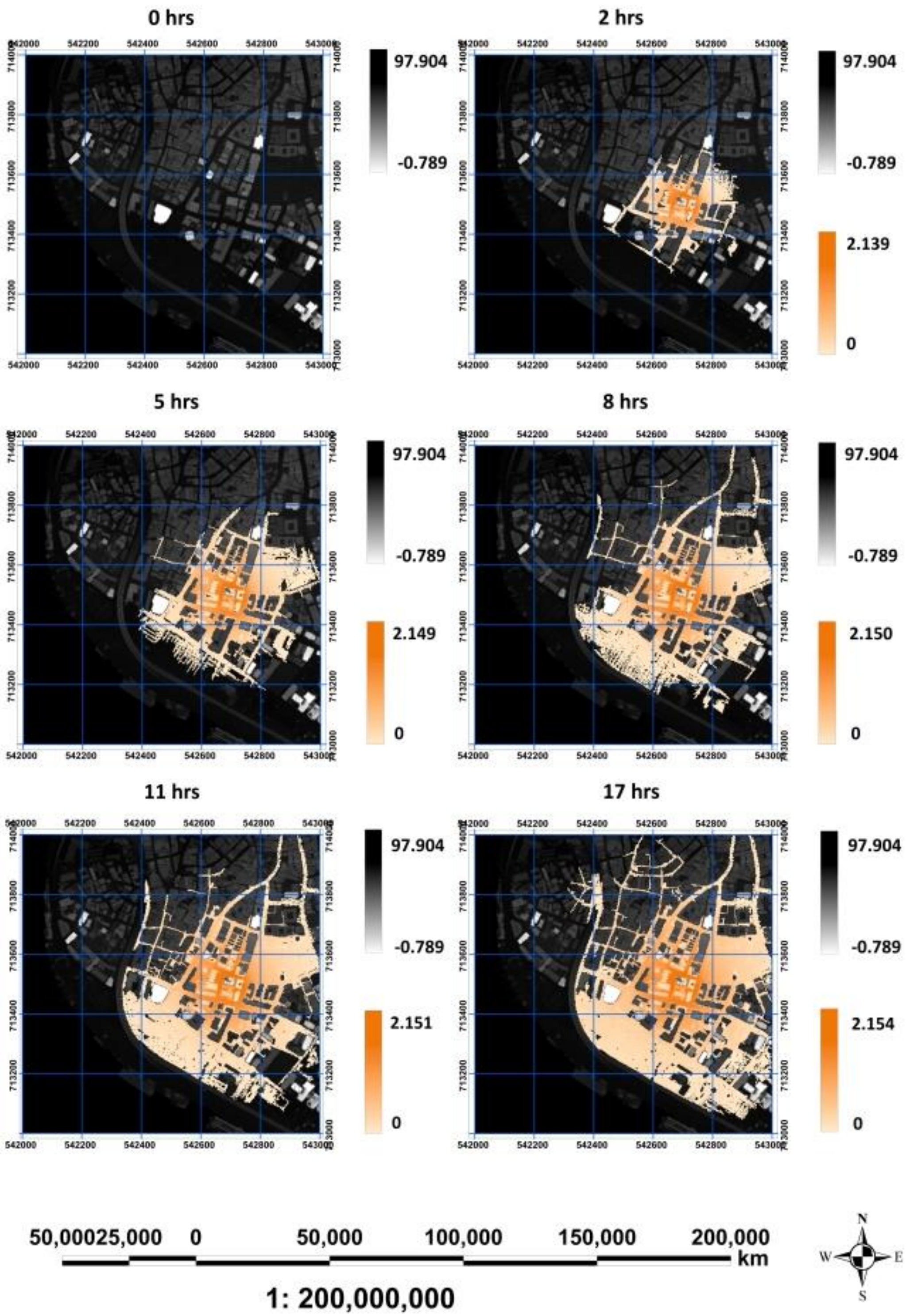

Figure 5: Simulated water depth at Broad and Balogun Street areas, Lagos Island.

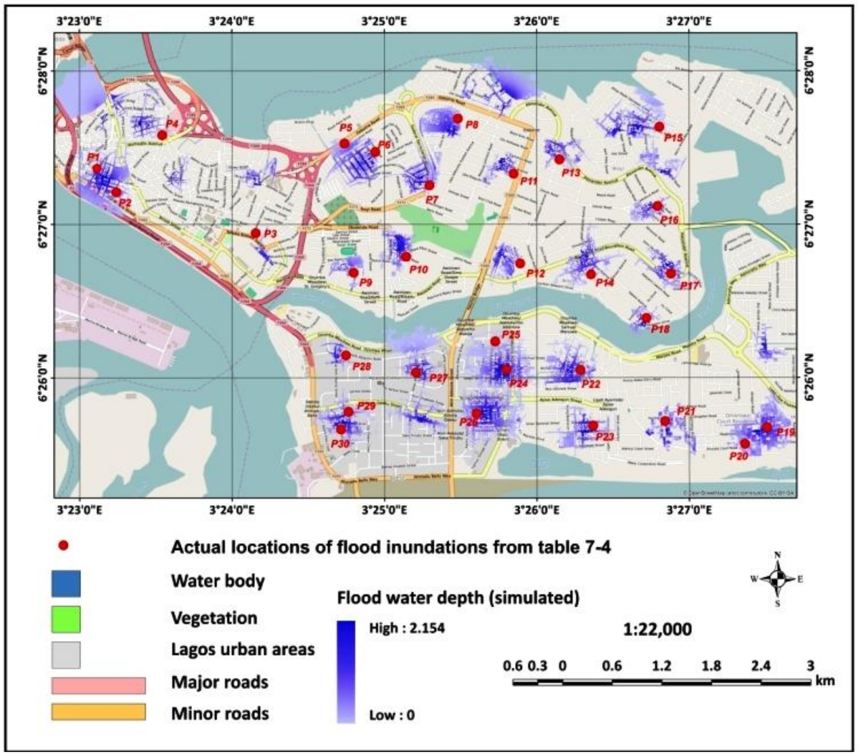

Figure 6: Simulated flood locations of the July 2011 Lagos flooding compared to locations of flood water identified during the reconnaissance survey

In validating *GFSP-1*, social media-based information has been used since there is lack of validation dataset. There is ample evidence to show the increasing utility of such dataset in the management of disasters and crises (Alexander, 2014; Houston *et al.*, 2015). 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. Using these social media datasets required a number of post processing which are necessary to obtain estimates of flood water depth and water extent. Please refer to the full doctoral thesis for a comprehensive discussions of the social media dataset and the post processing applied. *Figures* 7 and 8 show the results of validating *GFSP-1* using the photographs.

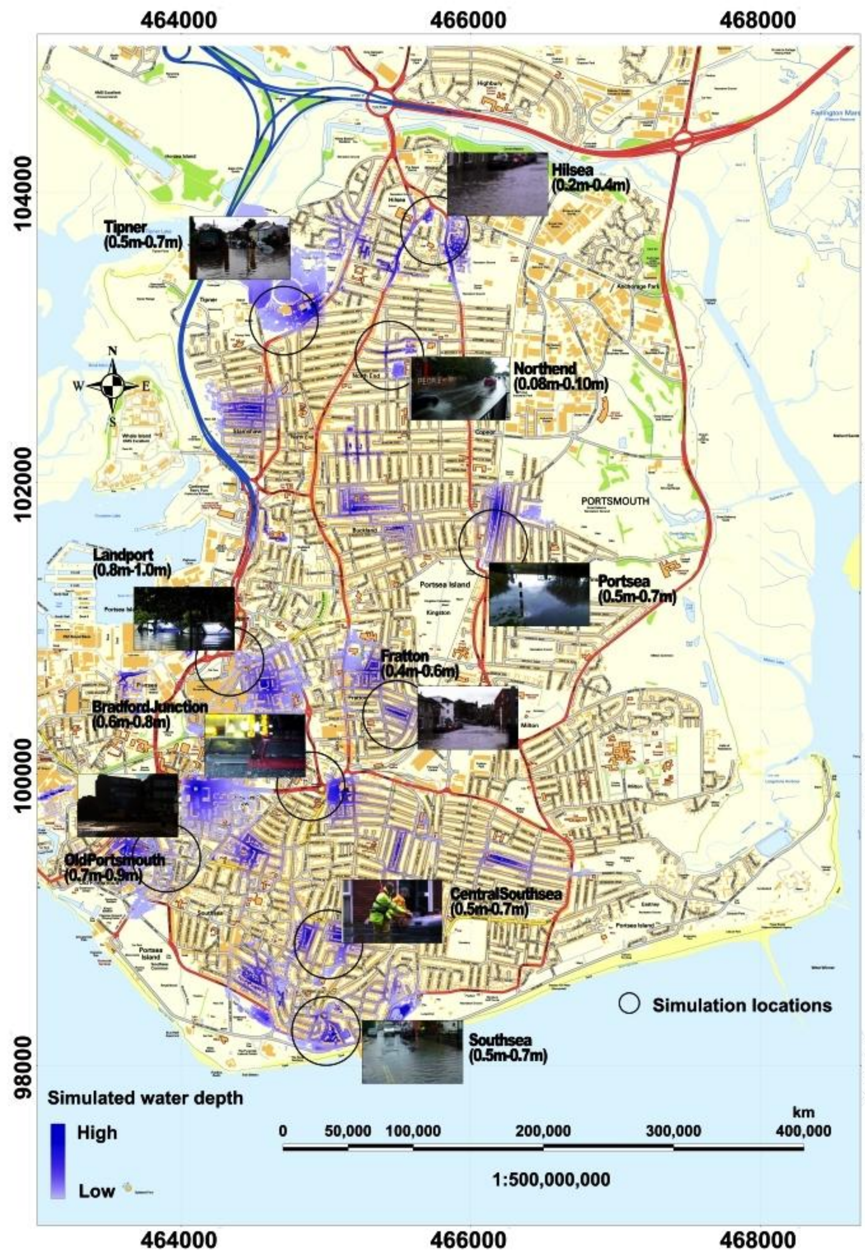

Figure 7: Thumbnails of selected photographs hotlinked to appropriate flooded locations on the Portsmouth basemap

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*. These values were described as bar charts and scatter plots 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.

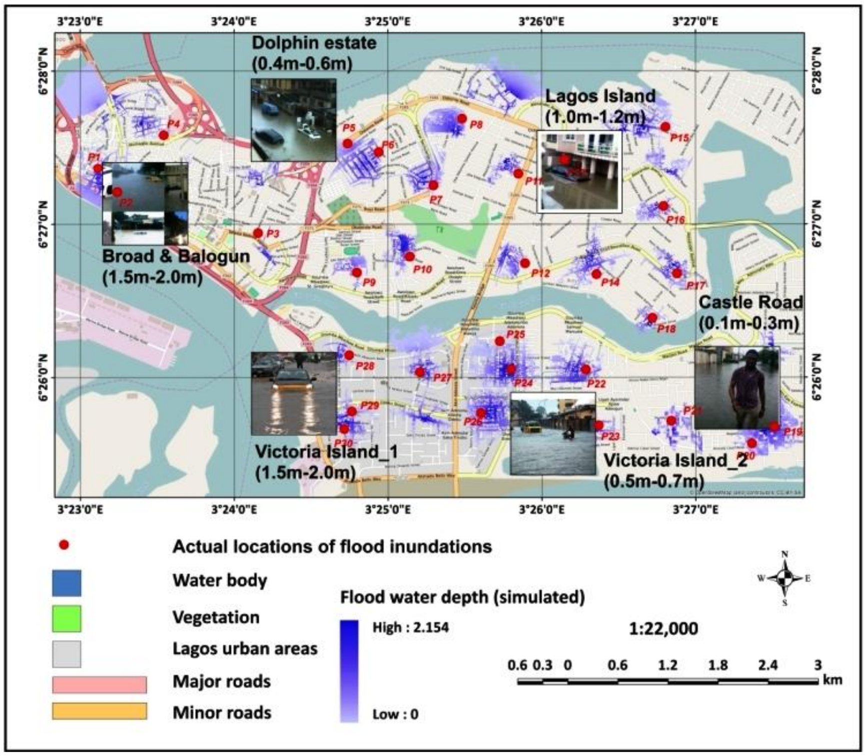

Figure 8: Thumbnails of selected photographs hotlinked to appropriate flooded locations on the in Lagos metropolis of Nigeria base map.

DISCUSSIONS

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 FRM. 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. Refer to the thesis for general discussions in relation to some isolated cases in both Portsmouth and Lagos whereby simulated water depths were higher than actual water depth.

This anomalous behaviours of *GFSP-1* 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 or even earlier prior to when 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 of 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 modelling. 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.

CONCLUSION

Urban flooding and its management in the developing countries (DCs) and data sparse localities 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. These studies suggest that flood modelling procedures, which support effective flood risk management, and initiate any radical flood risk reduction measures are lacking.

This monograph reports the research, which serves as a step forward towards finding solutions to the lack of flood modelling in the DCs. 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 (Geoinformation Flood Simulation Program -1)* was developed. This new flood model, forms the novelty and innovation of the doctoral research undertaken at the University of Portsmouth United Kingdom. The new model combines a semi implicit finite difference scheme (SIFDS) and a cellular automata (CA) mathematical principle, and 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.

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. In general *GFSP-1* is significant contribution to the science of flood modelling, but it also addresses the questions of model convergence, stability and computation cost which have since lingered within the flood modelling research.

MAJOR LIMITATIONS AND RECOMMENDATIONS

Model *GFSP-1* provides significant prospects and potential to the scientific community in that the model combined CA and SIFDS for simulating the hydrodynamic properties of flooding within a data sparse context. It is truism that 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. Despite the major contributions, few limitations which suggest the needs for future research were identified.

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.

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Glossary

S/No	Terms	Meaning
1.	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.
2.	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.
3.	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.
4.	Digital Elevation Model (DEM)	A specialized database that represents the relief or overall topography of a surface between points of known elevation.
5.	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.
6.	Flood modelling	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.
7.	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.
8.	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.
9.	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.
10.	Hydraulic flood models	A mathematical expression, computer code or smart application that is used to reconstruct and analyse the dynamic behaviours of flood inundation.
11.	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.
12.	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.
13.	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.

14.	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).
15.	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.
16.	Sensitivity analysis	This is a way to determine how variations in one variable, which constitute a model, impact the overall predictions of the model.
17.	Shallow Water Equations	A set of equations derived from the Navier -Stoke equation, and that underlie the formulation of hydraulic flood models.
18.	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.
19.	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.
20.	Urban flooding	This is the overflow of water in a built-up area caused mainly by climate change and poor drainage facilities.
31.	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.

Appendix

```
% 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.

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% Date:         October 2015.
% Archive:      University of Portsmouth, United Kingdom

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);
     tic;

     % 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 (5.19))
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
```

Dissemination

1. Nkwunonwo, U. C., Whitworth, M., & Baily, B. (2019). Urban flood modelling combining cellular automata framework with semi-implicit finite difference numerical formulation. *African Journal of Earth Sciences*, *150,* 272-281.

2. Nkwunonwo, U. C., (2017). Exploring the inadequacy of pertinent capacities for urban flood risk management in the developing countries. In C. N. Madu, & C. Kuei, Handbook of Disaster Risk Reduction & Management (pp. 150-167). USA: World Scientific

3. Nkwunonwo, U. C., (2017). Assessment of social vulnerability for efficient management of urban pluvial flooding in the Lagos metropolis of Nigeria. *Journal of Environmental Studies, 3*(1), 11-22

4. Nkwunonwo, U. C., Chiemelu, N.E., Nkwunonwo, U. A. (2016). Exploring the inadequacy of pertinent capacities for urban flood risk management in the developing countries. *Journal of Social Sciences*, *12*(3), 136-151.

5. Nkwunonwo, U. C., (2016). A review of flooding and flood risk reduction in Nigeria. *Global Journal of Human Social Sciences*, *16*(2), 23-42.

6. 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.

7. 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.

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9. 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.

10. 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).