Assessing vulnerability and modelling assistance: using demographic indicators of vulnerability and agent-based modelling to explore flooding emergency relief response

by

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I, Kurtis J. Garbutt, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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ABSTRACT

Flooding is a significant concern for much of the UK and is recognised as a primary threat by most local councils. Those in society most often deemed vulnerable: the elderly, poor or sick, for example, often see their level of vulnerability increase during hazard events.

A greater knowledge of the spatial distribution of vulnerability within communities is key to understanding how a population may be impacted by a hazard event. Vulnerability indices are regularly used – in conjunction with needs assessments and on-the-ground research – to target service provision and justify resource allocation. Past work on measuring and mapping vulnerability has been limited by a focus on income-related indicators, a lack of consideration of accessibility, and the reliance on proprietary data.

The Open Source Vulnerability Index (OSVI) encompasses an extensive range of vulnerability indicators supported by the wider literature and expert validation and provides data at a sufficiently fine resolution that can identify vulnerable populations. Findings of the OSVI demonstrate the potential cascading impact of a flood hazard as it impacts an already vulnerable population: exacerbating pre-existing vulnerabilities, limiting capabilities and restricting accessibility and access to key services.

The OSVI feeds into an agent-based model (ABM) that explores the capacity of the British Red Cross (BRC) to distribute relief during flood emergencies using strategies based upon the OSVI. A participatory modelling approach was utilised whereby the BRC were included in all aspects of the model development.

The major contribution of this work is the novel synthesis of demographics analysis, vulnerability mapping and geospatial simulation. The project contributes to the growing understanding of vulnerability and response management within the NGO sector. It is hoped that the index and model produced will allow responder organisations to run simulations of similar emergency events and adjust strategic response plans accordingly.

IMPACT STATEMENT

The goal of this project was to utilise free and readily available secondary data to identify communities that may require additional assistance before, during or after a flood event; and test a range of distribution strategies that could be used by the BRC, or other NGOs or local councils in the future, to reach those identified. The methodological approach presented, as well as the two main project outputs, can be divided into two distinct, but connected, components:

1. The OSVI provides a method whereby quality data on the core drivers of vulnerability can be used to create a versatile vulnerability index that provides information at a national level but at a sufficiently fine resolution so as to identify pockets of vulnerable communities. The OSVI focuses on common core drivers of vulnerability across spatial scales and rural and urban environments and can indicate areas where vulnerable communities live for which special emergency response strategies may need to be designed. The OSVI provides data in an informative and intuitive way that can be combined with other tools and knowledge to facilitate community emergency planning and anticipate an area's needs before, during and after an emergency.
2. The model provides responders and policymakers with an adaptable means of using available data to model and test response strategies and identify vulnerable communities at risk of flooding. The model will provide a visual, open-source and data-focused way of improving organisational development and strategic planning. The model provides a spatially-explicit emergency exploration and planning support tool that facilitates decision making and builds our knowledge of humanitarian response processes and furthers the progress of ABM within future emergency response management and other related domains.

Rarely do NGOs and emergency responders have the knowledge and skills required to format complex computational models. Thus, it is often academia that must provide the expertise required to simulate emergency situations and response procedures. Applied research in humanitarian logistics and emergency response operations is limited and partnerships between academia and humanitarian organizations are scarce. Further, within the literature, there is a focus on pre- and post-disaster supply chain management, specifically the logistics of getting resources from manufacturers or stockists to disaster zones or distribution points. Few studies focus on ‘last mile’ logistics *during* the event. This thesis does that.

In the short-term, the main project outcome is the production of institutional learning and awareness, and the development of knowledge, skills and opinions relating to vulnerability and flood response procedures. Medium- to long-term outcomes will be a greater understanding of response practices and decision-making processes; an increased awareness of the links between the socio-cultural characteristics of a community and the impacts of a flood hazard on their vulnerability; and an increased knowledge of the power of modelling for humanitarian relief planning and decision making. This will lead to greater policy and strategy development.

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GLOSSARY & ABBREVIATIONS

A&E – Accident and Emergency
AAR – After-action reports
ABM – Agent-based model/Agent-based modelling
ABS – Agent-based simulation
APHO – Association of Public Health Observatories
BRC – British Red Cross
CCA – Civil Contingencies Act
CCS – Civil Contingencies Secretariat
CFS – Cumulative Flood Score
CHANS – Coupled Human and Natural Systems
COBR – Cabinet Office Briefing Room
CONOPS – Concept of Operations
CSD – Closed Source Data
CSS – Closed Sourced Software
CVI – Composite Vulnerability Index
CVM – Community Vulnerability Maps
DCLG – Department for Communities and Local Government
DEM – Digital Elevation Model
DES – Discrete Event Simulation
DfH – Department for Health
DfT – Department for Transport
DoD – Department of Defence
DRR – Disaster Risk Reduction
DWP – Department for Work and Pensions
EA – Environment Agency
EngD – Doctor of Engineering
EWMW – Economic Wealth & Material Wellbeing Category
FIS – Flood Impact Score
FRM – Flood risk management
GDP – Gross Domestic Product
GPU – Graphics Processing Unit
GI – Geographic Information
GIS – Geographic Information System(s)
GIS-DT – Geographic Information System Design Team
HD – Hazards & Deprivation Category
HDI – Human Development Index
HSCIC – Health and Social Care Information Centre
HSS – Health, Self & Support Category
HXL – Humanitarian Exchange Language
IFRC – International Federation of Red Cross and Red Crescent Societies
IMD – English Indices of Deprivation 2010
ITN – Integrated Transport Network
JHLSCM – Journal of Humanitarian Logistics and Supply Chain Management
LA – Local Authority
LSOA – Lower Super Output Area
LRF – Local Resilience Fora
LTP – Local Transport Plans

MS – Management Science
MSOA – Middle Layer Super Output Area
NeSS – Neighbourhood Statistics Service
NGO – Non-Governmental Organisation
OA – Output Area
OFAT – One factor at a time
ONS – Office of National Statistics
ONSPD – ONS Postcode Directory
OR – Operations Research
OS – Ordnance Survey
OSD – Open Source Data
OSM – OpenStreetMap
OSS – Open Source Software
PAR – Pressure and Release
PRIOS – Priority Resident Score
QGIS – formerly Quantum GIS
SD – Systems Dynamics
SDSS – Spatial Decision Support Systems
SIMD – Scottish Index of Multiple Deprivation
SoVI® – The Social Vulnerability Index
SVI – Social Vulnerability Index
TIN – Triangulated Irregular Networks
TTSAT – Time Based Transit Service Area Tool
UML – Unified Modelling Language
UN – United Nations
UN-OCHA – UN Office for the Coordinate of Humanitarian Affairs
VCI – Vulnerability and Capacities Index

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ORGANISATION OF THESIS

This thesis is presented for the degree of Doctor of Engineering (EngD), not Doctor of Philosophy (PhD)[1]. An EngD research project focuses on a topic related to the business activities of the industrial sponsor. Researchers spend 50-75% of their allotted study period (usually two to three years) researching the topic set by their industry sponsor, with much of that time spent working directly within the sponsor organisation. The British Red Cross (BRC) is the industrial sponsor of the presented project. As such the project must support the work of the BRC and the reader must understand how the BRC works and how project decisions and discussions throughout this thesis relate back to the BRC's work. 'Context boxes' have been used to provide the reader with a greater understanding of aspects of the BRC's working methods and requirements that directly impact the project.

Chapter One presents an introduction to the research sponsor, the British Red Cross, as well as the requirements of the work, the research question and objectives. Chapter Two sets forth a review of relevant literature pertaining to vulnerability, emergency response, and agent-based modelling. Chapter Three details the stakeholder engagement process used to produce the OSVI. The OSVI and model are two distinct and separate projects, but the latter is directly fed by the former, thus it was decided to present a detailed review of the OSVI, even if all findings did not directly lead into the model. Chapters Four and Five present the methodology and the results for the OSVI respectively. Following this, Chapter Six details the stakeholder engagement and problem identification process undertaken before model development was undertaken. Chapters Seven and Eight present the methodology and results for the model. Chapter Nine discussed the results of both the OSVI and the Model in a broader context and finally Chapter Ten reviews the work presented, summarizing the findings and their research contributions as well as discussing potential future research.

[1] See: http://www.aengd.org.uk/programmes/engd-phd-comparison/ for more information

1 INTRODUCTION

Introduction	Literature Review	Stakeholder Engagement	Methodology OSVI	Results OSVI	Stakeholder Engagement	Methodology Model	Results Model	Discussion	Conclusion
Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5	Ch. 6	Ch. 7	Ch. 8	Ch. 9	Ch. 10

"Social and demographic changes also contribute to the lessening of social bonds and therefore play a part in increasing vulnerability and decreasing resilience."

~ Enarson, 2007:266

This chapter outlines the area of investigation and provides context to the problems being examined. The questions being asked, the aims and objectives of the work, and the outcomes, outputs and contributions of the work are summarised. The motivation and rationale behind the project's focus are set forth and an introduction to the research partner, the British Red Cross, is provided.

1.1 RESEARCH PARTNER & PROJECT REQUIREMENTS

The British Red Cross Society (BRC) is the UK branch of the worldwide humanitarian organisation the International Red Cross and Red Crescent Movement. Formed in 1870, it has over 21,500 volunteers and 4,100 staff (British Red Cross, 2015b). The BRC helps those in need without discrimination and regardless of their ethnic origin, nationality or religion (British Red Cross, 2011). It provides first aid training and assistance, helps communities prepare for disasters, responds to emergency situations, supports refugees and protects those in conflict, helps to reunite families separated by armed conflict, disaster or migration, and provides health and social care services (British Red Cross, 2015a).

In the UK, the BRC provides valuable short-term support to vulnerable people. The BRC helps tens of thousands of people across the UK, many of them elderly, recover following hospital discharge, by providing medical equipment, such as wheelchairs, and transport support for medical appointments and essential daily needs. It also provides first aid training, ambulance support for events and support to refugees and asylum seekers who have recently arrived in the UK. Much of its work in the UK focuses on helping the elderly, be it the provision of care services, the supply of medical equipment, or transport to and from hospital, and with 21.6% of Norfolk inhabitants aged 65 and over, Norfolk has been highlighted as one of the BRCs key areas of interest.

The BRC is *not* an emergency service and does not respond to a flood emergency without being asked to do so by a Category 1 responder[2]. However, the BRC has a long history of responding to flood events in the UK and is regularly asked to support response and recovery work, as it has access to thousands of trained staff and volunteers and can respond to flood events across much of the UK. It aims to support rescue services, local authorities and health authorities to ensure those most affected are cared for. In the UK, this work usually entails relief distribution, evacuation management, ambulance support, health and wellbeing care, rest centre management, and communications and coordination support, but can also involve emergency rescue when needed. A critical part of the flood emergency response and mitigation work is the distribution of appropriate resources and personnel to individuals and locations throughout an affected area to reduce risk and to ensure that demand for other services, such as health care, can be maintained (Widener & Liu, 2013).

The BRC was approached in early 2012 to provide guidance and project support for the project presented herein. It was hoped that the outcomes from the project would create a step change in the organisation's capability and knowledge. Conversations were held with members from multiple BRC teams, including the *Emergency Response and Management, International*, and *Support at Home* teams. Group discussions were held to determine the needs of teams, project

[2] Category 1 responders are organisations at the core of the response to most emergencies - the emergency services (Police, Ambulance, Fire), local authorities (city and county councils), and NHS bodies (hospital trusts, commissioners etc). Category 1 responders are required to assess risks, put in emergency plans, and provide advice and assistance following emergencies.

outputs that would be relevant to their work, and the availability of data and resources. It was decided to bring together a wide array of stakeholders and potential users from both BRC staff and volunteers and from outside of the BRC and include those from other Red Cross societies (*e.g.* American Red Cross, Norwegian Red Cross *etc*.), other NGOs (*e.g*. *Médecins Sans Frontières*, AgeUK) and other organisations such as the London Ambulance Service and UK Power Networks. More information on the discussions and interactions with the BRC and others is provided in section 6.2.

The BRC has a dedicated Geographical Information System design team (GIS-DT) who provided support throughout this project. The GIS-DT is working towards improving geographical analysis capability within the BRC that is scalable, in-house and cost effective. The GIS-DT supports staff and volunteers and provides tools and data sources needed to improve BRC geographical analysis capability as well as the understanding as to how maps and geographical data and analysis can be used for fast and effective visualisation and decision making. The GIS-DT provided technical guidance and support throughout.

It was necessary for the BRC to outline some key project requirements to maximise the use of the resultant work by the BRC and others:

- The project must **align with the BRC's 2010–2015 corporate strategy**: *Saving Lives, Changing Lives*[3] (and later the 2015-2019 corporate strategy: *Refusing to ignore people in crisis*[4]).
- All work, including all products, reports, briefings and external materials, must **abide by the BRC's Fundamental Principles**[5]. This ensures such materials can be widely disseminated within and by the BRC.
- The project must **focus on methods and understanding that are currently beyond the abilities of the BRC** and must guide the organisation's internal development.

[3] Available here: https://goo.gl/rOs1Mb
[4] Available here: https://goo.gl/o1M38B

[5] See Appendix 11.2 for more information on the BRCs Fundamental Principles.

- The project must **lead to outcomes and/or outputs that can be utilised by BRC staff and volunteers to assist their work**.
- All **secondary data used must be from the public domain and free to use**. This corresponds with the desires of the BRC to limit its use of proprietary data in an effort to reduce costs and support the wider use and dissemination of their data and findings. Where possible, open source software should be utilised. Failing this, only proprietary software that the BRC has access to should be utilised in an effort to reduce expenditure and maximise the use of the resultant techniques and software by BRC personnel.
- The use of any **data provided by the BRC must conform with the BRC's Information Governance Guidelines**[6].

These requirements suited the EPSRC EngD structure and its focus on combining PhD-level research projects with taught courses and direct collaborative work between the researcher and the sponsoring organisation.

1.1.1 ENGAGING WITH THE BRC

The BRC, like many other organisations, does not work to academic schedules. Excluding corporate management and major international operations or fundraising schemes, much of the work the BRC does focuses on the short- to medium-term (weeks to months), not the long-term (years). This required work to be structured in a way so that project outputs could be delivered regularly and timely. In addition, during the timeframe of this project the BRC's corporate strategy and much of the senior management team was restructured and its domestic focus shifted towards health and social care support, with a particular focus on supporting NHS services such as patient transport and assisted discharge services. It was therefore necessary to undertake formal project framing exercises periodically throughout the entire project timeframe to ensure

[6] For more information, see British Red Cross: Information Governance Policy Available here: https://bit.ly/2T2IvDr

the work met the BRC's requirements and remained beneficial (see chapters 3 and 6).

Throughout this thesis, context boxes, like the one below, will provide background information on how the BRC operates and help the reader understand why certain project decisions were made.

Context: BRC Floods Research

During 2010-2012 I worked for the British Red Cross as a researcher within the *Research, Evaluation and Impact* team. My work focused on hazards and risk and I was a lead researcher on a national floods study aimed at enhancing the voluntary sector's collective understanding of the needs of flood-affected communities. This work was published in 2013 (see: McNulty & Rennick, 2013). The findings of this report, along with information from the wider literature and BRC experience, will help guide the development of this thesis. For example, findings of the report suggest the following are key needs of those affected by flooding:

- early and widespread distribution of sandbags before the flood event and during the early stages;
- hot food and drinks distribution to those affected throughout the entire lifespan of the flood event;
- cleaning supplies for post-event clean-up;
- information, particularly:
    - flood prevention and property maintenance and protection;
    - direct, accurate and timely information on the state of the flood hazard, particularly for those more vulnerable;
    - suitable communication for areas made up of large non-English speaking residents;
    - contact information for agencies responding to the event and offering assistance;
    - knowledge of where to access physical and mental health assistance, particularly relating to stress and anxiety;
- regular checks and sympathy;
- advice centres within the communities.

Many of these elements will be factored into different strategies to test response capabilities and capacities under different flood scenarios.

1.2 SOCIAL VULNERABILITY & FLOOD RESPONSE IN THE UK

1.2.1 VULNERABILITY

Demographic, economic and climatic shifts across the UK are changing the patterns of vulnerability across the country. Dealing with emergencies and times of crisis is a major challenge for modern society, particularly the adverse effects of severe weather and related natural hazards. More than ever, it is necessary to expect and adequately prepare for times of crisis.

Collectively, vulnerability in the UK appears to be increasing (Lewis & Lewis, 2014). With an ageing society and increased disparity between wealth and healthcare (Appleby, 2013; Beard *et al.*, 2016; Rechel *et al.*, 2013), modern society includes groups whose vulnerability increases their level of risk during times of crisis. The elderly proportion of the UK population is increasing and it is estimated that one-third of people born today will live to 100 (Office for National Statistics, 2014). However, it is likely that they will also live with long term chronic health problems and comorbidities and may have reduced pensions, state support and be increasingly isolated (AgeUK, 2014; Humphrey, Lee & Green, 2012). In addition, unemployment, increasing living costs and low economic growth is likely to lead to an increase in vulnerabilities amongst the young and low-income families (Wallace *et al.*, 2014; Ranci, Brandsen & Sabatinelli, 2014).

It is widely accepted that gender, social, economic and political patterns exist within society that result in some groups of people living with an amplified state of vulnerability (Morrow, 1999; Enarson, 2007; Bolin & Kurtz, 2018; Laska & Morrow, 2007; Cutter *et al*., 2000; Shirley *et al*., 2012; Eriksen *et al*., 2005; Koks *et al*., 2015; Tierney, 2006). Socially vulnerable populations are often restricted in their ability to respond – often due to increased likelihood of health problems (Marmot, 2005) or limited economic support (Morrow, 1999) – and more often than not lack access to critical resources during disaster events (Halden, Jones & Wixey., 2005; Morrow, 2008). This often augments the way in which individuals and their wider communities are affected by environmental hazards, as well as how they respond and recover (McNulty & Rennick, 2013; Bolin & Kurtz, 2018; Joakim, 2011).

A household's capacity to respond and adapt to emergencies, such as floods, has been shown to be related to their social vulnerability (Cutter *et al.*, 2012; Narzisi *et al.*, 2007). The challenge for the UK Government and interested non-governmental organisations (NGOs) is to identify these populations and mitigate vulnerability with a focus on prevention and resilience building. Recent reviews have emphasised the importance of establishing pre-emptive mechanisms to identify such populations and to provide the necessary support for vulnerable groups during crises as well as the importance of sharing information amongst governments, responders and communities (Rufat *et al.*, 2015; Röthlisberger, Zischg & Keiler, 2017; Vogel *et al.*, 2007; Armaş & Gavriş, 2016; Goldstein Hode *et al.*, 2014; Chandra *et al.*, 2011; Sahay, Vinod Chandra Menon & Gupta, 2016; Civil Contingencies Secretariat, 2008).

1.2.2 FLOODING IN THE UK

Flooding is a significant concern for much of the UK and is recognised as a primary threat by most local councils, with surface water flooding - when an area floods during heavy rainfall, often due to rain-water not infiltrating already saturated ground (European Water Association, 2014; Falconer *et al.*, 2009) - considered one of the highest priority risks across nearly all counties (UK Cabinet Office, 2017). The UK has a lengthy history of flooding, from the 1864 Dale Dike flood that killed 270 people and the 1953 East Coast storm surge that killed 307 people, to the series of floods that affected much of the country throughout 2007, 2009, 2012, 2013, 2014 and 2016 and that, combined, caused in excess of £5billion damage and led to the deaths of 34 people (Pitt, 2008; Brakenridge, 2015).

The Pitt Review: Lessons learned from the 2007 floods, published on 25 June 2008, was prepared by Sir Michael Pitt following the widespread flooding that took place in England in June and July 2007 and resulted in 13 deaths and damage to 55,000 properties. The report presented 92 proposals to better protect communities from future flood events, including, for example:

- a 25-year plan to address the issue of flooding, along with the creation of a dedicated Cabinet committee
- an overhaul of building regulations for homes built or refurbished in flood-prone areas
- definitive electronic maps of all drainage ditches and streams, including details on who is responsible for maintaining them
- more investment by utility companies to protect key infrastructure sites
- a national flooding exercise at the earliest opportunity

A final progress report was published in 2012 and reported that 43 of the 92 recommendations in the original Pitt Review had been fully implemented or implemented with work ongoing, including the five listed above. However, little or no progress has been made on 12 recommendations, including the use of natural catchment measures to reduce flood risk, the implementation of a sustainable drainage plan, or the repeal of regulations that allow private connections to the public sewerage system (Balmforth, 2016).

Since 2012 a number of preventative local- to national-level schemes have been put in place or considered to combat the UK's growing flood risk. The Government has increased budgets for flood risk management since 2012, with the 2017/2018 total reaching £777 million (DEFRA, 2018), however it is recognised that this is unlikely to deliver sufficient protection in future decades (House of Commons, 2016). In addition, the UK Government has teamed with insurers in a joint initiative, Flood Re[7], to make flood insurance policies more affordable for homeowners for the next 25 years, up to 2039. Flood Re does not reduce the risk of flooding and offers only a limited temporary reactive safe-guard[8]. Unless long-term preventative measures are put in place, it is unlikely

[7] See: https://www.floodre.co.uk/

[8] Flood Re collects a levy from insurers offering home insurance in the UK that totals £180million per year. This annual budget is used for administering the scheme and reimbursing insurers for valid claims. In comparison, an average of £1.3billion in damages are incurred annually in the UK (DEFRA, 2010; Environment Agency, 2013; DEFRA, 2012).

that an affordable insurance market based on risk-reflective pricing will be developed that can assist those who live in the highest flood risk areas.

Flooding, as with other hazards, can negatively influence location-specific vulnerability as well as existing socio-cultural, response and recovery mechanisms by, for example, changing hazard patterns, increasing the number of vulnerable people or amplifying the loss of urban fabric and assets (Wamsler, 2014). Floods also pose an environmental and fiscal challenge to the United Kingdom. More than five million homes and businesses are at risk of flooding (Bevan, 2018) and an estimated annual cost of £1.3bn to £2.2bn (DEFRA, 2010; DEFRA, 2012; Environment Agency, 2013). In addition, changing precipitation patterns presented in the UK Climate Projections (UKCP09) - more days of extreme precipitation during the winter and summer periods (IPCC 2013) – are expected to result in an increase in surface water flooding by 60-220% by 2060 (Dubbelboer et al., 2016; Ramsbottom et al., 2012; Downing & Patwardhan, 2004; Sub-Committee, 2012).

Flooding can have a far-reaching and long-lasting impact on a community (Bennet, 1970; Milojevic *et al*., 2011). Those in society most often deemed vulnerable - the elderly, poor or unemployed, for example - often see their level of vulnerability increase during hazard events as both risk and exposure increases (Bolin & Kurtz, 2018; Tierney, 2006; Koks *et al*., 2015). The features of a person's life that makes them vulnerable in the first place are often intensified: the loss of income following a flood exacerbating poverty, for example. As such, the social characteristics of households living within flood zones is a key concern of flood risk managers. However, the issue of social vulnerability is often absent from flood risk assessments (Koks *et al.*, 2015). Such assessments rely on projections of flood water depth or physical vulnerability to measure potential damage (*e.g*. Jongman *et al*., 2012; Koks *et al*., 2014) or assume those affected are a homogenous population (*e.g.* Jonkman, Van Gelder, Vrijling, 2003). Neglecting the spatio-temporal socio-economic variations in vulnerability severely reduces the effectiveness of flood risk management (FRM) strategies (Koks *et al.*, 2015).

A greater knowledge of the spatial distribution of vulnerability within communities is therefore key to understanding how a population may be impacted by a hazard event (Cutter & Emrich, 2006). Highlighting those who are exposed to a hazard, as well as those who are potentially more vulnerable due to their circumstances, can aid emergency response and risk reduction strategies (Nelson *et al*., 2007).

More information on flooding in the UK and findings and recommendations from the Pitt Review are presented in Appendix 11.1.

1.2.3 FLOOD EMERGENCY RESPONSE & MANAGEMENT IN THE UK

Flood emergency response and management focuses on attempts to prevent or avert disruption, damage, injury and loss of life, and to secure the scene and mitigate the effects of an emergency (Haddow *et al*., 2013; UK Cabinet Office, 2010). It also includes search and rescue, evacuation, healthcare, and the dissemination of public information. Many, if not most, of these features run in parallel and rely upon interlinked aspects that impact one another (Lindell *et al*, 2006).

In the UK, flood emergencies (and most major incidents) are managed by the emergency services and other local responders, known as Category 1 responders. Major flooding emergencies require coordinated multi-agency responses with quick decision-making (see Figure 1). Work includes relief and response work, but also managing the wider consequences of the flood, such as restoring transport networks or electricity supplies, and maintaining services such as local health and access agencies (UK Cabinet Office, 2017).

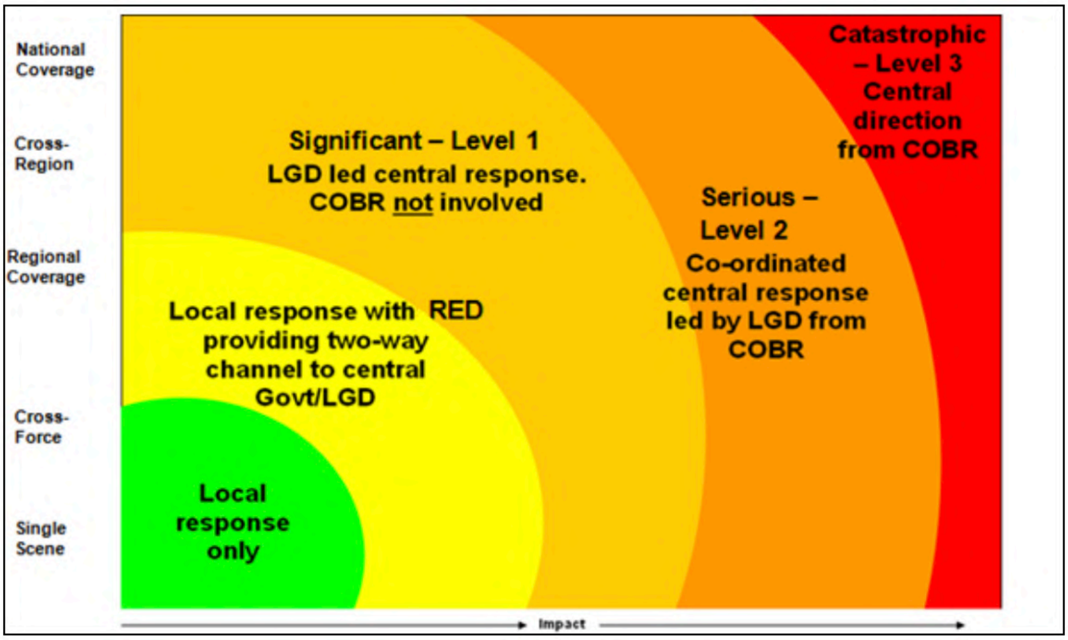


Figure 1: Characteristics of different levels of emergency and the likelihood of central government engagement according to the actual and potential spread of an emergency and its affects (taken from The National Flood Emergency Framework for England, 2014)

The specific arrangements for coordinated response operations are set forth by the UK Government and outlined in the Concept of Operations (or CONOPS) (Cabinet Office, 2010)[9]. In England, the primary responsibility for emergency planning and response lies with local organisations that coordinate through Local Resilience Forums (LRFs) and Strategic Coordination Groups (SCGs). LRFs work to develop plans for maintaining critical services and business continuity and work with communities to develop specific flood response plans that compliment generic Major Incident Plans or Strategic Emergency Response Plans.

Flooding has distinctly local impacts and a comprehensive locally focused plan aids recovery (Smith, 2012; Berke *et al.*, 2014; Cançado *et al.*, 2008). Many interacting factors determine the level of response and the responders that are involved, be it local organisations, central government departments, or the military. For example, the number of affected, the depth of flood waters, and the

[9] The Cabinet Office's (2010) Central Government's Concept of Operations document was first approved in 2005; Chapter 6, which sets forth guidance on the government's role in supporting local responders during response and recovery work, was updated in 2013; and the full guidance document is being reviewed and an updated version is due for publication at an unspecified time.

impact on critical infrastructure are general indicators of the level of response and the type of responders that will be involved (see Table 1).

1.3 RESEARCH QUESTION

The British Red Cross expects an increasing demand for their 24/7 emergency response capabilities (Adamson, 2014). Such demands will come on top of their regular provision of essential social care and support programmes. As such, the BRC is concerned with "what if" research questions that examine complex and constantly developing emergency situations and test the potential impacts and outcomes of strategy decisions through simulation (Braye, 2016, personal communication). For example, the identification of vulnerability is an important part of NGO work and relief distribution. Pinpointing where those most likely to be adversely affected by an emergency are located and how they are likely to be impacted as well as what their likely needs may be, will help the BRC plan service provision and respond effectively. However, past studies of emergency response work within the humanitarian sector that have focused on vulnerability assessment and operational decision making have featured limited, if any, academia-NGO collaboration and stakeholder engagement (Leiras *et al.*, 2014) and there are a lack of grounded and applied model development that coordinates with emergency responders (Menth, 2016). Taking these points into consideration, the central research question this investigation will address is:

> *Can an open source index of geodemographic vulnerability be created and used in a model in order to better understand the dynamics of vulnerability and the capacity of different relief response strategies in an evolving emergency?*

My hypothesis is that social vulnerability, understood as a consequence of social inequalities, is, on average, higher for those living in a flood zone even when flood-related indicators are ignored and that the use of social vulnerability indicators when prioritising aid distribution can improve aid distribution performance.

Level of emergency	Description	Level of engagement
Local	Events which are routinely handled by the emergency services with local government, such as road crashes, localised flooding or industrial accidents. **Flooding example: local flooding; small scale evacuation; no risk to critical infrastructure.**	No significant central government involvement. Normally be led by the police/Gold Commander[10] for larger emergencies.
1 **Significant**	Has a narrower focus *e.g*. prison riots, severe weather or a terrorist attack with limited consequences. **Flooding example: floods in more than one county, some displaced persons and potential risk to critical infrastructure.**	The Lead Government Department Minister runs the crisis response from their premises using their own emergency facilities as appropriate. The Civil Contingencies Secretariat (CSS) advises as and when necessary
2 **Serious**	Has, or threatens, a wide and prolonged impact requiring sustained central government co-ordination and support from many Departments and Agencies. **Flooding example: floods in several counties; hundreds of displaced persons; actual, or risk of, critical infrastructure disruptions.**	Response coordinated from the Cabinet Office Briefing Room (COBR) by the Lead Government Department. The crisis response may require deployment of wider government resources. The Civil Contingencies Secretariat (CCS) provides overall co-ordination and support on impact management and recovery issues.
3 **Catastrophic**	A high and potentially widespread impact and requires immediate central government direction and support such as a 9/11 scale terrorist attack in the UK, or a Chernobyl scale industrial accident. **Flooding example: floods affecting a significant proportion of England; thousands of displaced persons; serious damage to critical infrastructure.**	COBR/Civil Contingencies Committee. Prime Minister or nominated Secretary of State leads in the event of a catastrophic incident requiring the involvement of central government from the outset to deliver an effective response, or where "Emergency Powers"[11] are invoked.

Table 1: CONOPS emergency levels, descriptions & levels of engagement with flood examples (adapted from The National Flood Emergency Framework for England, 2014)

[10] A Gold Commander is usually the local Police Chief Constable or deputy. The 2004 Civil Contingencies Act (see: Civil Contingencies Secretariat (2008) for more information) requires the Gold Commander to manage the response and recovery work from an off-site location, usually a dedicated local emergency command centre.

[11] Emergency Powers refer to a situation where the UK Government directly invokes Part Two of the 2004 Civil Contingencies Act to respond to emergencies that may pose a threat of serious damage or disruption to the UK's security or environment.

The BRC & Open Data

Open Data is data that is freely accessible for anyone to use and republish (Open Data Initiative, 2017). The BRC is committed to the use of open data and, where possible, making its data open. Open data is becoming an increasingly important part of NGO work (*e.g.* MissingMaps) and is supporting development goals in the UK and worldwide (Morrison *et al*., 2014). The BRC, particularly the GIS-DT, relies heavily on open data and open source products and platforms. This not only reduces costs (product licenses *etc*.) but ensures that all the work produced can be freely distributed and accessed by beneficiaries and partner organisations. It is hoped that the use of open data will encourage more citizen engagement, facilitate the promotion and sharing of work and attract more support and funding. A key tenet of the work presented herein is that, where possible, it utilises open data and open source software and makes all resultant data and findings freely available.

1.4 RESEARCH AIM & OBJECTIVES

This project aims to provide emergency response managers with a method of identifying social vulnerability and a tool to support the strategic and operational understanding of relief distribution during flood emergencies. The project will integrate a vulnerability index into an empirical agent-based model (ABM) of emergency resource distribution to simulate multiple flood emergency scenarios and test the performance of different relief distribution strategies[12].

Objectives include:

- To **identify a set of proxy indicators of vulnerability** and **produce a vulnerability index** based upon those indicators.

[12] See section 2.3 for a review of ABM literature, section 0 for an explanation as to why ABM was chosen as the modelling method of choice and how the model was developed, and appendices 11.3, 0, 11.5 for information on ABM toolkits, alternative modelling methods, and key ABM developments, respectively.

- To **create a spatially explicit agent-based model of BRC relief distribution** that incorporates the vulnerability index, real-world resource quantities and locations, and models likely emergency scenarios.
- To **test the performance of different relief distribution strategies and scenarios.** Distribution strategies will be guided by BRC practices and past emergency responses as well as best practices from the wider emergency response sector.
- To **develop a greater understanding of the influencing factors of vulnerability (both endogenous and exogenous) and the performance of humanitarian response efforts** under a domestic context.

1.5 RESEARCH OUTLINE

This study is primarily concerned with addressing the BRC's needs (outline in section 1.1) through two modelling techniques: GIS-based vulnerability analysis and agent-based modelling (ABM) and consists of two distinct but interlinked parts.

Open source demographic and geographical data will be used to create an open source vulnerability index (OSVI). The OSVI encompasses an extensive range of vulnerability factors, built upon readily available open source data from national datasets that provide data at a sufficiently fine resolution that can identify vulnerable populations and communities within census units, but also allow for the scaling up of the project if deemed appropriate. The OSVI is structured within and visualised using a Geographical Information System (GIS). The GIS will contain key geographical elements, including infrastructure network data (road, rail *etc*.), land use (housing, industrial *etc*.), and geographic features (rivers, coastlines *etc*.) provided by Ordnance Survey OpenData™ and amenities (hospitals, supermarkets *etc*.)[13] and base maps provided by OpenStreetMap (OSM). In addition, flood extent data was provided by the Environment Agency (EA) and service and logistics information (location of warehouses, number of

[13] The details of amenities will be obtained from OpenStreetMap using the amenity tag, for example: 'Tag: shop = supermarket' or 'Tag: amenity = hospital' or 'Tag: amenity = nursing_home'.

vehicles *etc*.) was provided by the BRC. GIS allows for customisation of the Index, examination of the data behind the Index and geo-spatial visualisation and analysis.

The OSVI acts as the starting point, feeding into an ABM that will explore the capacity of the BRC to distribute relief during flood emergencies and the subsequent impact on community vulnerability. The demographic, geographical, empirical model integrates the geo-demographics and vulnerability data from the OSVI, as well as a relief distribution framework produced in cooperation with the BRC to simulate multiple flood emergency scenarios and test the capacity of different relief distribution strategies. For example, under one relief strategy, the logistical distribution of resources (water, blankets, sandbags *etc*.) to those who require them based upon the demographics of the areas affected by flooding will be investigated. Under this strategy, an area identified by the OSVI as being predominantly elderly and/or ill and being within a flood zone would be a priority area for the distribution of medical supplies or specific patient transport vehicles. In comparison, areas with a high proportion of households with dependent children would be a priority for the distribution of family aid packages. A number of other relief strategies will also be modelled.

The spatially explicit ABM will utilise geographical data to dynamically model the movements, decisions, actions and interactions of NGO agents within a real-world setting to develop a greater understanding of the capacity of relief distribution strategies. Within the model, the characteristics of responder agents will be based upon real-world data. For example, the characteristics of BRC actions will be based upon past BRC interventions and key factors such as the number of staff and volunteers and their skills, available resources (ambulances, blankets *etc*.) and service locations (warehouses, distribution points *etc*.).

The model allows for the investigation of demographic change over time periods not available within the more data-dependent demography methodologies and the dynamic vulnerability ABM will explore and visualise the changing state of vulnerability within a flood affected region over the lifetime of an emergency.

The investigation includes the processing of a varied range of open source geo-demographic data streams as well as geo-spatial data and micro simulation methods to support an ABM of relief distribution. Empirical information (statistical demography, observations) will be used to define and classify the parameters of the model. Thereby equipping agents with governing behavioural rules based on plausible patterns of observed phenomena at the micro-population level. Multiple scenarios will also be generated allowing for the impact of changes, both low-level individual interactions and top-level macro entity changes (environment, hazard, strategies), to be investigated.

The challenge, and requirement of the emergency management domain as a whole (Adams *et al.*, 2008), is to use data and methods from a range of disciplines to create a system that functions effectively in a dynamic environment and that is customisable, scalable and adaptable to the needs, resources and strategies of emergency responders. It is hoped that the model produced will allow responder organisations to run simulations of similar emergency events and adjust strategic response plans accordingly.

2 LITERATURE REVIEW

Introduction	**Literature Review**	Stakeholder Engagement	Methodology OSVI	Results OSVI	Stakeholder Engagement	Methodology Model	Results Model	Discussion	Conclusion
Ch. 1	**Ch. 2**	Ch. 3	Ch. 4	Ch. 5	Ch. 6	Ch. 7	Ch. 8	Ch. 9	Ch. 10

"Vulnerabilities precede disasters, contribute to their severity, impede effective disaster response and continue afterwards."

~ Anderson & Woodrow, 1989: 10

This chapter[14] will examine the trends within past vulnerability assessments. After a discussion of definitions within the literature (section 2.1.1), focus will turn to the use of indicators to quantitatively measure vulnerability and the weighting of said indicators within vulnerability indices (section 2.1.2). The review will then move on to an examination of the role of accessibility within social vulnerability and the methods used to measure it. Although many more challenges and debates still exist that centre on the history, conceptualisation and definition of vulnerability, focus will not be paid to them here and instead the reader is pointed towards more detailed examinations of the theoretical developments of vulnerability within the academic literature (see, for example: Adger, 2006; Blaikie *et al*., 1994; Cutter, 1996; Gall *et al*., 2009; Liverman, 1989). The review will then move to the techniques and challenges of analysing emergency relief (section 2.2), followed by an examination of modelling techniques, particularly agent-based modelling, and the associated issues of model abstraction, and uncertainty, sensitivity and validation (section 2.3).

[14] The following chapter is adapted from: Garbutt, Ellul & Fujiyama. 2015 Mapping Social Vulnerability to Flood Hazard in Norfolk, England. *Environmental Hazards* Vol. 14 No. 2 pp. 156-186.

2.1 VULNERABILITY

2.1.1 DEFINING VULNERABILITY & THE STRUCTURE OF VULNERABILITY

The concept of vulnerability, although evolving, is central to analysis and research within many disciplines, including engineering, urban planning and sociology (O'Brien *et al*., 2004; Gow, 2005; National Research Council, 2007b; Füssel, 2007; White *et al*., 2001; Zandt *et al*., 2012). The definitional debates on vulnerability will not be examined in depth here. Instead, focus will be on explaining the need to focus on vulnerability within emergency relief management modelling, and the metrics used for measuring and addressing social vulnerability. Readers are pointed towards Füssel (2007), Hinkel (2011) and Luthar (2015) for extensive examinations of the definitions of vulnerability and the approaches taken to research vulnerability.

Vulnerability is a highly variable and dynamic aspect of life that fluctuates through space and time at different rates on an individual and societal level, be it a rapid onset following an emergency or slow life changes (*e.g.* the aging process) (Müller *et al*., 2011). Vulnerability is present within society in a number of forms: social, physical, individual, societal, urban, rural, economic, ecological and so on (*ibid*). Vulnerability is a complex notion with a surfeit of factors influencing it at the individual and societal levels. Communities are not homogenous, with neighbourhoods containing both wealth and poverty, leisure and crime, privilege and unemployment (Zandt *et al*., 2012). Thus, residents of the same geographical area are likely to have very different levels of exposure, vulnerability and resilience (Enarson, 2007): a farmer may have increased economic vulnerability due to his or her reliance on a single crop, but one more well-off neighbour may have health problems that significantly limit their movement, whilst another neighbour is a female lone-parent who works full-time. Which is the more vulnerable, and which is the more resilient?

In his discussion of the “arising complexities between human population and nature,” Hewitt (1983: 277) argued that the multifarious features of catastrophic hazards cannot be fully explained by conditions and/or behaviours peculiar to the events; these can only be explained by considering the social patterns of living and societal responses to extreme events. Thus, to understand fully natural hazard events, it is necessary to examine the social aspects of such events, as well as the geophysical processes involved. Hewitt (1983) argued, “hazards are neither explained by nor uniquely linked with geophysical processes that may initiate damage.” This is not to imply that geophysical processes are irrelevant, but simply that too much causality in the derivation of risk has been attributed to them.

Social Science’s attention to natural hazards has grown steadily over the past half century. Initially, natural hazards were simply seen as elements of the physical environment and caused by extraneous forces, devoid of human input (see: Burton & Kates, 1964; Tobin & Montz, 1997). However, this notion has been reassessed and it is now widely accepted that socio-economic factors are as important as the geophysical processes in understanding the effects of natural hazards (Cannon, 1994; Cutter, 1996; Blaikie *et al*., 2003; Masozera *et al*., 2007; Tobin & Montz, 2009). As such, Social Science’s interest in natural hazards has grown and issues of “risk”, “vulnerability” and the integration of these into livelihoods and well-being, have become principal areas of modern hazard research, providing a valuable means of addressing natural hazards within a geophysical, social, political and environmental context (Abramovitz, 2001; Bankoff, 2001).

Bankoff (2001), and later Furedi (2007), discuss what they term as the “vulnerability paradigm‟ present within contemporary society as a whole. Furedi (2007) put forth the idea that current Western cultural discourse and imagination now regards the world as “an increasingly out of control and dangerous place” (Furedi, 2007:473). The patterns of vulnerability present within society and the, albeit simplistic, depiction of regions as “more‟ or “less‟ vulnerable are central elements of natural hazard research (Oliver-Smith & Hoffman, 2002). However, within the literature, vulnerability has several different connotations, with subtext and implication varying depending on the research orientation and author perspective (Cutter, 1996; Cutter, 2003; Bolin & Kurtz, 2018). This lack of consensus regarding definition and context means vulnerability remains a contentious principle (Cutter, 1996; Blaikie *et al.*, 2003; Bolin & Kurtz, 2018). For some, vulnerability is a purely theoretical notion, used primarily as rhetoric within socio-economic discussions and by the media to evoke empathy for an event, person or issue (Adam, Beck & van Loon, 2000; Blaikie *et al.*, 2003; Oulahen *et al.*, 2015). For others, vulnerability is fundamentally a mathematically presentable figure; a measure or classification of susceptibility to hazards or the vulnerability of an area, encompassing exposure (one's location relative to a hazard), resistance (livelihood, health *etc*.), and resilience (adjustments, preparation *etc*.) (Noy, 2009; Pelling, 2003; Müller, Reiter & Weiland, 2011; Mechler & Bouwer, 2015) often rooted in the theory of risk and presented in the following equation:

Risk = Vulnerability × Hazard (Blaikie et al., 2005; UNDP, 2004)

Similarly, it is common to express vulnerability in the form of economic language, with hazard events often ranked by the subsequent level of economic damage. Though fiscal measures ultimately make it difficult to draw global or even regional scale comparisons between events and their impacts (Bankoff, 2001). For example, Briguglio (1995) developed the concept of economic vulnerability indices when examining small island states. It was noted that, despite many states registering relatively high gross domestic product (GDP) per capita scores, such as Malta, they were in fact economically fragile. From this study and later studies (Briguglio, 2003; Briguglio & Galea, 2003), it became commonplace for vulnerability to be examined in terms of economic insecurity, with, for example, vulnerability defined as "the risk a household will fall into poverty in the future" (Pritchett *et al*., 2000:2). However, authors such as Cutter, Boruff, and Shirley (2003) and Carreno, Cardona, and Barbat (2005, 2007) argue that a measurement of vulnerability should not be limited to an estimation of the direct impacts of a hazard but must include secondary impacts too.

Blaikie *et al.,* (1994) and White *et al*. (2001) identified three major uses of the term vulnerability:

- First, its conventional meaning and the most widely used concept: ***being prone to or susceptible to damage or injury from natural hazards*** (taken from Blaikie *et al*., 1994:9).
- Second, combining the degree of exposure or sensitivity to a threat and the adaptive capacity of an agent to respond to such threats, vulnerability implies ***a measure of risk combined with the level of social and economic ability to cope with the resulting event***" (Smit *et al*., 2000).
- Finally, Blaikie *et al*., (1994:11) refined their definition to include the characteristics of specific groups: the "***characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard***".

Enarson, (2007) built upon Blaikie *et al*., (1994) to suggest that relative vulnerabilities and capacities are both "***structural and situational...shaped by structural patterns grounded in politics, economics, environmental...race and class...gender...shaped by social status and situational or context-specific living conditions***." It is this last definition that will be used as the working definition of vulnerability throughout this report.

Whatever the definition of vulnerability being used, one must discuss the issue in context to the event being examined. Vulnerability changes in both space and time and from one event to another (Cutter, 1996). Vulnerability conditions the actions and responses of individuals and organizations differently for each hazard event encountered and these elements alter for every event; no two people will act or respond to a natural hazard in the same way (Oliver-Smith & Hoffman, 2002).

The features of a person's life can cause them to be marginalised within society and increase their overall vulnerability (Morrow, 1999). Likewise, the demography of a community alters its level of vulnerability. Throughout the literature, a number of socio-demographic and socio-economic determinants of social vulnerability have been presented, the most common being related to wealth, age and ethnicity (Koks *et al*., 2015; Cutter, 2003; Fekete, 2009). Examples include, but are not limited to:

- **Economics**: An individual's, or household's, economic status is often used as the main determinant of their social vulnerability (Cutter *et al*., 2003; Shirley *et al*., 2012). It is argued that wealth increases a person's ability to prepare for, respond to and recover from an emergency (Blaikie *et al*., 1994; Cutter *et al*., 2000). Studies have used a range of economic indicators, from averaged annual income (Chantarat *et al.*, 2015) to average monthly income (Koks *et al*., 2015) as a proxy for wealth.
- **Age**: The elderly, a community increasing in size in the UK (Cracknell, 2010), are more likely to be poor compared to others and disproportionately female and sick and/or disabled (*ibid*). Elderly households are more likely to have mobility constraints that may hinder evacuations and are also more likely to rely on caregivers who themselves are disproportionately female, from low-income households and from minority ethnic groups (Hewitt, 1997; Cutter *et al*., 2000; Enarson, 2007; Vlachantoni, 2011). Likewise, a child's vulnerability is self-evident (Morrow, 1999) and households with young children may have more problems evacuating or may face financial difficulties when caring for children during an emergency (Koks *et al*., 2015).
- **Gender**: Single-women and female-headed households have been shown to be much more likely to be poor (Chant, 2010). Women are further marginalised based upon their race, ethnicity and age (Morrow, 1999). In addition, the predominant care-giving responsibilities of women increase their vulnerability within emergency contexts (Finch and Groves, 1983; Abel and Nelson, 1990; Blaikie *et al*., 1994) and in turn heighten the vulnerability of dependents, namely children and the elderly (Morrow, 1999).
- **Health and disabilities:** Physical and mental disabilities and health problems can amplify a person's level of vulnerability and risk during an emergency (Stough, 2009; Stough & Sharp, 2007; Peek & Stough, 2010). Studies have shown that those with disabilities are less likely to evacuate during an emergency (Dash & Gladwin, 2007; Van Willigen *et al.*, 2002; White, 2006), are more likely to be excluded from emergency preparedness planning (Rowland *et al.*, 2007; Rooney & White, 2007; Osofsky & Harris, 2007), and are more likely to require medical assistance

and are may be more susceptible to secondary illnesses when ongoing health needs are not appropriately addressed (Kinne, Patrick & Doyle, 2004). In addition, people with disabilities are more likely to live in poverty both in developed and developing nations (Fothergill & Peek, 2004; Blaikie *et al.*, 2003), further compounding their likely increased exposure to hazards and reduced ability to adequately prepare for, and respond to, emergencies.

- **Ethnicity and race:** The influence of an individual's, or even the proportion of a community's, ethnicity and race on their social and economic standing and marginality have been well documented (Bolin and Bolton, 1986; Phillips, 1993; Blaikie *et al*., 1994; Thorat, 2010; Hutto *et al*., 2011). The literature notes that, although data on gender and ethnicity are often presented separately, the two factors have been shown to interdependently influence vulnerability (Enarson, 2007).
- **Education:** A great amount of anecdotal evidence suggests that an individual's level of education can significantly influence their ability to respond to and recover from an emergency (an increase in education leading to a better economic standing and therefore increased coping capacity). However, little work was identified that expressly examines the relationship between personal education and vulnerability.
- **Lone parents:** Lone parent families, particularly those headed by women, are more likely to live on the edge of poverty due to the constraints and financial difficulties of supporting a family on one salary (Sapir, 1993).
- **Housing and households:** A household's living arrangements and the resources available to the household are controlled by an intricate set of inter-linking factors, including the ratio of healthy and employed members to those that are dependant, be it due to age or illness, geography and location, the style and quality of the dwelling itself, and the social and economic characteristics of the surrounding population (Hewitt, 1983; Quarantelli, 1987, 1995; Bates & Peacock, 1987; Morrow, 1999). Similarly, the literature suggests that those who rent, rather than own a home, often lack the local connections that aid response and coping capacity (Zandt *et al*., 2012) and are increasingly likely to reside in low-cost manufactured homes situated in high-risk places (Enarson, 2007). However, drawing

conclusions based upon housing is fraught with complications. Simply examining the proportion of renters in an area does not sufficiently describe the group's income, abilities or needs (*ibid*).

- In addition, the capacity of households to adapt and respond to emergencies has been shown to be an important factor, with evacuation plans, insurance coverage and other risk mitigation strategies helping to reduce vulnerability (Koks *et al*., 2015).

Any one household is likely to experience an emergency situation different to another as a result of a complex set of interacting exogenous and endogenous conditions and a combination of the above factors (Bates & Peacock, 1987; Hewitt, 1983; Morrow, 1999; Quarantelli, 1987, 1995). Further, it is often an erroneous assumption of emergency policies and practices that all residents of an affected area will respond to an emergency in the same way and have access to the same information and resources (Zandt *et al*., 2012).

Throughout the literature, two distinct paradigms within the vulnerability concept exist: the behavioural and the structural (Mileti, 1995; Smith, 2004). The former, the behavioural paradigm, is an approach that focuses on mitigation and management of risk (Hewitt, 1983; White, 1974). The latter, the structural paradigm, is an approach that focuses on adaptation of social, political and economic structures within society to limit risk and vulnerability (Alexander, 1993; Quarantelli, 1995).

An outline of the evolution of major theoretical models within the hazards/vulnerability literature can be found in Cutter *et al*., (2009), where the authors break down the history of hazards vulnerability literature into five key proceedings:

1. the pioneering work of Gilbert F. White and his students and the creation of the "**risk/hazards paradigm**";
2. O'Keefe *et al*.'s (1976) seminal paper, "Taking the Naturalness out of Natural Disasters" which **refocused hazards attention onto the human drivers of vulnerability**;

3. the development of the **pressure and release model** by Blaikie *et al*., (1994), the most frequently cited theoretical model within the hazards' literature;
4. the development of the **hazard-of-place approach** to vulnerability analysis, a hybrid of the risk/hazard and political ecology perspectives, formulated by Cutter (1996);
5. the development of the **vulnerability/sustainability framework**, which locates local vulnerabilities within the larger contexts of global issues, proposed by Turner *et al*. (2003).

The majority of the research into conceptual vulnerability undertaken over the past 20 years has focused on developing a framework that is applicable to various systems, scales and hazards (Stângă & Grozavu, 2012; Fussel, 2007; Taubenbock *et al*., 2008). However, relatively few of the frameworks and models identified throughout the literature were found to have been applied to or operationalized in real-world settings. Most conceptual studies utilise schematic diagrams (see Figure 2) to describe conceptual frameworks and to frame vulnerability at a number of scales, from macro (global- continental-scale, see: Füssel & Klein, 2006; Heltberg, *et al*., 2009; Ionescu, 2009) to micro (city-, country-scale, see: Ainuddin & Routray, 2012), or under themes, such as adaptive capacity or resilience (see: Brooks, 2003; Brooks, *et al*., 2005; Downing & Patwardhan, 2004; Füssel & Klein, 2006; Kelly & Adger, 2000; Smit *et al*., 2000; Yamin *et al*., 2005), or provide a methodology for conducting such analyses, such as meta-analyses or hazard-specific assessments (Cutter *et al*., 2009).

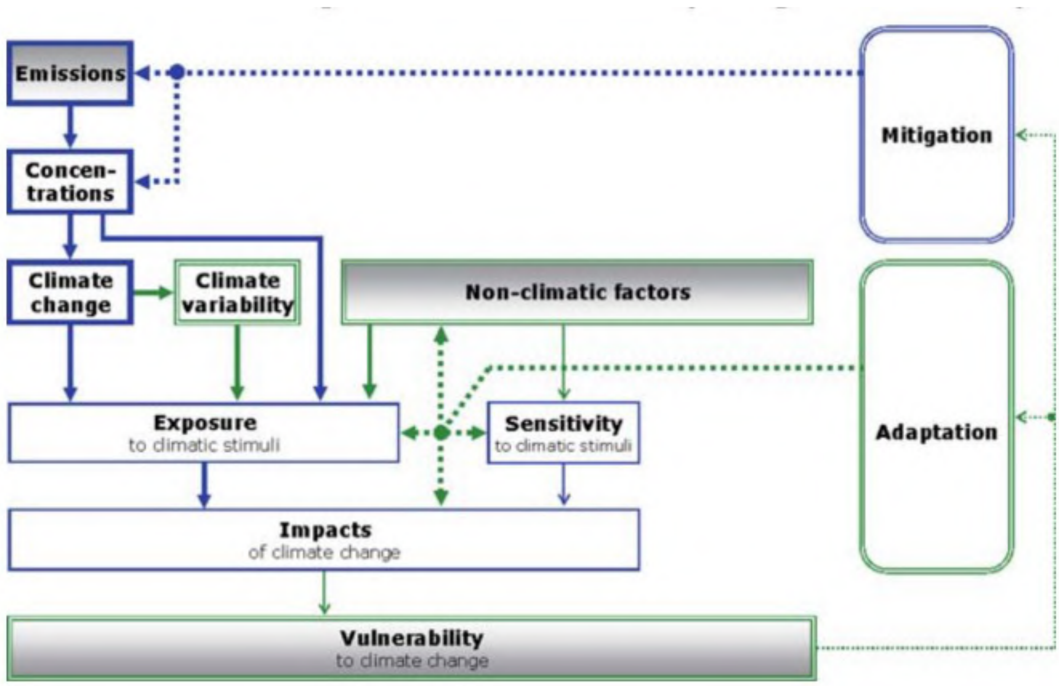


Figure 2: Example of a schematic conceptual framework of vulnerability (taken from Füssel & Klein, 2006)

2.1.2 MEASURING VULNERABILITY

A greater understanding of the spatio-temporal variances in vulnerability and knowledge of where those viewed as more vulnerable are concentrated within communities, as well as the wider socio-economic circumstances of those communities, is key to understanding a population's level of resilience to environmental hazards (Cutter & Emrich, 2006) and improving response service capability (Nelson *et al*., 2007). In order to provide practical identification and assessment of social vulnerability, the many influencing factors must be assigned measurable numeric indicators (Atteslander *et al*., 2008).

Birkmann (2005), and later Fussel (2007), examined the conceptual issues concerning vulnerability and the methodological approaches used, revealing the key schools of thought and vulnerability concepts within the literature, as shown in Figure 3: Key spheres of the concept of vulnerability (adapted from Birkmann, 2005 and Joseph, 2013). The different levels of conceptualisation of vulnerability measurement develop from a human centred intrinsic measurement to an all-encompassing multidimensional measurement that becomes conceptually wider, increasingly complex, and difficult to measure (Joseph, 2013). When attempting to measure vulnerability it is necessary to consider what level to focus on and how to balance complexity versus complicatedness (*ibid*).

Vulnerability research aids our understanding of the complex interplay between everyday life and hazards. To improve disaster risk reduction strategies and personal and community adaptive capacity, it is necessary to move from attempts to understand and define vulnerability and attempt to measure it through the production of metrics and indices (Mustafa *et al.*, 2011). Although it is impossible to reduce the concept of vulnerability down to a single quantitative measure, quantification of this kind does improve the functionality and effectiveness of using vulnerability when attempting to understand, compare and communicate the impact of an event to non-experts (*ibid*).

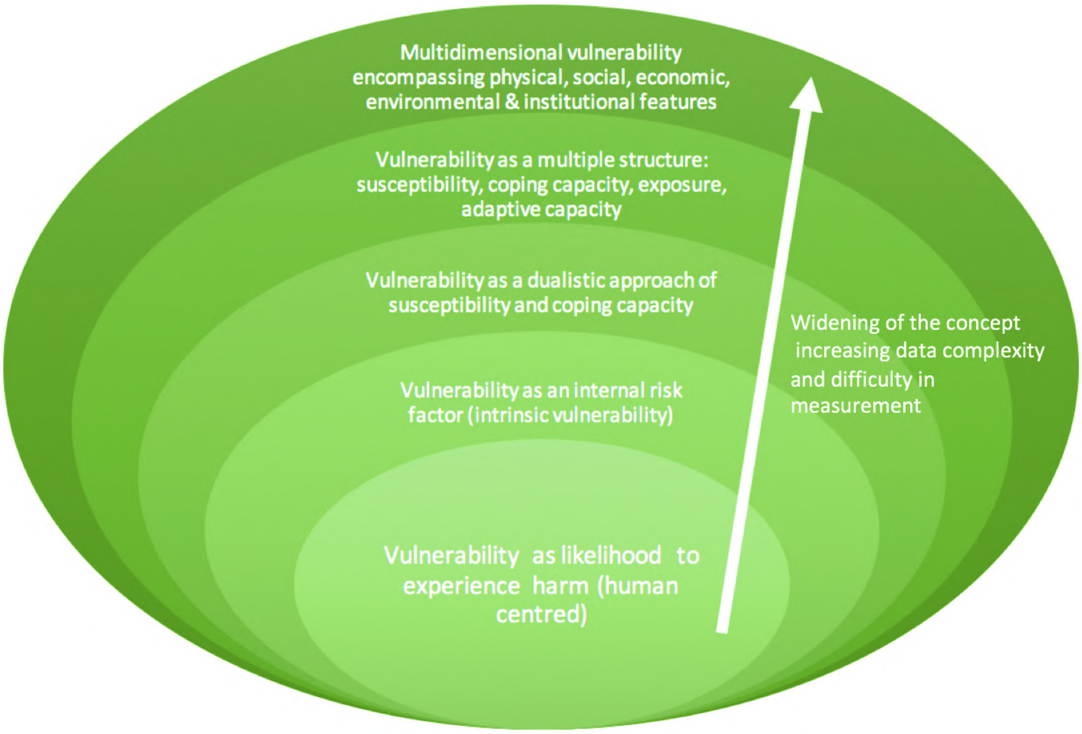


Figure 3: Key spheres of the concept of vulnerability (adapted from Birkmann, 2005 and Joseph, 2013)

VULNERABILITY ASSESSMENTS

As identified by the United Nations Expert Working Group on 'Measuring Vulnerability', the only expert approach to identifying socially vulnerable populations is the production of a vulnerability index: an aggregated or composite measurement of selected proxy indicators of vulnerability, be it mortality, morbidity or social capital, that determines a numerical value representing the social vulnerability of a given geographical unit (Birkmann, 2005). However, as will be shown throughout this review, the majority of vulnerability indices that have been produced are largely reliant upon a small number of indicators that are often presented at a geographically broad scale, such as city- or county-level, which do not provide the precision required for the fine resolution geography under examination here. Local councils and NGOs require information at a much smaller scale to understand adequately social vulnerability within the areas that they work so that they can plan appropriately. Such indicators have been shown by others to be able highlight areas of vulnerability, but it is argued here that an array of specific indicators spanning the many aspects of modern life – from accessibility and education to the strength of local economies – are required to gain a more substantive knowledge of modern social vulnerability.

Countries, counties and cities are not homogenous, but are instead made of unique communities that represent the most affluent and privileged, as well as the most destitute and deprived. Variations in socio-economic and health vulnerabilities exist in space and time and indicators are available that are regularly and systematically collected at a resolution small enough to allow quantitative measurement and mapping of such variations at a community level (Cutter, Burton & Emrich, 2010).

A vulnerability perspective has been shown to focus the attention of social research on the diversity within populations; concentrating on the broader social, cultural and economic factors that influence a community's vulnerability and moving focus away from a singular examination of the presence of hazards (Van Zandt *et al*., 2012). Vulnerability assessments are often the first step to identifying those groups in society who may require added assistance during an emergency (Blaikie *et al*., 1994; Morrow, 1999; Müller, Reiter, & Weiland, 2011).

However, due to its somewhat ambiguous nature, many assessments of vulnerability have, to a certain degree, been vague, oversimplified or ill-structured (Kværner, Swensen & Erikstad, 2006; Müller *et al*., 2011). Most vulnerability assessments examined were found to be concerned with locating physical structures or population concentrations at risk within known hazard-prone areas (Kværner *et al*., 2006; Müller *et al*., 2011). However, as events such as Hurricane Katrina showed, the nature of the population – race, employment, income *etc*. – is just as important a factor as where that population resides (Long, 2007; Oxfam America, 2009; Tate, 2013).

The majority of the research into vulnerability assessments undertaken over the past 20 years has focused on developing frameworks that are applicable to various systems, scales and hazards (Stângă & Grozavu, 2012; Taubenböck *et al*., 2008). However, scale and versatility have been identified as major constraints of many vulnerability assessments (Preston, 2012). Much of the literature examined focused on, and assigned great premium to, economic aspects of life, namely income (Preston, 2012), and limited research by geography (state, territory or census block) and the range and applicability of indicators used. Relatively few studies have been operationalised in real-world settings (Cutter *et al*., 2009), with fewer still replicable outside of their original focal zone. Assessments are often designed with a focus on a specific geographical area, often limiting their universal usage (Engle, 2011), or the methods and data used often render the indices inappropriate or incompatible with other areas, timescales or systems (Lankao & Qin, 2011). Further, limited attention was found to be paid to the use of open data, with proprietary data and technology utilised widely. Few studies were found to have produced an index that could be freely and easily utilised and adapted by NGOs and communities (Garbutt, 2013). Due to these problems of comparability between indices, variables and methods, vulnerability assessments are best thought of as a heuristic illustration of the conditions within the study area, be it existing or anticipated, and not as a predictive tool (Cutter *et al*., 2009).

In terms of scale, vulnerability assessments are generally undertaken at one of three levels: household, regional or national. Many studies exist that examine relative vulnerability across countries (Webber & Rossouw, 2010), such as Turvey's (2007) composite vulnerability index (CVI) of 100 developing countries, but rarely is attention paid to the differing vulnerability of regions within these countries. At the local level, there is a large and growing body of work examining local-level vulnerability, be it at the household level (Bird & Prowse, 2008) or Cutter's place-based vulnerability indices centred upon United States Census Bureau block-groups (Cutter, Mitchell, & Scott, 2000) or later community resilience studies undertaken at the larger county level throughout coastal US states (Cutter, 2006; Cutter, Barnes, & Berry, 2008). This lack of connection from global (macro) to local (micro) level indicators is a principal impediment to the development of an integrated vulnerability assessment methodology (Joseph, 2013).

There is a growing body of literature on vulnerability science that seeks to increase the usefulness and use of vulnerability assessments, with an academic focus on quantitative measures of vulnerability and the development of universal measurement tools or frameworks for vulnerability assessments. However, much of the literature reviewed also advocates a fine resolution, place-based, assessment methodology in an attempt to produce more local and relevant observations (see: Barnett, Lambert, & Fry, 2008; Cutter *et al*., 2009; Jones & Thornton, 2003; Kasperson & Kasperson, 2001; Polsky, Neff, & Yarnal, 2007). This may seem contradictory but instead of seeking convergence in vulnerability thinking in terms of universal metrics, there is now an emphasis on selecting frameworks that are appropriate for each context – a shift from 'one universal indicator or method' to a focus on the appropriateness of different measurement methodologies. Previously there was a drive to break vulnerability down to its component parts to measure more efficiently and broadly, and to improve comparability but this reductionist approach can narrow our view and we can miss emergent outcomes and non-linear, interdependent dynamics and relationships. A more holistic and system-wide thinking on indicators and a focus on context-specific frameworks may improve our understanding of vulnerability across different scales and contexts. Mustafa *et al*., (2011), for example, created an empirically tested quantitative vulnerability and capacities index (VCI) for use at the local scale aimed at connecting vulnerability research and policy. The authors drew upon 12 vulnerability indicators to represent the three core aspects of social vulnerability: material, institutional and attitudinal capacities. To make the VCI more suitable at small, local levels, they created four versions of the index to be used in rural and urban settings and at household and community scales.

INDICATORS OF VULNERABILITY

Indicators – 'quantitative measures intended to represent a characteristic or a parameter of a system of interest' (Cutter *et al*., 2008, p. 7) – are regularly used within vulnerability science to produce a single universal value that represents vulnerability at a particular temporal or spatial scale or location. A wide variety of indicators and assessment models are in use with common indicators including: mortality, morbidity, social capital and physical assets (see: Environmental Sustainability Index (Esty *et al*., 2005), Human Development Index (Anand & Sen, 1994; Burd-Sharps *et al*., 2008), Human Well-being Index (Prescott-Allen, 2001) and Social Vulnerability Index of Climate Change in Africa (Vincent, 2004)). The proxies available for each indicator are yet more numerous (Rygel, O'Sullivan, & Yarnal, 2006).

A wide-ranging selection of relevant vulnerability indicators is presented within the literature. Cutter, Boruff, and Shirley (2003) alone present a version of their index that utilises 42 indicators. However, this project was concerned with vulnerability in a rural/urban region within a developed country, which means that not all vulnerability indicators identified within the literature are appropriate. For example, common indicators used within vulnerability indices are measures of political stability, access to education and literacy rate (Mustafa *et al*., 2011; Patt *et al*., 2010). These indicators are arguably inappropriate for use within developed countries. Other indicators utilised in earlier studies, such as social-capital religion, local asset value and civic involvement (Müller *et al*., 2011), are unsuitable due to limited data availability.

Challenges to the production of vulnerability metrics, especially a universal index, and the use of such indicators do exist, with vulnerability indices limited by the lack of consensus on a strict definition of vulnerability across the discipline; selection of indicators; determination of indicator importance; data availability, quality and validation; and difficulty in quantifying social interactions and measuring concepts such as institutional capacity or readiness (Müller *et al*., 2011). Furthermore, indicators, like models and indices, represent reality imperfectly. The reliance upon measurable data, both quantitative and qualitative, to produce a vulnerability index limits it to those vulnerability components that are quantifiable (Moldan & Dahl, 2007). Interactions and feedbacks exist that are not sufficiently understood and thus cannot be factored into the production of accurate indicators (Damm, 2010). The impact of these 'non-quantifiables' must be gleaned from qualitative research, working with NGOs, for example, to further elucidate the findings from studies like the one presented herein.

To be effective, vulnerability indicators must be appropriate, representative of the phenomenon under examination, credible and feasible (Moldan & Dahl, 2007, Niemeijer, 2002). However, methodological trade-offs are often necessary and a balance between these dimensions, as well as scale and cost, is required to produce legitimate and usable indicators (Damm, 2010). As with using too broad a geographic scale of analysis – county over Census tract, for example – the use of general, broad-based indicators can reduce the effectiveness of the index as populations under analysis are grouped and classified too coarsely, perhaps even stereotyped (Goss, 1995), and the nuances of vulnerability and local minutiae are lost. Similarly, vulnerability represents social geography (Cutter, 2006) and, as such, indicators must vary with changing geography (Rygel *et al*., 2006). Indicators infer knowledge of a system (Balica & Wright, 2010) and to fully understand the vulnerability system, I believe, the indicators used should be as locally relevant as possible.

WEIGHTING

The process of weighting vulnerability variables is often idiosyncratic and is the subject of much debate (Bohringer & Jochem, 2007; Brooks *et al.,* 2005; Morse, 2004; Yoon, 2012). In Jones and Andrey's (2007) examination of vulnerability indices and their construction, the authors found that variable selection is the most critical issue, followed closely by the weighting of those variables. Two camps exist whereby studies either treat all factors equally within an index, or they apply weightings based upon perceptions of indicator importance, often with weightings assigned with little to no input from those within the society being examined (Dibben *et al.,* 2004). It is common for vulnerability assessments to include weighting schemes for indicators, with authors asserting it is necessary to assess vulnerability accurately as not all elements within society play an equal role in creating, fostering or reducing vulnerability (Haki & Akyurek, 2004; Meyer *et al.,* 2007). For example, the English Indices of Deprivation, which provide a relative measure of deprivation across England at the LSOA resolution, assigns a combined 45% weighting to issues of income and employment and 13.5% to issues around health and disability. Similarly, in developing their weighting schemes, Rygel *et al*. (2006) ranked the factors within each indicator to assign importance; Cox *et al.,* (2007) assigned weightings based on the percent variance explained by each factor; Brooks *et al.,* (2005) employed focus groups to identify vulnerability indicators, as well as relying on those previously identified by earlier studies, and to provide weightings for each indicator chosen.

However, most vulnerability studies examined preferred not to assign weights to indicators, asserting that they are of equal importance to the calculation of vulnerability or are independent of each other (Tate, 2012; Yoon, 2012) or that insufficient evidence exists to assign importance accurately to any one demographic factor over another to produce a robust weighting system (Collins *et al*., 2009; Fekete, 2009; Fekete, 2012). However, Fekete (2011:1167) does acknowledge that indictors are likely not of equal importance but “the avoidance of weighting is in itself a certain kind of weighting...because not weighting means equal weighting within the aggregation of input variables or indicators.” An “unweighted” index that is designed to be objective is arguably still subjective in nature and it has been argued by Oulahen *et al*. (2015) that it should therefore be subjective according to local practitioners, with those most knowledgeable about the area/community/hazard or those who are responsible for environmental management being involved in the weighting of index variables – discussed further in section 4.6 and section 5.6. Barnett *et al*. (2008) note that this involvement of those who implicitly populate vulnerability indices increases the legitimacy of the index and offers a level of inclusivity to those with the greatest stake in the assessment.

Those looking to measure vulnerability are beset by a number of challenges. First, vulnerability is a complex concept, nested throughout society at multiple levels and often hidden. It is often perceived in one of two ways: a holistic concept that encompasses a range of complex societal interrelations, or a more one-dimensional concept that focuses on individual factors within a specific hazard (Fekete, 2012). The former conceptualisation is perhaps too comprehensive, requiring an understanding of a complex array of human and physical features across different levels of society; the latter is, conversely, too limited in its scope. The modeller is tasked with deriving a set of proxy indicators which are relevant, yet broad enough to not limit analysis to a single location and/or event and allow for validation, but also minimal and transparent enough to clearly explain the phenomenon to target groups (Gall, 2007a). Second, the availability of data, particularly in developing nations, is a great challenge, with independent secondary datasets for validation rarely available (King, 2001; Fekete, 2009). Third, if data are found, measuring social vulnerability relies upon the quantitative assessment of a qualitative phenomenon through the use of generalised numerical surrogates (indicators and indices) (Fekete, 2012). Benson and Twigg (2004) and Birkmann (2006) have described the criteria for quality vulnerability indicators, but there remain concerns within the community over the use of indicator aggregation and composite indices within risk and vulnerability research. Nardo *et al*., (2005) and Fekete *et al*., (2010) both note the subjectivity inherent within indicator selection, as well as within statistical analysis, with Fekete (2012) going further and questioning whether or not vulnerability indicators show more than just the patterns or areas where many indications accumulate and that such static visualisations of vulnerability are inherently limited due to their exclusion of temporal effects.

However, although challenging, if a greater understanding of vulnerability is going to improve disaster risk reduction and adaptation strategies, then indices must be devised that allow us to measure it. Mustafa *et al*., (2011) point out that the reduction of vulnerability to a quantitative measure is necessary as such quantification increases the utility and comparability of the concept of vulnerability (Mustafa *et al.*, 2011). Vulnerability research has aided our understanding of the linkages between society and hazards through a focus on the complex nuances between geographies of poverty, inequality, and exclusion, and geographies of hazard impact.

2.2 EMERGENCY RESPONSE, RELIEF & MANAGEMENT

Emergency is a managerial term describing a situation that requires extraordinary measures and is usually defined in space and time by somebody in authority and sets forth rules of engagement and response strategies (ReliefWeb, 2008). During emergency situations "the provision of essential needs to individuals, families and communities" is crucial (Bayside City Council, 2014:2). Emergency relief helps those affected by an emergency event to meet their basic needs to stay alive, be it food, water, shelter, or healthcare. Emergency management, defined as "the managerial function charged with creating the framework within which communities reduce vulnerability" with an aim to "protect communities by coordinating and integrating all activities necessary to build, sustain, and improve the capability to mitigate against, prepare for, respond to, and recover from threatened or actual natural disasters, acts of terrorism, or other man-made disasters" (Emergency Management Institute, 2007).

Each emergency is distinctive and is manged in different ways and those affected may require different relief and assistance. For example, the relief provided and the management of short-term response efforts to a flood or earthquake is very different to that provided during a protracted situation such as a famine or drought (Cozzolino, 2012). The timing and longevity of emergency relief is dependent upon the timing, scale, and location of the emergency, but also the preparedness of the response teams and area affected, the vulnerability and accessibility of those affected, and the resources available (Crutchfield, 2013). For example, communities and government agencies were unprepared and under-resourced to respond to the 7.0M_w earthquake that struck Haiti on 12 January 2010, likely due to limited earthquake experience and the country's fragile economy (Crutchfield, 2013). Subsequently, response and relief efforts lasted for many years (IMF, 2012). In comparison, Chile and New Zealand, which both suffered large earthquakes in 2010 also, had far more advanced response, relief and resilience strategies in place due to their history of earthquakes and their relatively high level of preparedness (Wilson, 2013; Crowley & Elliott, 2012; Dussaillant & Guzmán, 2014).

Although there is disagreement over the precise structure and nomenclature of emergency management (see: Kovács *et al*., 2007; Kovács & Spens, 2008; Altay & Green, 2006; Pettit & Beresford, 2005; Van Wassenhove, 2006; Garrett & Sobel, 2003; Silva, 2001; Cottrill, 2002), there is agreement on the following four stages (McLoughlin, 1985; Cozzolino, 2012; Waugh, 1990; Ozen, 2018; National Governors Association, 1979):

- **Mitigation**: actions taken *before* an event in order to reduce loss of life and lessen the impact of emergencies (analysing, reducing, and insuring against risk, for example) (Reddick, 2011). Preparedness is often included within this stage, as well as the following stage, with a focus on activities such as pre-event evacuations, vulnerability analyses updates, and public education.
- **Preparation**: practical actions taken by governments, responders and communities to increase the efficiency and effectiveness of response systems and improve preparedness through activities and training. For example: strategic stockpiling of food, equipment and medical supplies, mutual aid agreements, and exercises and training.

- **Response**: actions taken *after* the event, often according to emergency plans set forth during the mitigation and preparation stages, to preserve lives, properties, social and political structures, and the environment. The focus of this stage is often meeting the basic needs of those affected by providing temporary shelter and food but can include infrastructure repairs. This stage is the focus of this study.
- **Recovery/reconstruction**: the return to pre-emergency state of being for systems and communities. Ideally, recovery activities should feed into mitigation and preparation activities for the next emergency, with legislation and policies implemented based upon lessons learned (Ginger *et al*., 2007; Queensland Government, 2009; Victoria Bushfires Royal Commission, 2009).

Recovery is the most contentious stage of emergency management, with a lack of empirical evidence to support the how, when, or how long it takes for a system or community to 'recover'. It is widely accepted that different people/ groups/institutions recover at different rates, and that some may never fully recover. There is also a growing understanding that recovery processes can take days to decades, however there is a lack of work on how to measure recovery accurately, what it looks like, and how it is impacted by multiple shocks/stresses, and what work has been done has focused on multiple large-scale shocks, and not the more frequent and lower impact stresses. The scope of this study did not allow for this gap in the literature to be addressed, but the reader is pointed towards the work of Brown *et al*. (2008), Chang (2010), Jordan and Javernick-Will (2013) and Cheng *et al*. (2015) for examinations of the issue.

2.2.1 RESPONSE EFFORTS

The three key elements of the emergency response stage are coordination, collaboration and logistics (Van Wassenhove, 2006; Kovács *et al.*, 2007). However, the work the emergency response and management domain aims to undertake is complicated by its distributed control network; multiple stakeholders with different (often competing) aims and objectives competing for funding and access; uncertainty, ambiguity and imprecision within most aspects of work; and limited and continually fluctuating resources (both stock and personnel) (Adams *et al.*, 2008). Response efforts are often defined by the actions and bottom-up decision-making of those directly impacted by the emergency, and the (more often than not) top-down governance and coordination of responder organisations, neither of which are easily optimized (Stirling, 2003; London Resilience Team, 2010; Hawe *et al*., 2012). Emergency relief and response operations often include a number of key organisations, including emergency response services (police, fire and ambulance services), aid agencies and non-governmental organisations (NGOs), the military, government agencies, and private sector companies all of whom are heterogeneous, with organisation-specific mandates, interests, capacity and expertise (Cozzolino, 2012; Balcik *et al*. 2010). Coordination and collaboration between so many actors is vital to ensure that those affected by an emergency receive the relief they need and that resources are not wasted, duplicated or delayed (Balcik *et al*., 2010; Kovács & Spens, 2007; Maon *et al*., 2009; Tomasini & Van Wassenhove, 2009). Similarly, it is essential that emergency logistics operations be well planned and organised to ensure that the correct kind and amount of relief is delivered to the correct locations in a timely manner (Tomasini & Van Wassenhove, 2009).

However, at the operational level, well defined objectives during the response stage of an emergency are often a luxury (Hawe *et al.*, 2012). Klein (2007b) discusses what he refers to as the flexible execution, or 'flexecution', of emergency plans in response to changing situations and emergent goals and goal conflicts. Objectives and priorities are likely to shift as the emergency develops (UK Cabinet Office, 2010) and the difficulty faced by responders is how to trade the relative priorities against one another (Branke *et al*., 2004). In the UK, government guidelines[15] set forth strategic objectives for emergency response efforts, but it is understood that "not all…objectives may be achievable at the outset of an emergency" and that "in reality they will evolve and their relative priority may shift as the emergency develops" and that Ministers will "advise on the appropriate balance to strike in light of the circumstances" (U.K.

[15] Cabinet Office (2010) Responding to Emergencies: The UK Central Government Response – Concept of Operations

Cabinet Office 2010b). These pareto-optimal trade-offs are likely the only acceptable option available (Sawaragi *et al*., 1985; Klein, 2007). Klein (2007) uses the example of firefighters to demonstrate how ‘flexecution’ works within the emergency response field and how refinement and revision of goals “on the fly” as the emergency develops can be a viable option, with tools and support concepts needed to ‘simultaneously define and pursue goals’ Klein (2007a) or to support and anticipate improvisation (Mendonc & Fiedrich, 2006; Mendonc, 2007).

2.2.2 DISASTER OPERATIONS MANAGEMENT & HUMANITARIAN LOGISTICS

The effectiveness and expediency of emergency response efforts are almost entirely dependent upon timely and successful operations management and humanitarian logistics. Cozzolino (2012) provides an introduction to the key concepts of emergency logistics and supply chain management and underlines the complexity of such operations. Worldwide, emergency logistics accounts for 80% of total emergency response spending (Van Wassenhove 2006), estimated to be $15 billion (Christopher & Tatham, 2011). Thus, improvements in operations support, logistics and supply chain management, and investment in planning and modelling, could result in more effective and efficient use of resources and have a direct, tangible effect on the ability of NGOs and others to respond to emergencies and improve their overall effectiveness (Leiras *et al.*, 2014).

Considering the lengthy history and importance of logistics and operations management within emergencies, academic research in the area is relatively new (see: Beamon & Kotleba, 2006; Van Wassenhove, 2006). Altay and Green (2006), Natarajarathinam et al., (2009) and Pettit & Beresford (2009) conducted early literature reviews of the limited relevant literature available. Altay and Green (2006) reviewed 109 papers published from 1980 to 2004 in operations research (OR) and management science (MS) journals. The authors found that research linking theory and practice were rarely explored, a finding supported by later reviews (Natarajarathinam *et al*., 2009; Kunz & Reiner, 2012; Leiras *et al*., 2014). From 2011, when the Journal of Humanitarian Logistics and Supply Chain Management (JHLSCM) began publishing and research institutions (e.g. The Fritz Institute and INSEAD (Institut Européen d'Administration des Affaires)) and groups (*e.g.* Massachusetts Institute of Technology Supply Chain Lab) dedicated to the study of humanitarian logistics were created, the quality, quantity and relevance of emergency logistics research improved (Leiras *et al.*, 2014). Subsequently, reviews of the literature grew in scale, allowing for the analysis of niche research areas. For example, Caunhye *et al.* (2012) reviewed 70+ studies of optimization models in emergency logistics and found that most studies surveyed were concerned with improving responsiveness (minimizing response times, distance costs *etc*) but few considered negative effects such as oversupply of resources and increases in scheduling complexity and Kunz and Reiner (2012) reviewed 170+ papers published across 68 journals and found that empirical research was underrepresented, as was the consideration of slow onset disasters and reconstruction efforts. More recently, Kovacs and Altay (2018) performed a systematic review and synthesis of humanitarian supply chain literature and found, like Kunz and Reiner (2012), that research is undeveloped.

Leiras *et al*., (2014) reviewed 22 papers, using the 4-step content analysis methodology as discussed in Mayring (2008): material is collected, formal characteristics of the material are assessed, structural dimensions and related analytic categories are selected, and material evaluation. The authors found that the majority of research focused on network flows/routing problems, with little attention paid to the recovery phase of an emergency (attested earlier by Altay and Green (2006); Kovacs and Spens, (2007); Overstreet *et al*., (2011); Natarajarathinam *et al*., (2009); and Kunz and Reiner, (2012)), and few studies presented a real-world case study or worked in collaboration with an NGO (although IFRC, FEMA and MSF were regularly referenced amongst the minority applied research studies). Leiras *et al*., (2014) concluded that relationships between academia and NGOs/emergency organisations must be strengthened to ensure effective applied research, empirical data collection and utilisation, and case study analysis. Further, attention should turn to slow onset emergencies (famine *etc*.) as well as full event examination, including recovery.

Literature review	Main operations and logistics needs identified
Kovacs and Spens (2007), Overstreet *et al*. (2011), Kunz and Reiner (2012), Leiras *et al*., (2014)	Research on humanitarian logistics, with a focus on learnings from business
Altay and Green (2006), Kovacs and Spens (2007), Kunz and Reiner (2012)	Research on recovery
Natarajarathinam *et al*. (2009), Kunz and Reiner (2012)	Empirical research
Altay and Green (2006), Kunz and Reiner (2012)	Research on mitigation tools/phase
Overstreet *et al*. (2011), Caunhye *et al*. (2012)	Research on optimization of facility location and resource distribution
Kunz and Reiner (2012), Leiras *et al*., (2014)	Research on cooperation, coordination and collaboration between NGOs, stakeholders and responders

Table 2: Main operations and logistics needs as identified by past literature reviews (adapted from Kunz and Reiner (2012) and Leiras *et al*., (2014)

While the recommendations set forth by Leiras *et al*., (2014), namely the strengthening of NGO/academia relations and data collection, are commendable, the complexity and uncertainty within global supply chains during emergencies due to infrastructure and logistics disruptions, as well as the inherent confusion and urgency on the ground, severely limit the availability of data and opportunities for collaboration. In their examination of the US Department of Defence (DoD) Overseas Humanitarian Disaster and Civic Aid program, Drifmeyer and Llewellyn (2003) found that coordination between the U.S. DoD and NGOs was inadequate; no formal program evaluation process was in place; and after-action reports (AARs) were inconsistent, lacked quantitative details and measures of project effectiveness. Similar such findings were noted by Sandwell (2011) in his qualitative exploration of the challenges of humanitarian organisations, namely ineffective management tools and techniques that rely upon non-standardised processes; a lack of data on logistics; and a focus on outcomes, not effectiveness.

2.2.3 DOMESTIC VERSUS INTERNATIONAL EMERGENCY RELIEF OPERATIONS

Domestic emergencies are events that affect public welfare, property, or disrupt usual processes but that can be responded to using the resources available at hand by local, regional or national groups (UN-SPIDER, 2017). International emergencies, or what the United Nations refers to as disasters, are events whose impacts overwhelm the capacities of local responders and place demands on resources which are not available locally and so there is a need for external assistance and international relief operations are put in place (*ibid*).

Tierney (2008), and later Alexander (2015), further differentiate events into *incidents, major incidents, disasters,* and *catastrophes* and outline the differences of each in terms of impact, resources required, and challenges (see Table 3). As outlined, incidents and major incidents can, for the most part, be responded to by domestic organisations such as local Police, Fire Department and Ambulance services, Armed Forces, or NGOs, such as the BRC. Recent examples of domestic (UK) incidents include: the 2007 floods, 2013 St Jude storm, and the 2017 Grenfell Tower fire and Manchester Arena bombing. In comparison, disasters and catastrophes require international response efforts, with international governments and NGOs, again like the BRC, offering aid and assistance. Most such events relate to natural hazards, such as floods and earthquakes. Recent examples of international events that the UK responded to, be it governmental or NGO assistance, include: the 2010 Pakistan floods, the 2016 Philippines typhoon, and the 2018 Indonesia tsunami.

Despite the structure and stages of emergency relief being comparable between domestic (UK) and international emergency management, there are stark differences with regards to what relief is needed, how it is disseminated, who disseminates it and when. Similarly, the scale of operations, the numbers involved (individuals and cost) and the types of emergencies are very different. No studies were found that directly compare emergency response procedures in both national and international settings.

In their extensive review of humanitarian logistics and emergency response operations literature, Leiras *et al*., (2014) found that applied research was limited and that partnerships between academia and humanitarian organizations were scarce. Where partnerships were reported, and when real-world problems were examined in collaboration with stakeholders, more grounded studies were produced that, the authors argue, may lead to more applied tactical and operational research. A bias towards sudden-onset disasters, such as earthquakes, was noted, affirming the results of Kunz and Reiner (2012) and Altay and Green (2006), with slow-onset disasters, such as famines and some floods, seldom researched (as previously asserted by Long and Wood (1995)). Few studies were found to link theory and practice, as noted by (Altay & Green, 2006; Natarajarathinam *et al*., 2009; Kunz & Reiner, 2012).

	Incidents	Major incidents	Disasters	Catastrophes
Size of impact	Very localized	Fully or partially localized	Widespread and severe	Extremely large in the physical and social sphere
Size of response	Local resources used	Mainly local resources used, with some mutual assistance from nearby areas	Intergovernmental, multiagency, multijurisdictional response needed	Major national and international resources and coordination are required
Plans and procedures activated	Standard operating procedures used	Standard operating procedures used; emergency plans may be activated	Disaster or emergency plans activated	Disaster or emergency plans activated, but huge challenges may overwhelm them
Impact on response resources needed for response	Local resources will probably be sufficient	Local resources and some outside resources needed	Extensive damage to resources in disaster area; major interregional transfers of resources	Local and regional emergency response systems paralyzed and in need of much outside help
Involvement of public in response	Public generally not involved in response	Public largely not involved in response	Public extensively involved in response	Public overwhelmingly involved in response
Challenges to post-event recovery	No significant challenges to recovery	Few challenges to recovery processes	Major challenges to recovery from disaster	Massive challenges and significant long-term effects

Table 3: Functional differences between different sizes of emergency events (adapted from Tierney (2008) and Alexander (2015)

Context: How the BRC Responds to International and National Emergencies

The BRC responds to emergencies in the UK and internationally. During an international emergency, such as the 2015 West Africa Ebola outbreak or the 2011 Pakistan floods, the BRC, as well as its partners across the global Red Cross and Red Crescent Movement and local NGOs and governmental agencies, will work together to organise relief efforts. Aid will either be sent directly to the affected area or the BRC will work with partners who have networks already in place. Supplies provided are dependent upon the needs of those affected and are communicated through personnel on the ground, but are likely to include food, blankets, and water. The BRC maintains a global logistics network that includes a number of strategically located warehouse sites that contain supplies, contracts with local logistics and shipping organisations, and a network of thousands of personnel and volunteers across the globe who can respond to events. This global network is organised and continually updated so that when an airport, road or phone network is damaged or destroyed they can maintain logistical support and deliver the right type and amount of relief and that resources are not wasted or delayed. Each Society has a special area of expertise and response personnel are deployed when required. For example, the BRC specialises in water and sanitation, and is only deployed when such infrastructure is damaged during, for example, an earthquake. The Australian Red Cross in comparison specialises in healthcare needs and is deployed when domestic healthcare facilities are overwhelmed. This specialisation ensures that resources and personnel skills are not duplicated, and that the wider Movement can respond to as many emergencies as possible.

The BRC's emergency response work in the UK follows the same general structure, however a strict set of guidelines and a national predetermined command control structure is in place that requires a Category 1 responder (a core responder, or "blue-light" responder, such as the police, fire or ambulance service, a local authority) to request that the BRC be activated and provide additional support. The support the BRC provides during a flood in Cumbria, for example, is likely to include the provision of bottled water, food parcels, blankets, physical and psychological support in rest centres, medical support supplies such as wheelchairs, and cleaning supplies. The BRC also offers emergency response support, such as rescue operations if asked to do so by the Category 1 responder.

The emergency response work done by the BRC in the UK is more supportive, rather than responsive and managerial as it is in international emergencies. Both entail similar operational frameworks: assess the situation; determine what is needed, when and where; distribute relief quickly and precisely; maintain operations as needed. However, the volume of relief and beneficiaries, the geographic and temporal scale of the emergencies, the command structure, the potential problems (for example environmental: large-scale damage and destruction; logistical: disrupted/damaged infrastructure and networks; political: unstable or overextended governance *etc*.) greatly increase the complexity and difficulty of responding to international emergencies.

No studies were found that examined NGO emergency response operations from a vulnerability perspective within the literature examined, with most favouring an operations management perspective. This is despite vulnerability, both in terms of event location and those affected, being a principal indicator of the likely response effort required following an emergency (Alcantara-Ayala, 2002; Leiras *et al.*, 2014).

In summary, the majority of research to examine emergency response operations focuses on major international relief operations following high-profile natural disasters (see: Moore *et al*., 2003; Telford & Cosgrave, 2007; Bennett *et al*., 2006; Thompson, 2010; Ahmad *et al*., 2011) or U.S. responses to domestic events, namely hurricanes Katrina (Eikenberry *et al*, 2007), and Sandy (Subaiya *et al*., 2014; Cobb *et al*., 2014). Much of the academic literature concerned with humanitarian relief work falls within two camps: social examinations of the impact of humanitarian work and reviews of humanitarian response efforts to certain events (Enarson *et al*., 2006; Lindell & Prater, 2003); or examinations of humanitarian logistics operations and supply chains, usually from a project management (*e.g*. Van Wassenhove, 2006; Kovács & Spens, 2007; Waugh & Streib, 2006), decision-making (Darcy & Hofmann, 2003; Zhang *et al*., 2002) or modelling perspective. Facility or resource location analysis (Balcik & Beamon, 2008; Salmerón & Apte, 2010; Fiedrich *et al*., 2000), inventory modelling (Ozbay & Ozguven, 2007), supply-chain logistics (Afshar & Haghani, 2012; Kovács & Spens, 2008; Day, Junglas & Silva, 2009), or route optimization (Balcik *et al*., 2008; Wohlgemuth *et al*., 2012) are common topics. Again, most of this work is concerned with major international humanitarian events, with particular focus on the 1994 Rwandan genocide (Borton *et al*., 1996), 2004 Indian Ocean tsunami (Telford *et al*., 2006; Perry, 2007), 2005 Hurricane Katrina (Takeda *et al*., 2006; Harrald, 2006), or the 2010 Haiti earthquake (Luis *et al*., 2012; Brattberg & Sundelius, 2011).

2.2.4 GEO-SPATIAL ANALYSIS OF EMERGENCY RELIEF

GIS are a primary method for uniting, analysing and visualising multiple information sources and presenting them in a form that is geo-spatially explicit in nature and is both understandable and easily accessible (Petersen *et al.*, 2010). A GIS can unite seemingly unrelated data by using location as the key index variable, be it specific longitude, latitude, elevation or spatial extents, for example. GIS data elements are depicted as either points, lines, polygons, satellite imagery and are geographically referenced using a coordinate system or data indirectly located to, for example, a postcode or statistical area or boundary (see: Figure 4). Multiple elements can be overlaid, allowing for a user to gain a greater understanding of the relationships, patterns, and trends within spatial data.

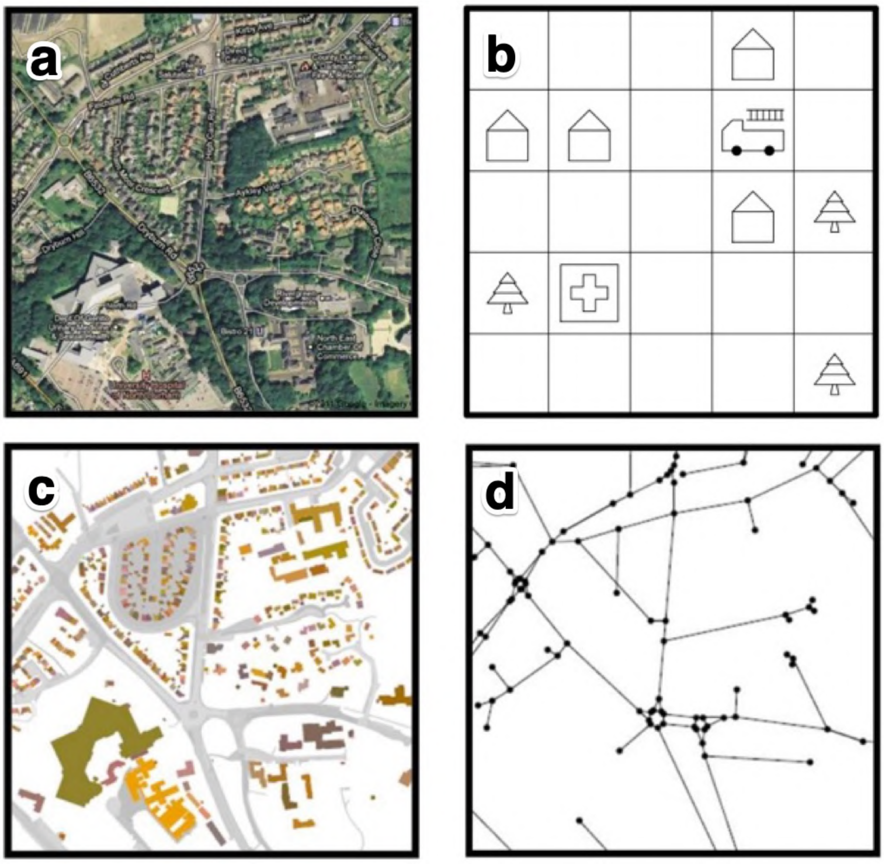


Figure 4: (a) a geographical area and its representation as a satellite image or using (b) a grid, (c) vector GIS files and d) a network (adapted from Hawe *et al.*, 2012).

More broadly, Geographical Information Science (or GIScience) – which represents a broad collection of geographical methods, such as remote sensing, spatial analysis and modelling, and geospatial processing and visualisation to address geographical issues – is one that is continually growing and is becoming a staple part of business and modern life: from the prevalence of Google Maps to the growing use of geospatial data within a broad range of businesses, for example banking (MacDonald, 2001), real estate (Rodriguez, Sirmans & Marks, 2009), policing (Chainey & Ratcliffe, 2013) and emergency relief operations (Giardino *et al.*, 2012).

The use of spatial data and geospatial analysis within emergency management and relief is not new (see: Cova, 1999; Cova, 2005; and Figure 4). All phases of an emergency (planning, mitigation, preparedness, response, and recovery) have a distinctly spatial nature and their representation within physical (and temporal) space can add valuable context (Smith *et al.*, 2009) and aid in identifying spatial relationships (Crooks & Wise 2013b). Geospatial analysis of emergencies and emergency relief comes in many guises; for example:

- hazard occurrence tracking and mapping (Petley *et al*. 2007; Garbutt 2010).
- pre- and/or post-event risk, vulnerability and resilience assessments (Tralli *et al.*, 2005; Notenbaert, Massawe & Herrero, 2010; Malcomb, Weaver & Krakowka, 2014).
- needs assessments (Benini *et al.*, 2009; ACAPS, 2014).
- evacuation planning and zoning (de Silva & Eglese, 2000; Cova & Johnson, 2003; Saadatseresht, Mansourian & Taleai, 2009).
- resource, logistics and transport planning (Mete & Zabinsky, 2010; Campbell *et al.*, 2008).
- post-event damage/impact and reconstruction mapping (Yamazaki, 2001).
- humanitarian relief distribution management and modelling (Cimellaro, Koh & Roh, 2014; Dolinskaya, Smilowitz & Chan, 2013; Sokat *et al.*, 2014).
- crowd sourcing of impact, response and recovery (Crooks & Wise, 2011, 2013; SandyCoworking, 2013; Wise, 2014).
- geospatial agent-based modelling of migration (Crooks & Heppenstall, 2012; Onggo, 2008), disease propagation (Hailegiorgis & Crooks, 2012; Carpenter & Sattenspiel, 2009; Eubank *et al.*, 2004) and the location of relief distribution centres (Turner *et al.*, 2011; Crooks & Wise, 2013).

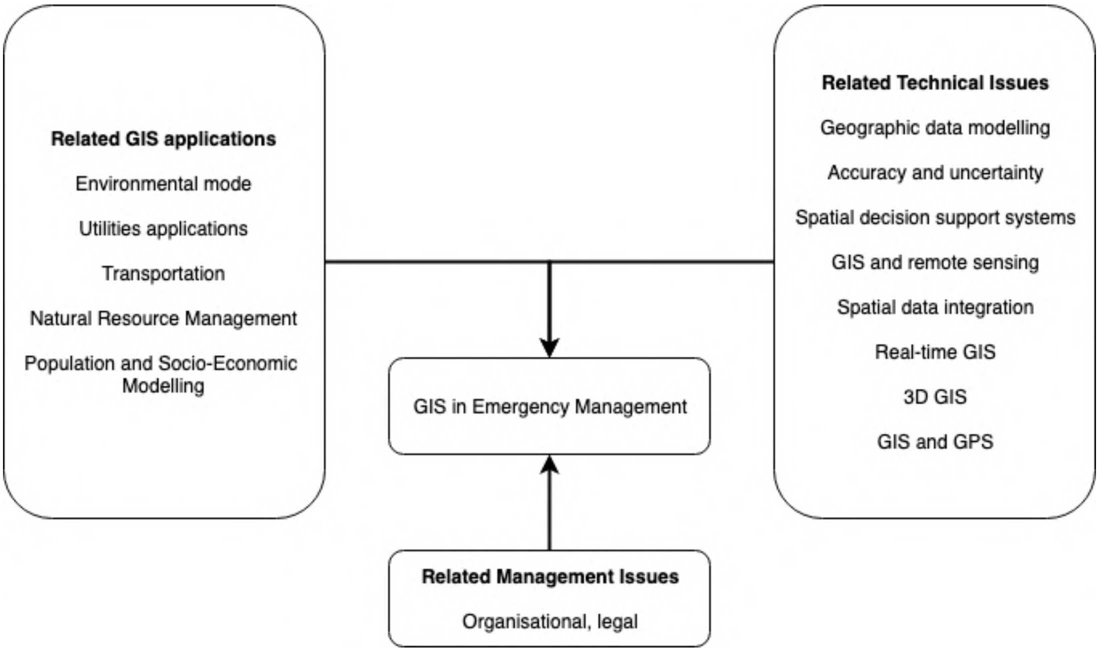


Figure 5: GIS in emergency management and related areas (adapted from Cova, 2005)

Cutter (2003) broadly examined the use of GI Science within disasters and emergency management and concluded that GIS-based incident command systems can help emergency personnel throughout the entire lifespan of an emergency, but that the vast majority of first responders (police, fire and ambulance personnel) and support staff are not familiar with GIS and are unlikely to use such systems in the immediate response or rescue phase. Although the use of GIS and geospatial content management systems (GeoCMS), such as GeoNode, SpatialHadoop and Marmot (Jo & Lee, 2018), have become widespread since Cutter's review (Cutter, 2003b; National Research Council, 2007a; Granell, Fernández & Díaz, 2014), technical limitations, namely data quality, quantity and integration, and up-to-date and interoperable asset infrastructure, remain major constraints to the proliferation and use of GIS within emergency management and relief operations (Cutter, 2006; Kaiser *et al*., 2003; NRC, 2007; Tran *et al*., 2009; Granell *et al*., 2014). However, the work listed above and that of the Humanitarian OpenStreetMap Team (Humanitarian OpenStreenMap, 2014), MapAction (MapAction, 2014) and the mapping teams of the American and British Red Cross societies who are actively working to integrate and showcase the use of GIS in emergency situations and train communities and humanitarian personnel to utilise GIS shows the growing use cases and work left to be done.

2.2.5 MODELLING (EMERGENCY RELIEF)

Models are simplified descriptions of a system and are used to simulate a given phenomenon for analysis (Downey, 2018). Traditionally, models took the form of complex formulae and algorithms, but increasingly cheap, fast computational hardware and software led to the advent of computational models that could take advantage of these resources (*ibid*). Computational systems and techniques have developed in recent years and have allowed for a wide range of phenomena to be explored and models with vast numbers of heterogeneous agents and dynamic environments to be produced (Miller & Page, 2007; Burkart, Nolz & Gutjahr, 2017).

Computational modelling is a broad field, with many sub-divisions and interconnected theories and methods (see: Miller & Page, (2009), Conte & Paolucci (2014), and Gilbert (2010) for reviews of the field). A great deal of research has focused on the computational modelling of social, physical and economic crises and the impacts on populations and systems (see: Conte *et al*., (2012) for a manifesto on the need for a greater comprehension of the complexity of our interconnected global society and the challenges involved in it). Computational modelling of risk analysis of natural disaster occurrence started in the 1980s (Sampson & Smith, 1982) along with simulations of traffic patterns and routing models to better understand emergency evacuations (Sheffi, Mahmassani & Powell, 1982; Knott, 1987). Emergency relief modelling began to develop in the 1990s and continues to grow, with a particular focus on emergency response logistics and population movements. Jain and McLean (2003) examined uses of computational simulation within emergency response and preparedness at different points of the emergency timeframe as part of their 'Integrated Emergency Response Framework' and noted five distinct applications of computer modelling and simulation within emergency response work:

- **Planning**: emergency impact estimation and determination, response procedure planning and testing.

- **Vulnerability analysis**: evaluation of event impact on existing response strategies, structures and resource networks, testing of existing response strategies to hypothetical scenarios.
- **Identification and detection**: probability determination of event occurrence.
- **Training**: interactive simulations of response procedures and decision-making to aid personnel learning.
- **Real-time response support**: testing of response strategies under evolving scenarios and user knowledge to determine the viability of alternative response strategies.

Of these five application areas, planning and training have received the most attention within the literature. Focus has been on event impact modelling (Kruchten *et al.*, 2008), planning and testing response scenarios/drills (Balasubramanian *et al.*, 2006), and personnel training (Albores & Shaw, 2008).

In comparison, the most common use of computer modelling within the emergency response domain spans multiple application areas, namely planning, identification and detection, and real-time response support: logistics networks and supply-chain management. Emergency logistics and supply-chain management is a complex part of all emergency responses and, as stated above, often accounts for a large percentage of an operational budget (UNDP, 1993; Pettit & Beresford, 2009). It is the understanding of this high level of complexity, with coordination among dozens of aid-providers, logistics organisations and stockists, that is critical to ensure the fast and effective delivering of relief to those in need (Menth, 2016).

Before the mid-2000s there is relatively little published academic work that examines supply chain management and logistics work during emergency responses (Pettit & Beresford, 2009). The availability of data and limited data collection opportunities due to the priorities of responders and the unexpected and precarious nature of emergencies, as well as the limitations of computing power, may be the cause of the limited research scope (De la Torre *et al*., (2012)). I believe that the 2004 Indian Ocean Tsunami and its widespread, multi-national impact and the unprecedented size of the response and relief efforts to the

Tsunami as well as the increasing digitalisation of emergency work and data collection acted as a catalyst for major research projects into such emergencies. Kovacs and Spens (2007) noted the increase in academic research into emergency logistics around this time. De la Torre *et al*., (2012) examined relevant literature and found the focus of emergency logistics research to be on the problems of vehicle routing during emergency situations and distribution point location decision-making, with particular focus on: provision allocation policies, beneficiary needs assessments, the uncertainty in demand and supply, and vehicle routing.

Emergency relief and response work is frequently seen as a sequence of distinct and disconnected stages, much to the detriment of research and often leading to wastage of money, supplies and man hours (Taylor & Pettit, 2009; UNDP, 1993; Pettit & Beresford, 2009). Computational modelling, particularly logistics and supply-chain modelling, that expressly examines the multiple distinct, interconnected and non-sequential stages and actions of emergency relief is required to accurately model events as well as simulate the impacts of relief work.

Despite the increase in research over recent years, there remains scant literature that quantitatively models emergencies or is concerned with theoretically grounded and empirically validated modelling (Cioffi-Revilla & Cioffi-Revilla, 2014; Macal, 2016). The majority of the work examined lacked real-world case study examination and attempts to validate the presented models. Addressing this gap within the literature, particularly a valid scientific understanding of the complex inter-related crisis phenomena and model validation, could advance the overall understanding of emergencies and improve response and management efforts.

Although it is not possible to predict the occurrence of most natural disasters, steps can be taken to mitigate the complex crises and the negative impact the events have on those directly and indirectly affected (Kovács *et al.*, 2007; Kabra & Ramesh, 2015b, 2015a). Simulating emergencies and response scenario testing is an integral part of preparedness (UK Cabinet Office, 2011; Hawe *et al.*, 2012). Humanitarian supply networks are often unstable and unpredictable especially in developing nations and/or following rare or catastrophic emergencies (Yadav & Barve, 2015). To test mitigation steps and improve network stability, responders regularly run simulations and exercises to test institutional readiness, response assumptions and uncover unforeseen impacts. Real-world exercises and emergency simulations are a mainstay of emergency response organisations and offer personnel hands-on experience and preparedness building (UK Cabinet Office, 2011). However, such exercises are expensive, often limited in their scope, and not easily adapted (Crook, 2010). Take, for example, the 2016 Exercise Unified Response simulation, a multi-million-pound cross-nation exercise that saw more than 70 partner agencies from around the world respond to a simulated rail crash and building collapse disaster that utilised 2,000 volunteers, seven crashed London Underground train carriages and thousands of tonnes of rubble. Such exercises are valuable learning experiences, but the prohibitive expense and inability to re-create many real-world scenarios limit their use (Straylight 2010; Hawe *et al*., 2012). Similarly, the 2010 Orion training exercise was designed to simulate a large-scale earthquake that overwhelmed the UK's response capacity and leads to the activation of the European Civil Protection Mechanism and the assistance of a number of agencies from across Europe (Orion, 2010). The exercise ran for 56 hours and included hundreds of participants and cost in excess of £1 million (Crook 2010; Hawe *et al*., 2012). Real-world exercises offer responders a level of detail and realism that is hard to surpass, but the cost of running such organisations limits their use. In addition, donors often insist that donations go directly to those in need (the purchasing of food or emergency housing, for example) and rarely is funding made available for back-office preparation, training and simulation operations (Banks, Hulme & Edwards, 2015; Heiss & Kelley, 2017).

Computational models provide a means of simulating emergencies and response procedures *in silico* and offer a number of advantages over real-world exercises, particularly for large-scale events that many organisations cannot afford to put in place, or for situations that are too complex or too dangerous to recreate in the real world. Computational emergency relief models allow for the evaluation of response strategies in a risk-free and relatively cheap environment.

Being able to simulate events computationally that would be too expensive, dangerous or impossible to recreate adequately in the real-world is the main benefit of computational emergency simulation (Straylight 2010; Hawe *et al*., 2012). However, rarely do NGOs and emergency responders have the knowledge and skills required to format such computational models (Gralla, Goentzel & Chomilier, 2015; Van Wassenhove & Allen, 2012). Thus, it is often academia that must provide the expertise required to simulate emergency situations and response procedures.

Jain and McLean (2003) examined uses of computational simulation within emergency response and preparedness at different points of the emergency timeframe as part of their 'Integrated Emergency Response Framework' and noted five distinct domains:

A great many computational simulation studies have been developed to understand and improve various aspects of emergency relief within the above five domains put forth by Jain and McLean (2003), including:

- inventory management (Beamon & Kotleba, 2006; Duran, Gutierrez & Keskinocak, 2011), facility pre-positioning (Balcik & Beamon, 2008; Roh *et al*., 2015; Salman & Yücel, 2015) transportation and routing (Barbarosoglu, Ozdamar & Cevik, 2002; Hwang, 1999), and last-mile delivery (De la Torre *et al.*, 2012; Noyan, Balcik & Atakan, 2015)
- information flow (Day *et al*., 2009) and real-time decision support tools (Hadiguna *et al.*, 2014)
- performance measurement (Balcik, Beamon, *et al.*, 2008; Apte *et al*., 2016; Anjomshoae *et al*., 2017) and situational awareness in emergencies (Huang & Xiao, 2015).

What these studies all have in common is that they assume particular scenarios will unfold in set ways and that input data (particularly known nodes of demand) exist and are readily available (Kovács *et al.*, 2007). The majority of reviewed articles were conceptual or abstract in nature, preferring to focus on logistics and provide mathematical solutions for vehicle routing under specific conditions, with few studies focusing on dynamic events or the immediate response stage following an emergency (Habib, Lee & Memon, 2016). There are notable exceptions to this, including the work of Das and Hanaoka (2014), Huang *et al*. (2015), Bozorgi-Amiri and Khorsi (2016) and van der Laan *et al*. (2016) but these studies remain atypical. In addition, Oloruntoba *et al*. (2016) noted that much of the humanitarian logistics and emergency relief modelling literature lacks theoretical development and could benefit from the use of behavioural, organisational, and economic theories. Further, framing emergency relief modelling as a dynamic network problem allows for the inclusion of systems thinking, including complex adaptive systems that can learn from past experiences and adapt to changing circumstances – ideal for the dynamic characteristics and flexible systems of emergencies and emergency response.

Modelling emergencies and response operations is an inherently difficult task due to the sheer number of inputs, assets and uncertainties that must be included and accounted for (Leiras *et al.*, 2014). Common methods used to model emergency response and relief operations include, but are not limited to, mathematical modelling, discrete event modelling, system dynamics, microsimulation, decision support systems, and GIS-based techniques. Examples exist for each method that show its promises and limitations within computational emergency modelling, but not all methods are appropriate for modelling all emergencies or relief efforts and as the scenario being modelled increases in complexity it is often necessary to combine methods or accept limitations within the model. Table 4 shows the main modelling methods used and lists their key attributes and examples of where the method has been applied. Table 5 lists the requirements of the modelling approach to be used and if the approach supports it. Each method is described in more detail in Appendix 11.4.

Method	Attributes	Abstraction Level(s)	Management Level(s)	Areas of Application	Simulation Modelling Software
System Dynamics (SD)	Aggregates, stock-and-flow diagrams, feedback loops	High (minimum details, macro level)	Strategic	Ecology and Population Dynamics (Weller *et al.*, 2014), Ecosystems (Levin & Lubchenco, 2008), Logistics (Abosuliman, 2014)	VenSim, PowerSim, iThink
Agent-Based Modelling (AB)	Active objects, individual behaviour rules, direct or indirect interaction, environmental model	High, Middle & Low	Strategic, Tactical, Operational	Logistics (Anand, van Duin & Tavasszy, 2016), Manufacturing (Coates *et al.*, 2019), Business Processes and Services (Sulis & Di Leva, 2017), Finance (Paulin, Calinescu & Wooldridge, 2018), Warehousing (Ribino *et al.*, 2018)	AnyLogic,MASON, Swarm, RePast, NetLogo, ASCAPE
Discrete Event Simulation (DES)	Entities (passive objects), flowcharts, resources	Middle (medium details, meso-level) & Low	Tactical, Operational	Business Processes (Pezzotta *et al.*, 2016), Manufacturing (Omogbai & Salonitis, 2016), Warehouse (Bottani *et al.*, 2017)	Arena, GPSS, ExtendSim, SimProcess, AutoMod, Promodel, Enterprise Dynamics
Dynamic Systems (DS)	Physical state variables, block diagrams and/or algebraic differential equations	Low (maximum details, micro level)	Operational	Automotive control systems (Shahbakhti *et al.*, 2015), Traffic micro level (Corman & Meng, 2015)	MATLAB, LabView, VisSim
Spatial decision support systems (SDSS)	(Geographic) Database objects, flowcharts, feedback loops	High, Middle & Low	Strategic, Operational	Landuse management (Lombardi & Ferretti, 2015), Watershed management (Jafary, Sarab & Tehrani, 2018), Forestry Management (Accastello, Brun & Borgogno-Mondino, 2017)	ArcView, Expert Choice, IDRISI, SPANS, TNT-GIS
Mathematical Modelling	Governing and sub-model algebraic differential equations, initial and boundary conditions	High, Middle & Low	Strategic	Finance (Walter, 2016), Health Policies (Meier *et al.*, 2016), Stock management (Malik, Tomar & Chakraborty, 2016) Engineering (Cárcamo Bahamonde, Gómez Urgellés & Fortuny Aymeni, 2016)	MATLAB, GAMS, Maple, SciLab, SageMath

Table 4: Comparison of modelling methods and associated attributes and business applications (adapted from Serova, 2013)

Method	GIS integration	High, middle & low levels of abstraction	Active objects	Individual behaviour rules & direct interaction	Well documented, open source software available
System Dynamics (SD)	X				X
Agent-Based Modelling (ABM)	X	X	X	X	X
Discrete Event Simulation (DES)	X				
Dynamic Systems (DS)					X
Spatial Decision Support Systems (SDSS)	X	X		X	
Mathematical Modelling		X			X

Table 5: Key requirements of modelling approach to be used. 'X' denotes the requirement is available within that method.

2.2.6 STAKEHOLDER ENGAGEMENT

Despite the growing interest in big data for demographics analysis, vulnerability mapping and supply chain management (see, for example, Waller & Fawcett, 2013; Murdoch & Detsky, 2013) there remains a level of data scarcity within academic analysis of such issues. Studies like the one presented here must rely upon the best data available – in this case, Census data and similar such healthcare, employment and accessibility data that is available at national levels – and the input and participation of experts and stakeholders.

Participatory research is best described as researchers engaging non-scientists in the scientific process. The premise is that the stakeholder or end-user has the domain knowledge that is required to understand fully the phenomena being examined and will benefit from the process, the model and/or the results. In many cases, the participants help to structure the problem, describe the system and help the researchers to understand the processes involved, and then, in participatory modelling, assist in creating a model, developing and testing policy interventions, and proposing amendments to the model one or more solutions.

ABMs have been at the forefront of participatory modelling due to the methods reliance upon explicit rules, the limited reliance on relatively complicated equations, and the increasing use of user-friendly GUI-based modelling programmes (*e.g.* NetLogo) (Lee *et al.*, 2015). In contrast, mathematical models and Systems Dynamics (SD) models are often too complex for non-experts to understand without significant training and can alienate collaborators (Habib, Lee & Memon, 2016). Further, the bottom-up approach of development used when creating an ABM, as opposed to the top-down approach most often adopted during SD modelling, is ideal for participatory modelling within NGOs, like the BRC, who work closely with communities and develop response programmes using similar bottom-up approaches.

As outlined above (section 2.2.5), ABM is particularly well suited for modelling interactions amongst autonomous agents and studying the emergent and adaptive responses with environments of different scales and in response to changing policies. However, a challenge when creating ABMs is obtaining enough domain knowledge to model a given phenomenon accurately.

Participatory modelling can help researchers to gain a greater understanding of the phenomenon under consideration and the processes involved through interaction with local stakeholders and domain experts. Simple, easy-to-understand models, designed in collaboration with the stakeholders have proven to be useful tools in domains such as planning (Berkhoff, 2007) and resource management (Robles-Morua *et al.*, 2014; van Eeten, Loucks & Roe, 2002; Mendoza & Prabhu, 2006). In addition, participatory modelling can slightly relieve the burden of data collection as the knowledge provided by experts and stakeholders can often replace data requirements or fill data gaps (Argent & Grayson, 2003). The participatory approach has been shown to increase motivation, ownership and engagement amongst stakeholders and facilitate decision-making, management, and consensus building (Voinov & Bousquet, 2010). This can lead to better academia-beneficiary relationships and future engagement.

Of interest for this study is the use of participatory modelling within the disaster and emergency response sector. Henly-Shepard *et al*. (2015) utilised a participatory modelling approach to facilitate disaster planning in response to the threat of tsunami in Hawai‘i. A community committee was setup that allowed the communities' dynamic nature to be understood by the researchers and modelled appropriately, tsunami hazard scenarios to be described, including potential direct and indirect effects, and the comparison and demonstration of community adaptation strategies and any trade-offs. The researchers were able to demonstrate the progression of model development and the associated social learning that occurred across individual to institutional levels, and over short- to long-term time scales. Similarly, Butler and Adamowski (2015) examined participatory modelling with a view to improve stakeholder engagement and inclusion within decision-making through group model building. The authors focused on engaging with marginalised communities and set forth recommendations for stakeholder identification, anti-oppression practices, problem framing, and workshop facilitation including: addressing power imbalances through improved communication and outreach to marginalised groups, involving stakeholders in the formation of the research process, and providing support to reduce barriers to workshop attendance.

Prell *et al*. (2007) examined participatory modelling in reference to socio-environmental systems, using a case study of water catchment management in the Peak District, UK. The researchers outline the complex systems involved (from hydrology, soil or atmospheric models to econometric and human-environment interaction models) and conclude that if such complex and dynamic models are to be accurately represented, then it is necessary to have those who interact with the systems in reality be involved in the modelling process. However, the authors note the considerable challenges that such requirements can place on research, namely increased model complexity and project length, uncertainty and funding. Similarly, Gurung *et al*. (2006) examined resource management in Bhutan, utilising a companion modelling and multi-agents methodology. Like Prell *et al*. (2007), the authors conclude that to simulate the complex systems and the institutional norms involved accurately, those actors involved must be consulted to ensure the accurate representation of their actions and interactions with one another and their environment.

Participatory research has been shown to reduce quantitative uncertainties in simulations through the inclusion of stakeholders and the utilisation of their domain knowledge to guide all aspects of modelling: from data collection and input to model calibration and validation (Ritzema *et al.*, 2010). The iterative participatory modelling process and the problem evaluation and discussions that come from such work have also been shown to benefit both researchers and participants through knowledge sharing and have proven useful methods of examining community disaster planning and adaptation (Henly-Shepherd *et al*., 2015) and natural resource management (Naivinit *et al*., 2010). The research presented herein aims to respond to the challenge of adequately collaborating with stakeholders and interested parties and using their tacit understanding to develop, refine and validate a model of flood vulnerability.

2.3 AGENT-BASED MODELLING

2.3.1 WHAT IS AGENT-BASED MODELLING

A methodology that is increasingly being utilized to examine many of the problems discussed in section 2.2 is agent-based modelling (ABM). ABMs simulate the relationships, interactions and exchanges between individuals *within* an environment and *between* the individual and the environment, unlike other microsimulations that lack these direct interactions, such as SDSS (Gilbert & Terna, 2000). It is this agent's perspective within ABM that is its distinctive quality and stands it in contrast to techniques such as DES or SDSS that focus on process or activity (Macal, 2016). Axtell (2000) argues that ABM offers significant benefits over standard analytical models and provides, potentially, the only way to explore processes systematically and examine the structure and dynamic properties of models as well as the dependence of results on the modelled assumptions and also be a source of unique information and counter-examples. ABMs can integrate data and theories from a range of different sources and, most importantly, at many different levels of complexity and analysis and can offer an insight into system trade-offs and efficiencies, or demonstrate the links between policies and concepts (Bruch & Atwell, 2015). The bottom-up modelling approach of ABM (in comparison to the predominantly top-down modelling approaches of SD, DES and SDSS) is better able to model the complexity inherent within emergency relief situations and the dynamics of human interactions and the hierarchical institutions and relationships involved (Ferraris, 2010).

To begin, it must be noted that there is ambiguity within the agent-based modelling literature with regards to terminology (Hawe *et al.*, 2012; Hare & Deadman, 2004). A specific definition of the term "Agent-based modelling" is somewhat elusive, with many competing and often contradictory definitions within and across disciplines (Hawe *et al.*, 2012). For example, as pointed out by Hawe *et al*. (2012), even within the context of emergency response simulation multiple terms are used: multi-agents system (Gonzalez, 2009), multi-agents simulation (Massaguer *et al.*, 2006), multi-agents simulation system (Takeuchi,

2005) and Agent-based simulation (Schoenharl & Madey, 2011). However, there is near consensus regarding three key elements that all ABMs must have:

- **Autonomy**: agents are not centrally governed and are able to process and exchange information with other agents to make independent decisions;
- **Heterogeneity**: each agent within the model can have their own properties, allowing for more aggregate phenomena to develop;
- **Activeness**: agents have independent influence on a simulation through proactive or reactive actions, perception of their surroundings, prior knowledge and on-going observation as the model develops.

Similarly, Epstein and Axtell (1996) refer to the "three basic ingredients" of an ABM: agents, an environment, and rules. Macal and North (2010) explicate, stating that a typical ABM consists of three elements:

- Agents endowed with attributes and behaviours;
- Relationships and methods of interaction between agents; and
- An environment that agents interact with in addition to each other.

ABM will be used as an umbrella term to cover most studies that create models utilising what Epstein and Axtell (1996) refer to as the "three basic ingredients" of ABM: agents, an environment or space, and rules.

ABM is a form of computational simulation that allows for 'the representation of complex systems into a simplified computational framework' (Sobiech, 2008: 2). It provides researchers with a way to develop theories and discover social mechanisms and patterns *in silico*, reducing the need for expensive and time-consuming primary data collection and real-world simulations (Gilbert & Terna, 2000; Sobiech, 2008; Hawe *et al.*, 2012). This is not to say that ABMs are not based upon empirical data. Researchers are increasingly using empirical data to inform and verify their assumptions and attempt to explain phenomena, not just recreate or predict it (see Silverman and Bullock, (2004), for discussion, or Grim *et al.*, (2012); Geard *et al*., (2013); Hills and Todd, (2008); Billari *et al.*, (2007);

Todd, Billari and Simão, (2005); and Aparico-Diaz *et al.,* (2011) for further examples).

ABM is distinct from other forms of modelling (numerical simulation, differential equations, stochastic simulations *etc*.) due to its focus on heterogeneous agents (Crooks & Heppenstall, 2012; Crooks, 2015). ABM provides the user with the ability to endow agents with abilities, knowledge, multiple decision-making strategies, and other heterogeneous properties and virtually simulate the interactions, decisions and consequences of changes to these agents characteristics (Anderson *et al*., 2007). ABMs can also include feedback mechanisms, something traditional micro-simulations often neglected to include or avoided due to computational limitations (Billari & Prskawetz, 2003). Similarly, ABMs can include formal networks whereby heterogeneous agents can not only interact with one another, but whose actions influence the behaviour and attributes of other agents and their environment allowing emergent behaviour to develop. This interaction between agents has been described as 'colliding' or 'overlapping, even 'messy', and compared more favourably to real life, compared to 'old-fashioned' macro-socioeconomic modelling methods (Macal & North, 2014). Instead of reducing complex systems to a small number of variables, modellers use ABM to replicate real life, including its randomness and lack of rationality. This ability allows for the study of complex societal phenomena and behaviour and theoretical hypothesis testing of previously observed macro-level processes (Diaz, 2010). Simply put, one does not develop an ABM that includes an aggregate representation of one million commuters in a city to uncover the impact on traffic congestion. Instead, in an ABM, one would create a model that includes one million 'commuters' and let them loose on a digital representation of the road network of the city being studied, each one with a home and work location[16].

[16] See the GeoMASON example model 'Gridlock' available here: https://cs.gmu.edu/~eclab/projects/mason/extensions/geomason/

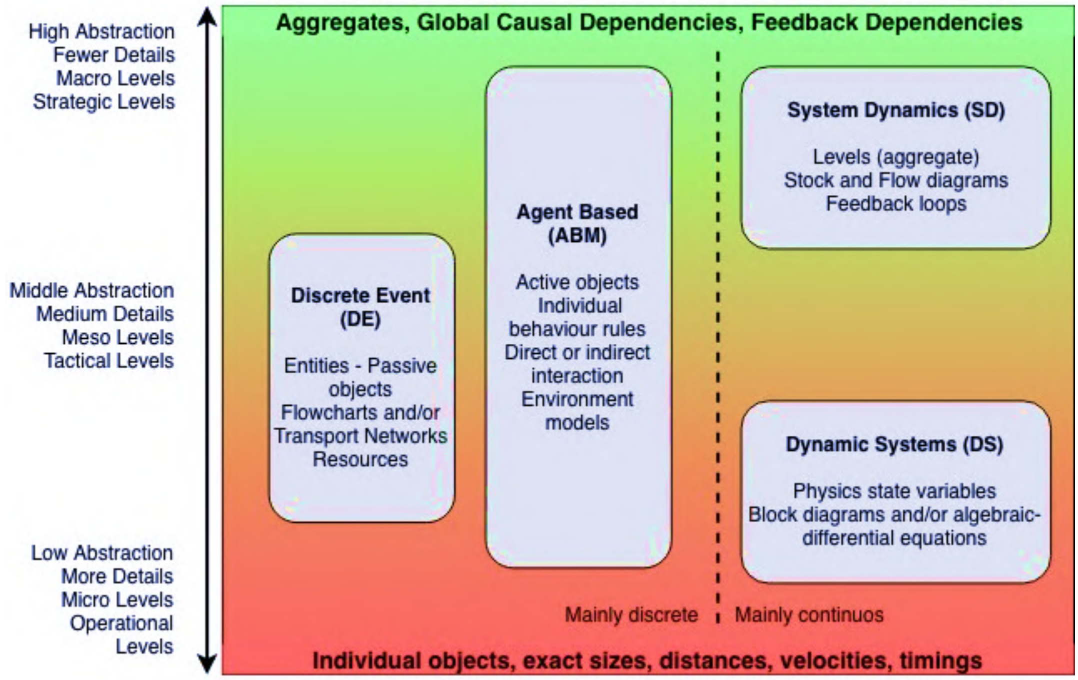


Figure 6: Abstraction Level and Scale of DE, ABM, SD and DS (adapted from Borshchev & Filippov, 2004)

ABM emerged from complex systems theory in the 1960s when interest turned to the dynamic relationships within environmental systems and between agents and the resultant changes in social structures (Perez & Dragicevic, 2010; Gimblett & Gimblett, 2002; Batty & Torrens, 2005; Yin, 2007; Hashemi & Alesheikh, 2013; Gilbert & Terna, 2000; D'Aquino *et al.*, 2002). As suggested by the name, it is the interactions between autonomous agents that is important within ABM. In an ABM, each agent is an autonomous decision-maker: individually assessing its situation and making decisions on the basis of a set of predefined rules and relationships (Crooks, 2015). Agents can be individuals, be it humans or animals, aggregated groups such as families or communities, inanimate objects such as vehicles, locations in space such as homes, businesses or regions, even biological cells (Menth, 2016). Agents and their behaviours represent the fundamental nexus of ABM and these behaviours can affect the behaviours of all agents as well as the wider modelled environment (Macal, 2016). This process allows for the emergence of aggregate behaviours from the micro-level (individual) actions to macro level phenomena and the production of complex systems of interactions over space and time (Comfort, 2004; Perez & Dragicevic, 2010; Macal et al., 2010; Marion, 1999; Ramalingam et al., 2008). It is these aggregate patterns that economists, epidemiologists, policy-makers *etc*. want to understand and in some cases change, for example the effects of economic policy changes on demographic groups, or the spread of disease under a range of healthcare initiatives (Bruch & Atwell, 2015). This ground-up development and emergence is what separates ABM from more traditional top-down modelling approaches (Menth, 2016). ABM allows researchers to examine both the implications of theory and the causal explanations of modelled phenomena (Macal, 2016). Even a simple ABM can exhibit complex behaviour patterns (see: Schelling's (1969) seminal segregation model Figure 7 and Appendix 10.5 for more information) and provide valuable information about the dynamics of the real-world system that it emulates (Bonabeau, 2002).

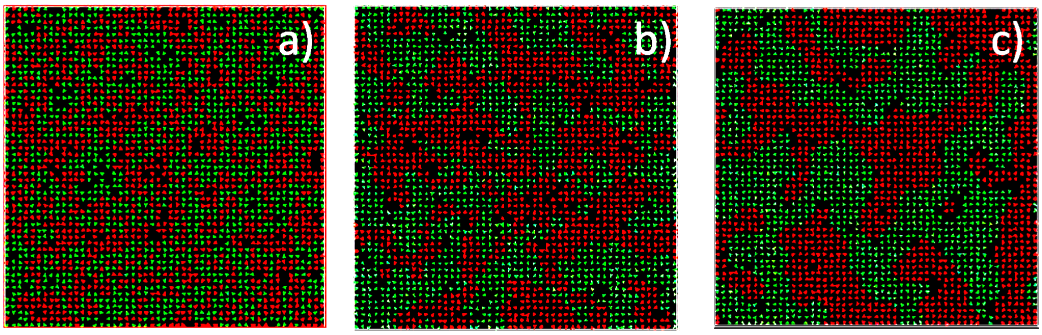


Figure 7: Example of Schelling's Residential Segregation model with household threshold preferences of similar neighbours at (a) 25%, (b) 33% and (c) 50%

These abilities make ABMs particularly adept at modelling social phenomena, such as vulnerability or migration, as multiple social mechanisms, agents' preferences, complex behavioural rules and social policies can be modelled and allowed to interact (Borshchev & Filippov, 2004). This intuitive way of modelling the linkages and human decision-making processes allows for a range of different scenarios and strategies to be tested and understood (Deffuant *et al.*, 2012). By performing parameter sweeps and running simulations an appropriate number of times with different parameter values each time, an understanding of how different model elements depend upon or impact each other and can improve our understanding of said elements and the emergency as a whole (Mysore *et al.*, 2006; Hawe *et al.*, 2012). A key benefit of ABM is its ability to account for the complex and often unpredictable actions of autonomous agents, making it a more suitable modelling choice to examine emergency relief operations over techniques whose focus is not stochasticity or multiple objectives or dynamic factors (Aakil *et al.*, 2012; Leiras *et al.*, 2014; Menth, 2016).

ABM has been utilised across a diverse range of topics and disciplines to examine and emulate social phenomena, but also physical and economic market phenomena, and has been shown to be useful in a number of contexts, including for example:

- supply chain management (Chen *et al.*, 2013; Swaminathan, Smith & Sadeh, 1998), cargo shipping and handling (Seibel & Thomas, 2000; Reis, 2018).
- retail store design and theme park capacity and demand (Bonabeau, 2000).
- consensus analysis and culture diffusion (Li *et al.*, 2016; Desmarchelier & Fang, 2016), 'flock' leadership (Will, 2016), cognitive science and psychology (Bedau, 2003; Smith & Conrey, 2007; Kennedy, 2012).
- social migration (Heppenstall *et al.*, 2012; Onggo, 2008).
- housing and social mobility (Ardestani, O'Sullivan & Davis, 2018; Patel, Crooks & Koizumi, 2018).
- energy demand and system flow (Barabási & Bonabeau, 2003; Tesfatsion, 2018), domestic water demand (Koutiva & Makropoulos, 2016) and nuclear power fuel cycle modelling (Huff, 2016).
- marketing (Rand & Rust, 2011), consumer markets and hiring strategies (North *et al*., 2010; Bonabeau, 2003b, Macal *et al*., 2010; Barabási & Bonabeau, 2003).
- traffic and pedestrian modelling (Helbing & Balietti, 2011; Wong, Chou & Yang, 2018), passenger terminal safety (Yatskiv *et al.*, 2016), transit station and classroom evacuation (Li *et al.*, 2016).
- natural hazard occurrence and response training (Carrera *et al.*, 2013; Fikar *et al.*, 2018), ecological changes and their impacts on wildlife (Railsback & Harvey, 2002).
- drug development (Barabási & Bonabeau, 2003), disease dynamics (Eubank *et al.*, 2004), public health (Tracy, Cerdá & Keyes, 2018),

epidemiology and the spread of infectious diseases (Hailegiorgis & Crooks, 2012; Carpenter & Sattenspiel, 2009; Eubank *et al*., 2004; Smiley *et al.*, 2012; Epstein, 2006).

- decimalization within stock markets (Bonabeau, 2003b; Darley and Outkin, 2007), finance and economics (Hamil & Gilbert, 2016; Farmer & Foley, 2009; Tesfatsion & Judd, 2006).

2.3.2 IMPLEMENTING AGENT-BASED MODELLING

AGENT-BASED MODELLING IN THE SOCIAL SCIENCES

Interest in understanding complexity in the social sciences goes back hundreds of years, with Smith's (1776) *The Wealth of Nations* representing one of the earliest discussions of the topic (Miller & Page, 2007). Economic, physical and social science researchers have since attempted to understand an array of complex adaptive systems, such as stock markets (Tesfatsion, 2003), manufacturing supply chains (Choi, Dooley & Rungtusanatham, 2001), social insect colonies (Theraulaz, Bonabeau & Deneubourg, 1998), terrorist networks (Ahmed, Elgazzar & Hegazi, 2005) and wars (Solvit, 2012). The use of ABM in social science research is not new (see Macy and Willer (2002) for a comprehensive review of early work and Gilbert (2008) and Borrill and Tesfatsion (2011) for slightly more contemporary reviews), but it is over the past 20 years that ABM has developed in both scale and power and its flexibility and focus on space, movable heterogeneous agents and emergent behaviour has led to its use in key social science domains such as environmental modelling (Parker, 2005; Parker *et al.*, 2012; Magliocco, 2012), gentrification (Jackson, Forest & Sengupta, 2008), traffic movement (Beuck *et al.*, 2008), pedestrian and crowd models (Johnasson & Kretz, 2012), pedestrians in urban centres (Haklay *et al.*, 2001; Schelhorn *et al.*, 1999; O'Sullivan & Haklay, 2000), large crowds (Batty, Desyllas & Duxbury, 2003) and emergency evacuation (Gwynne *et al.*, 2001; Roan, Haklay & Ellul, 2011; Wise, 2014; Uno & Kashiyama, 2008).

The study of emergent phenomena crosses the boundaries of most disciplines, particularly the social, political and economic sciences and the use of computational simulation, particularly ABM, is an increasingly common experimental method within the social sciences (Silverman *et al.*, 2013; Bonabeau, 2002). Axelrod (2003) and later Epstein (2006) argue that ABM is the third scientific method, in addition to inductive and deductive processes, and that the ability to grow artificial societies within an ABM and develop frameworks for explicitly specifying causal mechanisms that underlie societal models represents the prospect of a new Generative Social Science (Macal, 2016).

Deffuant *et al*. (2012) suggest that an ABM is best used when:

- individual behaviour within the model is central to defining the system's characteristics;
- the population being modelled is heterogeneous;
- the relationships and interactions between agents are complex, nonlinear, discontinuous, or discrete;
- space is a fundamental part of the model and the agents' positions are not fixed (for example, a simulation of traffic or pedestrian flow through a fire escape, theme park or supermarket);
- model scenarios are not easily or adequately represented within a statistical or mathematical model;
- agents need to exhibit complex emergent behaviour, learn or adapt (Bonabeau 2002).

Many of the social systems humanitarian organisations are concerned with, such as disaster response procedures, refugee communities and changes in community vulnerability satisfy all the above characteristics. The principal characteristic of such systems is their inherent nonlinearity and the disproportionate and unpredictable outcomes that can result from policy decisions and changing response procedures (Anderson, Chaturvedi & Cibulskis, 2007). The behaviours of such nonlinear systems are difficult to understand analytically and outcomes cannot be predicted using traditional equation-based mathematics (Gilbert & Troitzsch, 2005). Anderson *et al*., (2007:332) argue that "the only effective way of exploring the behaviour of such nonlinear systems is by building and running simulation models". Population groups affected by emergencies are, like all groups, heterogeneous and as will be shown throughout this review, their actions, needs and interactions are not easily defined, and thus not easily represented in traditional linear and/or discrete models. An ABM is capable of modelling the complexity of such social groups and systems by factoring in the knowledge of behaviours, motivations, and relationships among social agents garnered from the wider social sciences and then the macro-level outcomes and emergent phenomena that emerge from the individual interactions within a set space can be determined and examined.

It is the ability to describe populations across a range of levels - from individuals to whole societies - and across all geographies - from households to nations – and assign micro- to macro-level interactions across all that makes ABM an appropriate and increasingly common method for examining population phenomena and addressing policy challenges (Courgeau, 2007).

AGENT-BASED MODELLING AND DEMOGRAPHY

Building upon the early agent-based sociological modelling of, for example, Epstein and Axtell (1996), computational demography and the use of ABM within social simulation developed in the 2000s. Led by Billari *et al*. (2007), who utilised ABM to study the cultural evolution of marriage age norms across generations and gain a greater understanding of societal-level dynamics of life-course norms, agent-based demographic studies quickly began to be applied to major sociological areas of interest: migration (Heiland, 2003; Kniveton, Smith & Wood, 2011; Willekens, 2012) household dynamics (Billari *et al*., 2007; Benenson *et al*., 2003; Geard *et al*., 2013), societal sustainability (König, Möhring & Troitzsch, 2003), and socio-sexuality and mating (Mata, Wilke & Todd, 2005). Gilbert and Troitzsch (2005) and Courgeau (2007) presented early reviews of the then state of the art uses of ABMs and multi-level multi-state modelling respectively within social simulation. Later, Silverman *et al*., (2011) proposed that ABMs could provide a way for demographers to gain a greater understanding of demographic change processes without having to rely upon immense datasets. The authors argue that modern demography is beset by three challenges:

1. The need for analysis to operate across a range of levels (from individuals, through households and different geographies, to whole societies) to

describe the increasingly complex world and population phenomena correctly and address policy challenges appropriately (see: Courgeau, 2007; Willekens, 2005; Zinn *et al*., 2009). Problems with the assumptions made about the homogeneity of systems at multiple scales within models have been highlighted by several researchers (Borrill & Tesfatsion, 2011; Bansal, Grenfell & Meyers, 2007; Jones *et al.*, 2007) as well as the problems of representing adequately cognitive complexity within computational demography (Chattoe, 2003).

2. The need to link statistical data with rare, or simply unavailable, demographic data to examine future multidimensional demographic trajectories and processes. A particularly acute problem is the cognitive "preferences" that are designed within demographic models that are not based upon empirically measured data, for reasons of availability or modeller knowledge, but are instead inferred from assumptions of behaviour.
3. The desire to build demographic models on increasingly complex, cross-sectional, multi-dimensional and longitudinal empirical data and the need to balance this complexity with the constraints of model processes (statistical, qualitative *etc*.) and data availability/usability.

Data availability, or the lack thereof, links all three challenges. In an ideal world, demographic models would rely on foundational empirical data to create social simulations. However, we must acknowledge that, in many cases, the data is not available and what is available often comes with restrictions in terms of use or applicability. It must also be noted that, even if data was available, the modelling processes needed to examine, utilise and present it adequately to address any demographic question would increase vastly the complexity of the model and open it up to problems of manageable scale (Chattoe, 2003). Thus, the modeller must balance the desire for empiricism with the desire to limit complexity.

Silverman *et al.* (2013) present a substantive step toward the integration of statistical demographic methods within ABM and to address the three challenges the authors presented in their earlier work (Silverman *et al*., 2011).

The authors present a proof-of-concept model of partnership formation and changing health status over the life course. The work presented allows for the study of linked individuals across various levels, can be easily adapted and embedded in to different social or physical spaces, and statistical emulators used allow for the easy exploration of the underlying parameters of ABM. The authors argue the work overcomes some of the data-related limitations of the available statistical demographical data, but the method presented relies upon assumptions of behavioural rules and somewhat basic restrictions, such as a limit on divorce, the presence of children only permitted in households, and agents automatically leaving the parental home and moving to a new house when a partnership is formed. Further, the model relies upon the rudimentary "checkerboard" grid environment (specifically a 72-by-72 square grid) and the authors espouse the complexity of their underlying model, but do not validate it, stating the "task is non-trivial and extends far beyond the scope of this paper" (pp. 14); a common limitation of ABM studies and one regularly affirmed by its critics (Pullum & Cui, 2012; Fagiolo, Windrum & Moneta, 2006; Windrum, Fagiolo & Moneta, 2007; Fagiolo, Birchenhall & Windrum, 2007).

REALISM IN AGENT-BASED MODELS: ABSTRACT, SIMPLE, AND HIGH DIMENSIONAL SIMULATIONS

Realism and abstraction are important issues within ABM. An abstract ABM includes agents defined by a single attribute that reside within a grid-based environment and have simple deterministic rules governing their movement and interaction. A simple ABM may retain the grid-based environment, but agents and the environment are endowed with multiple attributes and behaviours that are built upon empirical data. A high dimensional ABM consists of agents endowed with a great many attributes and behaviours that may adapt over time and can be determined by changes in, and interactions with, the environment. Again, a high dimensional ABM may retain the grid-based environment, but it is increasingly likely that the environment will include a range of attributes that may respond dynamically throughout the model process and is likely to be a more realistic visualisation of the area being modelled. When micro-level behaviours are known or assumed and a simulation is needed to explore the aggregate effects, or when a phenomena is observed empirically and the model aims to examine alternative explanations, a low-dimensional realism model may be effective (Bruch & Atwell, 2015). When the goal of the simulation is to explore behaviours under hypothesised social conditions, then a high-dimensional realism model may be more appropriate (*ibid*). More information on realism and abstraction within ABMs and case studies are available in Appendix 11.5.

In areas of public health (particularly epidemiology) and urban studies (particularly pedestrian movement and evacuation), the majority of ABMs are highly realistic simulations of scenarios and locations (Bruch & Atwell, 2015). These models may include, for example, demographics information, real-world geography and empirical data to support movement, decision-making and options. In many other areas of social science research however, most ABM are not designed to realistically replicate real-world situations or predict outcomes, but are used to explore the mechanisms within systems, the robustness of those mechanisms under change and identify key relationships among model parameters (*ibid*).

That is not to say that if the goal of a model is to explore the robustness of a system's mechanisms that the model cannot be highly realistic, or if the goal is to predict the outcomes of policy changes on a system that the model cannot be abstract or simple. The appropriate level of abstraction and realism depends upon the intended use of the model, the data available, and its audience. Increasing the level of detail within a model, and thus its complexity, is not desideratum *per se* (Hawe *et al*., 2012; Evans *et al.*, 2013). The modeller must aim for an optimal zone of complexity, structural realism, and usefulness (as well as availability of resources, time *etc*.); or what is often referred to as the 'Medawar Zone' (Grimm *et al.*, 2005). As described by Grimm *et al*., (2005): if model design is guided only by the problem to be addressed (which often is the explanation of a single pattern), the model will be too simple. If a model is too simple, it neglects essential mechanisms of the real system, limiting its potential to provide understanding and testable predictions regarding the problem it addresses. If model design is driven by all the data available, the model will be too complex. If a model is too complex, its analysis will be cumbersome and likely to get bogged down in detail. There is a zone of intermediate complexity where the payoff is high: the "Medawar zone".

Bazzan and Klügl (2014), in their review of agent-based technology for traffic and transportation noted a marked increase in the level of complexity of traffic related ABMs, likely in response to the increasing complexity of global transportation and traffic systems. The authors point to multi-level models (van Katwijk *et al*., 2005; Langley & Choi, 2006; Anderson *et al*., 2004; Laird, 2008; Franklin *et al.*, 2007) that integrate and visualise agents, environments and relationships at different levels of representation in the same model with respect to time, space and behaviour (Bazzan & Klügl, 2014). Many of the models are high dimensional simulations that aim to recreate a realistic representation of traffic and are thus highly complex models. The authors point to the growing use of Graphics Processing Unit (GPU) computing to improve computational performance and viability (in terms of increase in scope and decrease in computing time) of increasingly complex ABMs (Strippgen & Nagel, 2009; Oliveira *et al.*, 2016; D'Souza, Lysenko & Rahmani, 2007).

When examining an ABM, we must remember that the level of abstraction does not relate to appropriateness or validity: a simple ABM built upon a limited number of parameters and dimensions can be grounded with empirical data and a highly dynamic model aimed at examining a complex social phenomena can be built entirely upon anecdotal evidence (Bruch & Atwell, 2015). Validation is also discussed in section 7.4.6.

Figure 8: Applications of Simulation Modelling: Abstraction and Scale (adapted from Borshchev & Filippov, 2004)

EMPIRICALLY GROUNDED AGENT-BASED MODELS: BEHAVIOUR & CHARACTERISTICS

ABMs should be designed to examine a specific question and as such the level of empirical realism within the model depends upon the analytical goals of the researchers (Bruch & Atwell, 2015). Simple ABMs that are empirically validated can be used as “virtual laboratories” (Heppenstall *et al.*, 2012; Gilbert & Troitzsch, 2005) to explore the impacts of policy decisions on synthetic populations, predict future changes in a population’s demographic makeup or examine individual or group decision-making (Bruch & Atwell, 2015).

A number of reviews are available that show that abstract ABMs greatly outweigh more empirically-grounded models within academia (Macy & Willer, 2002; Sawyer, 2004; and, more recently, Squazzoni, 2012). Casini and Manzo (2016) argue this is undoubtedly due to the foundational work that introduced ABM to the social sciences (*e.g.* Sugarscape (Axelrod, 1997) *etc*). However, the authors do point towards a growing trend for calibrated, validated and empirically-orientated models (see: Bianchi & Squazzoni, 2015; Boero & Squazzoni, 2005; Hassan *et al*., 2010). In their meta-analysis of ABM literature, Casini and Manso (2016) identify three distinct sub-trends:

1. "**theoretical realism**" – models built upon common-sense understanding of relationships and/or informed by existing theoretical and empirical literature in sociology, psychology;
2. "**empirical calibration**" – models built upon empirical/experimental information; and
3. "**empirical validation**" – models built upon empirical information used to assess the realism of the model's macroscopic consequences (Casini & Manzo, 2016).

Although such models are increasing in frequency, the authors note they are still a minority within the wider ABM literature.

Simple models can be created that do not aim to reproduce societal phenomena exactly, rather they are used to develop theory and new ways of thinking about a problem or existing empirical knowledge (see: Willer *et al.*, 2009; Centola *et al*., 2005; Centola & Macy, 2007; and Epstein, 2009 for examples of such computational sociology).

Such "virtual laboratories" are not limited to simple models and can be developed as advanced high dimensional, policy-driven simulations. The characteristics and behaviours of agents, and to a lesser extent the environment, within an ABM can be built upon a range of empirical measures, including, for example (Herrera-Restrepo & Medina-Borja, 2018):

- demographic composition (age, sex, mortality, employment status *etc*.);
- individual and group preferences (voting results, sales and marketing figures *etc*.);

- behaviours (crime and marriage rates, attraction attendance *etc*.);
- the ability to discern changes amongst agents and the environment (agents' movement, climate, housing *etc*.);
- network structures (social, transport, managerial *etc*.); and
- geographic boundaries and spatial relationships (voting constituencies, geological regions, species distribution *etc*.).

It is critical to create empirically defensible ABMs (Hedström & Åberg, 2005) and the inclusion of the above measures improves the empiricism of models and allows for detailed examination of the impacts of policy changes. Further, the use of ethnography, observation and participatory assessments allows for agents to be assigned empirical real-world beliefs, values and philosophies that can guide decision-making (Yang & Gilbert, 2008; Geller & Moss, 2008). More complex models can also include limited or extensive memory of past individual or group actions to guide agents' behaviour and decision-making. For example, the addition of heuristics – rules of thumb for making decisions under conditions of uncertainty (Lichtenstein *et al.*, 1982) – that update an agent's predefined behavioural rules based upon the accumulation of experience (Todd *et al.*, 2005) or are combined with weightings of desirability of outcomes (Ogawa, Geller & Wallace, 2015) can improve the realism of agent processes. See Appendix 11.5 for further information on empirically ground ABMs.

AGENT-BASED MODELS AND EMERGENCY RESPONSE

The use of ABM in emergency relief and humanitarian research is relatively new and few studies exist within the literature (Menth, 2016). Of those that do exist, focus has been primarily on logistics and supply chain management or asset location. For example, Zhao *et al*., (2012) simulate inter-organisational collaboration networks amongst humanitarian agencies, Altay and Pal (2014) examine the role of information sharing between management personnel during humanitarian responses and Turner *et al*. (2011) employ ABM to analyse optimal resource placement and in post-disaster humanitarian missions. ABM's ability to capture emergent phenomena makes it a valuable modelling tool when examining emergencies, particularly when the movement and actions of large populations are key to a simulation (Bonabeau, 2002). Challenger *et al*. (2009) and Lin and Manocha (2010) point to the need for such large-scale population simulations and conclude that intelligent and autonomous agents are essential to realistic simulations and that ABM is a key part of the most realistic simulations.

Bonabeau (2002) and North and Macal (2007) both describe how ABM is a suitable method for emergency response and preparedness modelling as it captures emergent phenomena that are of great interest to responders; provides a natural description of the system being simulated; and is highly flexible. Hawe *et al*., (2012) build upon the reviews of Bonabeau (2002) and North and Macal (2007), suggesting that ABM offers advantages over other simulation techniques when examining emergency response and preparedness, namely systems dynamics, discrete-event simulation, stochastic modelling, and queueing networks, as many emergencies involve the presence of crowds (Samuelson *et al.*, 2008; O'Guz *et al.*, 2010; Lin & Manocha, 2010; Challenger, Clegg & Robinson, 2009) and that ABMs populated with intelligent, autonomous, decision-making and reactive agents represent the state-of-the art for emergency simulation. The authors found that the use of agent-based simulations for emergency response and relief management has increased over the past ten years. Focus was on the "planning" and "pre-preparedness" stages, with past emergencies used to calibrate models and replicate real events, and then used to determine optimal response procedures after the fact (Hawe *et al*., 2012). The usage of such models was found to fall in to two groups:

1. Training
    a. Development of decision-making skills as scenarios are played out with the results of user decisions affecting scenario outcomes.
    b. Development of operational skills through the simulation of adequately designed operational networks and procedures.
    c. Enhancement of motor skills through use of simulated equipment.
2. Experimentation, learning and decision support (O'Ren & Longo, 2008).

ABMs are also used in the "Vulnerability analysis" and "Identification and detection" stages and build upon threats that have been highlighted in, for example, the National Risk Register (U.K. Cabinet Office, 2010; Hawe *et al*., 2012). As identified in the National Risk Register, the greatest risks to the UK are "attacks on transport", "attacks on crowded places" and "pandemic human disease", each of which have been shown to be well modelled using ABM (Challenger *et al*. 2009b; Epstein 2009).

GEO-SPATIAL AGENT-BASED MODELS

Geospatial ABMs are a small, but growing, subset of ABMs (Cioffi-Revilla, 2009; Crooks & Castle, 2012; Latek *et al*, 2012; Heppenstall *et al*, 2016) and the integration and coupling of ABM and GIS has relevance to many geographical studies and problems (see Crooks & Castle (2012) for a review). Axtell *et al.* (2002) review the combination of ABM and GIS and the range of models and outputs; from integrated systems, to abstract expressions of space and time. An (2012) presents a more contemporaneous review, examining various agent-based models for the examination of coupled human and natural systems (CHANS) and concludes by advocating for the development of more process-based decision-making models, protocols or architectures. ABMs are not traditionally spatially explicit, preferring an organisational structure. The majority of geospatial models utilise a spatial element but are not geospatially referenced with real-world geography, for example Schelling's segregation model (1971) that represents a city as a grid, or simply utilise GIS data for model initialisation or output (Cioffi-Revilla, 2009). Fully geospatial models, such as the wildfire evacuation model presented by Wise (2014), represent landscape elevation, vegetation and a road network for the city of Colorado Springs, USA that is utilised and interacted with by agents within the model. The use of real-world geography in such models is essential to understanding how agents interact with their environment and how the elements of the geographic system evolve (Batty & Torrens, 2005).

Although the need to integrate GIS and ABM is encouraged by many (Gimblett & Gimblett, 2002), several conceptual and technical issues concerning current practices do exist. For example, determining the appropriate resolution and the level of aggregation in raster (the map area subdivided into grid-cells) simulations is a challenge (Griffin & Stanish, 2007). Format conversions also cause difficulties (Hashemi & Alesheikh, 2013). Many studies, the one presented here included, are utilising vector data (map features represented as points, lines, and polygons and defined by their XY coordinates) and the associated data layers and attribute tables to incorporate many aspects of real-world geography (Hammam *et al*., 2007; Moreno, Wang & Marceau, 2009; Crooks & Wise, 2011; Wise & Cheng, 2015).

GEO-SPATIAL AGENT-BASED MODELS & EMERGENCY RELIEF

There are relatively few studies within the ABM literature that focus on emergency response and relief, unlike the DES and SDSS literature where examples are more prevalent (Menth, 2016). Those studies that are available are not especially spatial in nature (*e.g*. Salgado *et al*., (2010)). Fiedrich and Burghardt (2007), and later Crooks and Wise (2011) and Albano and Sole (2018), argue that there is great potential for geo-spatial ABMs to assist emergency responders, particularly in the areas of logistical support and community response to natural disasters. Such research is still in its infancy (Crooks & Wise, 2013; Mishra, Kumar & Hassini, 2018), however a number of recent innovative models that address community functioning and emergency response and range from pre-, to through-, and post-disaster assessments are available. The complexity of such models ranges from conceptual models that examine organisational structure during emergencies to complex models that are used for prediction (Mishra, Kumar & Hassini, 2018).

One common trait noted amongst past studies of emergency relief is the misrepresentation of populations as homogeneous entities, temporally restricted or lacking dynamic interactions that make up everyday life (Crooks & Wise, 2013). For example, Kaplan *et al.* (2002) use mathematical modelling (queuing) to model the spread of smallpox through a large US city following a bioterrorist attack, comparing the success of isolated vaccination versus mass vaccination over time, but spatial dynamics are not examined. Hoard *et al.* (2005) used

Systems Dynamics to study the influx of patients in to a rural hospital following a disaster but focused on temporal dynamics and disregarded spatial dynamics. An 'agentised' approach lends itself to the capturing of micro- and individual-level interaction and stochasticity (Axtell, 1999). The combination of GIS and ABM has the potential to assist emergency responders and logisticians to understand the complexities of emergencies (Fiedrich & Burghardt, 2007) and offer a better insight in to how an emergency may develop by utilising the key aptitudes of each technology: spatial analysis for GIS and the capturing of emergent phenomena and interaction within a complex system for ABM (Crooks & Wise, 2013). Further, grounded ABMs that are able to be applied to the problems facing the emergency response sector can help to progress the geospatial ABM field and assist the emergency operations community (Menth, 2016).

Several studies have integrated ABM and geospatial data into models of complex urban problems (Benenson, Martens & Birfir, 2008; Turner & Penn, 2002) and natural ecosystems and phenomena (Nute *et al.*, 2004; Parry, Evans & Morgan, 2006). This integration of geospatial data is needed within emergency relief and response modelling as the spatial dimensions of an emergency or disaster play a key role in the type, extent and location of response procedures (Hashemi & Alesheikh, 2013). ABMs are particularly well suited to examining crises and emergency relief operations (Crooks & Wise, 2013). Agents within ABMs can be assigned heterogeneous attributes but also spatial heterogeneity, allowing for populations to move, adapt and react to each other and spatial changes. For example, studies have aimed to integrate GIS and ABM within the emergency management sector by 'agentising' evacuation models to add greater realism to their models (*e.g*. Thorp *et al.*, (2006)). A modeller can examine such complex geographical phenomena and systems, such as crowd evacuation, by using ABM to generate possible future scenarios, rather than definitive predictions, which is challenging (Batty & Torrens, 2005), thereby acknowledging, incorporating and highlighting the uncertainty inherent within such systems into their work (Epstein & Axtell, 1996; Heppenstall *et al.*, 2012).

Within emergency response and relief work, two approaches are regularly utilised to recreate and test emergency scenarios and response procedures: simulations and training (Massaguer *et al.*, 2006). ABMs allow for scenarios to be simulated and adapted and response procedures (modelled agents roles and interactions) to be refined in a safe and reasonably inexpensive way before real-world resources are utilised (Robinson & Brown, 2005). The safe and easy testing of theoretical assumptions and concepts of human behaviour (Stanilov, 2012) is the primary strength of ABM for this project (Crooks, 2015). For example, earthquake emergency planning, which includes the identification of evacuation zones and suitable sites for equipment and resource storage as well as the calculation of the amount of resources that may be required (Stanganelli, 2008), is a lengthy design and testing process. ABM is an effective way to test multiple scenarios and assess the reliability of plans (Tang & Wen, 2009; Taniguchi, Thompson & Yamada, 2010; Coburn & Spence, 2002; Hashemi & Alesheikh, 2013).

Crooks & Wise (2011) developed a spatially explicit ABM that utilised a range of geospatial datasets and crowdsourced geographic information to simulate where people search for food and how aid may have been distributed in the city of Port-au-Prince, Haiti following the January 2010 earthquake. Crooks and Wise (2013) further developed the model to simulate the movement of individuals and the spread of information about aid availability. The models produced explore the impact of aid distribution locality on a population as well as the propagation of rumours relating to aid availability through the affected population and, the authors argue, could provide a valuable link between the socio-cultural information about those affected by an emergency and the relevant emergency relief operations.

Similar in context to the work of Crooks and Wise (2011; 2013), Turner *et al*., (2011) developed an ABM to help analyse the importance of the size, number, operating time, and placement of resources dispensaries and processing centres in the response efforts following the Haiti earthquake. The authors incorporated a number of demographics-related elements that Crooks and Wise did not, namely the socio-economic attributes and ethnic makeup of the population and crime rates. However, the model produced focuses on organisational structure and, unlike Crooks and Wise (2011; 2013), is not spatially explicit.

The majority of emergency relief and disaster modelling has focused on the simulation of *post*-disaster scenarios and relief management. Sobiech (2008), in contrast, focused on the dynamics of *pre*-disaster scenarios and developed a conceptual agent-based vulnerability model. To the author's knowledge, this is the only examination of vulnerability using ABM and within the context of an emergency. However, the model presented is generic in focus, with no specific location, hazard or population, but the author notes that it could be adapted to coastal hazards.

Zagorecki *et al*. (2008; 2010) developed an ABM focusing on the specific issue of information exchange and organizational cooperation during emergency situations and conclude that flexible communication and information sharing between agents, particularly the lowest level agents, leads to a more efficient response. Similarly, Kostoulas *et al* (2008) examined the reliability of information in disaster relief operations, concluding that the spread of unreliable information is highly prevalent. Miles and Chang (2006; 2011) examined the recovery of critical services and community capital following a disaster, integrating focus group and participatory modelling methods to improve model development.

In comparison to Zagorecki *et al*. (2008) who focused on a single aspect of emergency management to examine best practices, models like the Life Safety Model (Lumbroso and Tagg, 2011) or MASSVAC (Hobeika and Jamei, 1985), for example, are complex simulations aimed at predicting evacuation times or expected loss of life. Similarly, Dawson *et al*. (2011) developed a detailed flood incident management model to determine flood risk under a number of hydrological, defence and evacuation scenarios. The model includes affected citizens as agents and simulates their movements in response to flood warnings and relies exclusively on publicly available datasets to increase its adaptability and usage outside of the case study example. Although, disaster management organizations are not represented, the model does demonstrate that ABM can "provide insights not obtainable from other methods" Dawson *et al*. (2011:186) and offers an operational tool for guiding the design of flood incident management plans.

Scale is an important aspect of emergency management and modelling. However, classification terminology differs across sectors and locations and between organisations. Berren *et al*. (1980) developed a five-dimensional classification that was different to de Boer's (1990) multi-dimensional disaster severity scale, which in turn was different to Gad-el-Hak's (2009) classification of disaster severity (Hawe *et al.*, 2012).

A 'large-scale' disaster in one country may be considered 'small' for a large city. Scale is a relative term that can, for example, denote the number of those affected/killed, the size of the geographic area affected, or the 'impact' on those affected in terms of a socio-economic indicator. Gad-el-Hak's (2009) classification of disaster severity examined both the size of the geographic area impacted *and* its 'impact' through the total number of those displaced, injured or killed when ranking events. A similar system is used by the UK Cabinet Office when classifying emergencies (U.K. Cabinet Office 2010b). The UK ConOps classification system uses both geographic scale and a generic 'impact' dimension to classify emergencies as either 'significant', 'serious' or 'catastrophic'. From analysis of recent events classified as 'serious', the number of fatalities appears to be the defining factor in 'impact', despite the numbers often varying by orders of magnitude[17]. However, it is possible that politics plays a part in the classification, with terror related events receiving greater attention, or event economics, with the huge cost of floods requiring a 'serious' classification to make governmental funds and resources available (Rodríguez-Espíndola & Gaytán, 2015).

[17] For example, the 7/7 London bombings in 2005 killed 56 and injured 700), the 2007 floods caused 13 fatalities and affected tens of thousands, and the 2009 H1N1 flu pandemic which led to the deaths of 300 infected thousands, were all categorized as 'serious' under the ConOps classification (Hawe et al., 2012).

AGENT-BASED MODELS AS DECISION SUPPORT TOOLS

It is not uncommon for decisions and policies in business, management and assistance to be *ad hoc*, based on past experience, and/or plagued by uncertainty. Stochasticity, a lack of domain knowledge, limited understanding of the homogeneity of agents, and inadequate computing capacity are several oft-cited reasons for a lack of modelling (Vermeulen & Pyka, 2016). However, modern modelling systems and increases in computational power at low costs means that ABM can support decision-making by simulating known processes and behaviours and exploring potential outcomes from strategy decisions. ABMs allow for the study of a system's underlying dynamics despite ill-defined behavioural rules (heuristics) or uncertainty across many modelling aspects (Lempert, 2002). Moreover, object-oriented programming and the discretization of systems within model environments means that large systems can be built upon an array of past models and implemented largely disaggregated and unabridged (Boero & Squazzoni, 2005). As demand for optimised decision support systems increases (Serova, 2013) and the systems being modelled become increasingly complex and built upon numerous decentralised and independent processes, ABM and multi-method approaches are becoming leading simulation methods of choice. ABMs should be used to abductively formulate hypotheses of agents' behaviour as cause for empirical realities (Axelrod, 2007; Brenner & Werker, 2007).

The "what if" questions that are often at the heart of management needs can be addressed through ABM and related multi-method decision support systems. Such systems allow for adjustments to parameters and the subsequent impacts on whole systems to be modelled, making more informed decisions possible (Taboada *et al.*, 2011). Model uptake and practical use outside academia is not high, likely due to the inherent uncertainty within modelled results and the lack of concrete recommendations from models, but it is increasing (Taylor, Coll Besa & Forrester, 2016). A way to improve the use of ABMs within the "real world" is to use participatory methods and include stakeholders within the model development process (*ibid*). Improving the utility of ABMs will lead to increases in reliability and trust of model outputs, further improving their use as decision support tools and utilisation by policy advisors.

Policy makers and advisors often require timely solutions that work within existing policy settings. While some ABMs are often bespoke, complex, multidimensional and produce disaggregated outputs that are not easily transferrable, the assessments that are increasingly needed by decision-makers require such models (Forrester *et al.*, 2016). ABMs shine in such instances due to the complexity and context that is possible and often unavailable in other modelling approaches (Taylor, Coll Besa & Forrester, 2016). ABMs allow for policy trade-offs, micro- and macro-level priorities and policy/project interdependencies to be explored across different temporal and spatial scales – such versatility is valued by decision-makers.

AGENT-BASED MODEL OUTPUTS, UNCERTAINTY, VARIABILITY & SENSITIVITY

To support the assertions drawn from one's model adequately, it is necessary to assess variance stability in the model's outputs as well as its impact on both model design (sufficient number of simulations) and the analysis performed (hypothesis testing, clustering, prediction *etc*.).

Stochasticity within a model allows the model process to unfold in a probabilistic manner, rather than a deterministic one. Put simply, stochasticity represents anything within the model that changes from run to run that is not an explicit part of the model design (Groff, Johnson & Thornton, 2018). Randomness within model elements influences agents' behaviour, interactions and model outputs. Randomness can be incorporated into many parameters, variables or other model components and, as a result, ABMs can be used to examine nonlinear relationships across multiple levels and, as such, ABMs are often more flexible and can address a broader array of research questions than traditional analytic approaches (Tracy, Cerdá & Keyes, 2018).

Assuming a model is stochastic, outcomes for the same model will vary across runs. Within most ABMs, agents and their decision-making processes are autonomous and the stochastic model components of actions, interactions and decisions means that each time a model is run, its results represent one potential realisation of the interactions in the model (Groff, Johnson & Thornton, 2018). Multiple runs of the model with variations in each condition or parameter will produce variations in outcomes (Groff, Johnson & Thornton, 2018). Typically, ABMs are run multiple times to examine the effects of chance and uncertainty and to average out the effect of stochastic variation within model elements. Sensitivity testing and validation methods are then used to evaluate the plausibility and accuracy of those model results. Sensitivity analysis and model run/sample size information is discussed in more detail in section 7.4.3, and the validation methods used are discussed in section 7.4.6.

The outputs of ABMs are more often than not a range of scenarios with measured and unmeasured uncertainty (Clarke, 2013). A typical stochastic ABM is run multiple times with pseudo-random sequences (most likely utilising a pseudorandom number generator, such as *Mersenne Twister* (Matsumoto & Nishimura, 1998)) to test hypotheses and distinguish between multiple model scenarios under varying parameter settings (Lee *et al.*, 2015). Thus, a high volume of output data is often produced that requires statistical analysis and visualization (*ibid*). In terms of geospatial ABMs, outputs are often maps showing movement or likelihood of the phenomenon being examined. For example, the output of Crooks' and Wise's (2013) research into post-disaster humanitarian modelling produces as output a map showing the movement of individuals throughout the environment and the spread of information about aid availability throughout the modelled population, as well as graphs and statistics tracking agents' activity and the utilization/status of aid centres over time and the overall health of the population. Similarly, the MAXENT model of species distribution (Phillips, Anderson & Schapire, 2006; Phillips, Dudík & Schapire, 2004; Phillips *et al.*, 2009), includes a map of species presence likelihood as output.

There are three main sources of uncertainty and variability within ABMs:

1. **Input uncertainty** – or *epistemic uncertainty* (Berger & Troost, 2014) – is primarily concerned with the architecture of the model (Bruch & Atwell, 2015) and arises from vaguely defined, incorrectly measured or unknown

empirical measures; an incomplete knowledge of key input parameters or processes; data measurement and transcription errors; inappropriate sample sizes, missing data, and classification discretisation error; and/or unverifiable assumptions of systems and agents interactions (see: Evans, 2012; Helton *et al.*, 2006; Saltelli *et al*., 2004; A. Saltelli *et al.*, 2008; Marino *et al.*, 2008; also Zhang & Goodchild, 2002) for a an overview of spatial data uncertainties). Input uncertainties are commonly assessed via Monte Carlo sampling procedures and systematic examination of model output distribution following variations in the model's inputs (see: Saltelli, 2002; Saltelli *et al.*, 2004; Saltelli *et al.*, 2008; Segovia-Juarez *et al*., 2004; Dancik *et al.*, 2010; Riggs *et al.*, 2008; and Marino *et al.*, 2008) for details on statistical and sensitivity analysis techniques and model assessment).

2. **Model uncertainty** is primarily concerned with model choice, such as errors in variable choice, model representation and scale, and the choice of parameters (see: Evans, 2012), as well as the assumptions about functional forms within the model, the sequencing of events, initial agents distribution, and the definitions of units of analysis (Bruch & Atwell, 2015). ABMs are particularly sensitive to initial model conditions and setup, and to small variations in interaction rules (Couclelis, 2002; Batty, 2012). It is possible that uncertainty associated with each step of the model process can propagate through each model step (Tate, 2013). In addition, errors in the model mechanics and programming errors (bugs in the code) and errors in data representation (digital imprecision - see: Walker *et al.*, (2003) and Beißbarth *et al.*, (2004) for discussions on avoiding such errors in general programming, and Izquierdo & Polhill, (2006) and Galán *et al.*, (2009) for specific ABM consideration). Model uncertainty can be examined through, for example, the testing of model assumptions and model architecture and their effect on model outputs or Bayesian model averaging whereby all possible model parameters are averaged and the robustness of results to alternative model specifications is analysed (see: Raftery, 1995; Hoeting *et al*., 1999; Toni & Stumpf, 2009; Sisson *et al*., 2007).
3. **Stochastic variability** relates to the variation in model outputs due to randomness within the model (Bruch & Atwell, 2015). Most ABMs include

a level of stochasticity in their design when, for example, agents are making movement decisions. This results in a fluctuation in model outputs from one run to the next (Bruch & Atwell, 2015). Stochastic variability can be reduced by averaging the distribution of estimated output values for a given set of input values across a suitable number of model runs (Marino *et al.*, 2008). See section 7.4 for further discussion on verification and validation.

The outputs and underlying dynamics of ABMs can be illustrated using a plethora of standardized descriptive statistics (central tendency, measures of variability, variance and standard deviation), statistical tests (t-test, multiple regression, clustering *etc*.) (Saltelli, 2002; Saltelli *et al.*, 2004; Hamby, 1994; Cariboni *et al.*, 2007; Thiele, Kurth & Grimm, 2014). However, the complexity, nonlinear interactions and emergent behaviour inherent within most ABMs limit the usefulness of such classical sensitivity analysis methodologies that link model output to model input (ten Broeke, van Voorn & Ligtenberg, 2016) and, given the stochastic nature of most ABMs, such analytics require a sufficient number of samples (*i.e.,* simulation runs), which can be limited by computational and temporal restraints (Lee *et al.*, 2015). As such, developing targeted methods of sensitivity analysis has been identified as a key challenge for ABM (Crooks, Castle & Batty, 2008; Filatova *et al.*, 2013; Thiele, Kurth & Grimm, 2014), as well as model analysis, verification, calibration, and validation (Brown *et al.*, 2005; Windrum, Fagiolo & Moneta, 2007; Crooks, Castle & Batty, 2008; Filatova *et al.*, 2013).

Three sensitivity analysis goals are common within ABM research (ten Broeke, van Voorn & Ligtenberg, 2016):

1. To gain insight in how patterns and emergent properties are generated in the ABM through the effects of changes in the model's parameters (Ligmann-Zielinska *et al.,* 2014).
2. To examine the robustness of model outcomes and emergent properties with respect to changes in parameter values (Leamer, 2010; Axtell, 1999).
3. To quantify the variability in ABM outcomes resulting from uncertainties in model parameters (Hamby, 1994; Saltelli *et al.*, 2004).

Sensitivity analysis of ABMs is focused on three main methodologies: extended one-factor-at-a-time (OFAT), and variance-based and model-fitting methods. ten Broeke *et al*. (2016) tested a number of such methods and found that no single method can provide a complete picture of the model and its outputs but recommended OFAT as the best method for uncovering the mechanisms and patterns produced within and by the ABM. Further, Hammond (2015) noted that special attention should be paid to both halting conditions and to initialization settings during sensitivity analysis. For an overview of sensitive analysis methodologies see, for example, Saltelli *et al.*, (2004), Saltelli *et al*., (2008) and Cariboni *et al.* (2007). Groff *et al*., (2018) examined a number of statistical analysis techniques used within the literature. Table 6 provides a summary of Groff *et al.*'s (2018) findings.

OFAT sensitivity analysis is the most common method used (ten Broeke, van Voorn & Ligtenberg, 2016) and, in practice, usually involves selecting a nominal base parameter setting and systematically varying one parameter at a time and the random number seed while keeping all other parameters fixed and exploring how changes affect model outputs (Groff, Johnson & Thornton, 2018; Grimm *et al.*, 2005; Manson, 2001). This analysis aids understanding of model mechanics through the examination of the relationships between the varied parameters and the output. OFAT analysis can, for example, determine if the modelled response is linear or nonlinear, or whether there are tipping points where drastic changes in outputs occur following a small parameter change. For example, in terms of modelling emergency scenarios like those being examined here, it is possible to develop a picture of how different response strategies are affected by resource levels by simulating the response to a suitably parameterized emergency scenario an appropriate number of times, each with different parameter values (Mysore *et al.*, 2006; Hawe *et al.*, 2012).

	Number of publications	%
Justification for number of model runs		
Stochastic nature of simulations	4	9.3
Allow analysis of change in SD, SE, or run statistical sensitivity tests	3	7.0
To get stable results	5	11.6
None provided	32	74.4
Time available to perform simulations	1	2.3
Total	45	100.0
Parameter sweep used for sensitivity testing		
No	22	48.9
NA, all parameters based on empirical data	1	2.2
Partial sweep	21	46.7
Full sweep	1	2.2
Total	45	100.0
Type of distribution used to validate outcomes		
Empirical distributions	17	37.8
Stylized distributions	15	33.3
Theoretical plausibility	11	24.4
Not mentioned	2	4.4
Total	45	100.0

Table 6: Type and justification of statistical analysis methods used in the wider literature (taken from Groff *et al.*, (2018))

In addition to the sources of model uncertainty above, modeller bias, be it an error in understanding or a systematic bias (such as the absence of a model variable due to the modeller's lack of knowledge of said variable's existence or lack of knowledge as to how to measure said variable) can lead to model outputs and results that veer away from the 'true' nature of the phenomenon being modelled (Heppenstall *et al.*, 2012). For social modellers, the problems associated with limited availability of large-scale long-term data samples for top-down analyses and the complexities associated with modelling the non-linear systems of interest are often balanced with the risk of error propagation from model inputs when designing bottom-up ABMs (Evans, 2012). Many of the techniques and solutions for addressing error propagation within more traditional mathematical models assume "normal" Gaussian noise distribution and stationary importance of input variables, and so are not suitable for the often-heteroscedastic nature of the non-linear social phenomena often examined (Evans, 2012).

A good model that informs policy effectively will quantify the uncertainties inherent within the model inputs, be it aleatory variability or epistemic uncertainty (Berger & Troost, 2014), as well as their impact on the model outputs, and generate a range of predictions (Manski, 2013; Wagner *et al.*, 2010). In most cases, the outputs from an ABM are best presented as summarised measures for a given population level or a sub-group – neighbourhood statistics, overall spatial distribution of agents or rates of change, for example (Bruch & Atwell, 2015) – though these can be misinterpreted. It is therefore necessary for modellers to communicate clearly the level of uncertainty within the model, including its nature and source, as well as the suitability of the model for study, how the model sits within the wider literature, and what the model does and, importantly, does not forecast (Ogawa, Geller & Wallace, 2015). It is important for modellers and policy makers to understand that models are only one input in the decision-making process (Ogawa, Geller & Wallace, 2015).

EVALUATING & VALIDATING AGENT-BASED MODELS

Validation is defined as: "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model" (AIAA, 1998: 3). A model is considered valid if the accuracy of its output variables are within an acceptable range required for the model's intended purpose – the limits of which are ideally specified before model development begins (Sargent, 2009). Validation is essential when an ABM is to be used to guide policy. This is because the goal of a policy-driven ABM is typically to compare model outputs with empirical data to evaluate the overall goodness of fit and ensure the model reflects actual mechanisms operating in the real world (Bruch & Atwell, 2015).

Several detailed model evaluation recommendations exist, such as the use of a model structure, analysis and replicability questionnaire (Richiardi *et al*., 2006); econometric validation techniques proposed by Windrum *et al*., (2007) (though the applicability of the methods proposed have been questioned by Moss (2008)); and evidence-based validation, typified by Axtell *et al*. (2002) use of archaeological evidence and present-day location of the Anasazi tribe. It has also been suggested by Berk (2008), and further examined by Bruch & Atwell (2015), that well developed methodologies for evaluating the results of computer experiments from within the physical sciences, particularly atmospheric modelling, be used to evaluate ABMs (see Bruch & Atwell (2015) for an outline of the proposed process). Todd and Miller (1999), and later Lenton *et al*. (2009) and Todd (2007), take a more hands-on approach to validating the mechanisms within their mate search strategies and marriage market ABMs. The authors modelled competition for mates within their ABMs under a number of assumptions regarding the "marketability" beliefs of agents following multiple encounters and then compared model outputs to the results of speed dating experiments.

In comparison, when the purpose of the ABM is to identify key relationships among parameters – for example more abstract ABMs like those primarily used in social sciences and like the one presented in this thesis – then it may be more suitable to resist the call to validate the model empirically and instead compare its outputs to empirical, aggregate patterns already observed (Bruch & Atwell, 2015). An ABM that recreates a process has not explained it (Grimm *et al*. 2005; Jones 2007), and most do not set out to do so. Instead ABMs should be used to identify key relationships among the model parameters and determine whether or not these modelled relationships are plausible explanations of observed phenomena (Bruch & Atwell, 2015). In this way, ABM could be seen more as a "virtual laboratory" and a way to generate hypotheses.

A key part of model validation is the act of replication. External scrutiny facilitates robustness in analysis and results in more reliable models (Donkin *et al.*, 2017; Axelrod, 2007; Axtell *et al.*, 1996; Easterbrook, 2014; Thiele & Grimm, 2015). However, model replication remains rare within the ABM literature (Donkin *et al.*, 2017). This is undoubtedly due to the high level of complexity and specificity of ABMs (Evans *et al.*, 2013; Sun *et al.*, 2016; Thiele & Grimm, 2015), but is confounded by the limited availability of model code and data within the literature (Rollins *et al.*, 2014; Thiele & Grimm, 2015). Donkin *et al*. (2017) present a rare example of ABM replication (replicating the work of Potting *et al*. (2005)), but, despite having access to model code, their findings point to issues around reproducibility of models across platforms and programming languages and issues around misinterpretation of sub-models and key model parameters. The authors' findings reaffirm the widespread belief that access to source code is paramount (Axtell *et al.*, 1996; Grimm, 1999; Grimm *et al.*, 2005; Thiele & Grimm, 2015).

Related to validity is model credibility, or the confidence a model user needs to accept the model process and outputs. For example, a rigorous validation process gives users of the ABM, particularly practitioners (emergency services, humanitarian organisations *etc*.) who are likely to pay for the model or rely upon it in emergency situations, a greater sense of confidence in the model. Takahashi (2007) reported that feedback provided by Japanese authorities on RoboCup Rescue, an ABM used to determine the optimal actions for police, fire and ambulance agents, and their coordination centres, in response to a simulated earthquake (Kitano *et al*. 1999), stated that a greater validity of the model would be needed to persuade fire-fighting departments to use it. Similarly, Duong (2010) asserts that practitioners will often require some form of accreditation or official certification of the model before use. As the effectiveness of a model and its adoption by users often depends on subjective, qualitative considerations (Bennett *et al*., 2013), clarity, transparency, and participation[18] in the modelling process is advised (Voinov & Bousquet, 2010).

[18] See section 6.1 for a discussion of participatory modelling and the process used within the creation of the model presented herein,

2.3.3 BENEFITS & CHALLENGES OF AGENT-BASED MODELLING

ABMs are an intuitive way to model complex systems as they allow for the inclusion of behavioural assumptions (Diaz, 2010). They can take into account inter-linked decision-making processes, multiple preference mechanisms and complex behavioural rules (Rounsevell, Robinson & Murray-Rust, 2012; Ostrom, 2000; Chen *et al.*, 2012).

Due to their ability to incorporate detailed, multi-layered empirical data on behaviour in both physical and social environments, as well as their ability to visualise model elements and clarify the interrelated macro-micro-macro relationships in action, and their ability to represent model granularity that is not easily handled by statistical or mathematical models (Bruch & Atwell, 2015), ABMs are often seen as "virtual laboratories," where theories can be developed, and intuition tested (Axelrod, 1997). Dynamic relationships between agents and their behavioural rules can be modified easily within the ABM, allowing for sensitivities and micro-level changes to be monitored and aggregation within the model means that it can be scaled up or down easily to adapt to changes in the crisis being modelled.

In terms of social sustainability and development modelling, ABMs allow researchers to simulate the conditions under investigation, as well as the consequences of actions taken under a range of response strategies. Data collection efforts and statistical analysis methods can be guided by the results of early models using simulated data based upon assumptions and aggregate data. Observed data can then be used to examine those assumptions. Scenarios can be developed based upon case studies, field work, institutional knowledge, or stakeholder priorities (Taylor, Coll Besa & Forrester, 2016). NGO resources, staff and practices can then be modelled, as well as different environments, circumstances and populations, and simulations can be run as many times as needed to determine the success/usefulness of different interventions and response strategies, all within a safe and relatively cheap and manageable virtual system (Yin, 2008).

ABM can allow researchers to go beyond the limits of SD and DE methods (Keenan & Paich, 2004), particularly when the system being modelled is primarily concerned with active objects (people, animals, vehicles, or products), timing, event ordering, and individual behaviours (Borshchev & Filippov, 2004) – as the model presented in chapter 8 is. ABM has many advantages over the other modelling methods discussed in sections 2.2.5 and 2.3.3 and Appendix 11.4. First, it is designed specifically to deal with heterogeneous and variable structures within systems (*e.g*. individual drivers and flocking animals) that interact directly or indirectly with themselves and their environment. Second, an ABM approach enables modellers to consider the impact of dynamic model parameters. ABMs can be developed that integrate behavioural, decision-making, and adaptive learning strategies, as well as constraints, at various levels, from the individual, to group and evolutionary development. ABMs are especially amenable to incorporating multi-layered empirical data on human and physical environments – like the data detailed in chapter 7 – that are not so easily handled within statistical or mathematical models (Bruch & Atwell, 2015). The explicit agents representation within ABMs supports visualisation of model heterogeneity across all levels, from, for example, different model contexts or parameter sets (Bazzan & Klügl, 2014). Third, a key strength of modern ABMs – and one of particular interest to modellers working closely with non-experts, as in this project – is their ability to visualise model elements and that the process of building a model helps to clarify the relationships and interactions between these elements (Yin, 2008) and aid one's intuition of the process under investigation (Axelrod, 1997). Finally, ABMs are particularly suited to technically advanced applications that may lack rich data sources – an issue of importance to this project and one discussed in greater length in sections 6.3, 7.4 and 9.4 – or do not rely upon a mathematically treatable or analytically solvable solution (Yin, 2008).

This does not make ABM a replacement for SD or DE modelling. There are countless applications where SD or DE models can efficiently solve problems. If the system under investigation fits well with SD or DE modelling paradigms, or if the required ABM knowledge is lacking, the use of such approaches is more appropriate. However, if the system under investigation features objects whose timing, ordering or autonomous behaviour is of importance, then applying an agent-based, or mixed-method, approach is more efficient (Serova, 2013).

The premise that ABM provides researchers with a theoretical explorative tool, as discussed above, also lies behind many of the criticisms of the method. For example, Gould (2002) argues that the results of ABMs depend too highly upon the (potentially biased) initial conditions programmed by the researcher. Further, Young (2006) and Gintis (2009) point towards the method's lack of transparency, with Fagiolo *et al*. (2007) determining that the results of ABMs are at best only moderately comparable and reproducible.

As with most methods, the defensibility of results produced by ABMs is often determined by the modeller's decisions on basic issues of sampling, namely the number of simulation runs. Lee *et al*. (2015) surveyed ABM literature and found that simulation runs are often subjectively determined: either extremely low due to the complexity of the model produced and its long run times, seemingly conveniently selected (25, 50, and 100 model runs are common), or exorbitantly high. Angus & Hassani-Mahmooei (2015) examined 128 ABM-related papers published between 2001 and 2012 and described what they referred to as 'anarchy' (previously identified by Richiardi *et al*. (2006)) within the published literature: limited use of methodological communication standards; little-to-no replication, likely due to most studies not presenting the parameters used; limited formal presentation of model structure, processes and relationships; and the lack of parametric estimation of ABM outputs. However, the authors note that their own study is limited by its focus on JASS only papers that may be subject to editorial flux, and the focus on presentation style, which does not determine the contribution of a scientific paper.

As is common with all modelling methods, ABM is limited by the scope, purpose and construction of a model, the availability, granularity and applicability of the data being used, and the inherent irrationality, complexity and subjective nature of the phenomena being examined (Bonabeau, 2002). Further, calibration and validation of ABMs is an active research area (Deffuant *et al.*, 2012), with sensitivity analysis of ABMs often limited (Becu *et al.*, 2003; Topping, Høye & Olesen, 2010; Lauf *et al.*, 2012; Saltelli *et al.*, 2008).

Bruch and Atwell (2015) point out that there are no governing operating practices or procedures for the use of ABMs within empirical research, something that may or may not hinder the field. Hall and Virrantaus (2016) build upon this and discuss the acquisition of domain knowledge, or lack thereof, when developing ABMs, something which Crooks *et al*. (2008) also note. The authors note how those who are generally more knowledgeable of the processes being modelled are not necessarily those doing the modelling and set forth a visualization approach to aid the interaction between domain and modelling experts and improve the grounded realism and validation of models.

The issue of domain knowledge, or the lack thereof, within the development of ABMs links to the issues raised by of O'Sullivan and Haklay (2000) that ABMs within the social sciences include assumptions that are not explicitly described or critically examined and built within so-called "black boxes", with assumptions and "underlying ontology…hidden within the code" (O'Sullivan & Haklay, 2000:1421). The authors state that this is "likely to become a more serious problem as various agent-based tools become more widespread" (*ibid*). Since the publication of the article, open source platforms, data and publishing have increased in popularity and the most prominent ABM toolkits, NetLogo, MASON and Swarm, remain open source and many of the models produced are freely available online (see: OpenABM.org). Improvements in model documentation and the increasing use of Unified Model Language (UML) (Fowler, Kobryn & Scott, 2004) and ODD (Overview, Design concepts, Details) protocol (Grimm *et al*., 2006; Grimm, 2010) to standardise the representation of models through schematic diagrams – independent of what programming language is used – aids the representing and explicit description of the underlying logic and assumptions of the model (Bersini, 2012). Further, as outlined above, one of the key uses of ABM is as a "virtual laboratory" to test theories and assumptions. The aim is often to experiment with simulated data and test ones assumptions about individual behaviour on a system's aggregate outcomes that can then be compared to observed data (Bruch & Atwell, 2015). However, this comparison with observed data is rarely done (Casini & Manzo, 2016). In many aspects of social science, a knowledge of global intricacies and interdependencies is lacking, but with ABM we can construct a model that takes our assumptions or perceptions of the individual level processes and model global aggregate behaviour (Borshchev & Filippov, 2004).

O'Sullivan and Haklay (2000) outline what they consider to be limitations of ABM in their overview of ABMs within the domains of life sciences, economics, planning, sociology, and archaeology. One of the key tenets of their discussion is the apparent individualistic social world view of ABMs, with agents representing individuals and ABMs often tending towards methodological individualism. Further, the authors note that this individualism carries through to the model outputs and that the emergent aggregate phenomena that is often noted as the ultimate advantage of ABM actually improves our understanding of processes and does not support ABM's "social" focus. For example, the authors point towards Epstein and Axtell's (1996) 'Sugarscape' model and whether or not "the insistent addition of complicating factors (trade, war, tribal/cultural traits, inheritance, disease transmission) adds anything to our understanding" (O'Sullivan & Haklay, 2000: 1413), condemning the model for its "reductive ontology" and "unsatisfactory model of cultural transmission and tribe formation" (O'Sullivan & Haklay, 2000: 1414). Ultimately, the authors concede that the model is intended as a simplistic way to introduce the reader to ABM and that it is not intended to simulate real-world cultural evolution, points Epstein and Axtell (1996) outline themselves. Epstein and Axtell's (1996) work aimed at presenting a new method of examining micro-specifications within artificial societies and the generative macrophenomena that emerge within those *artificial* societies and do not proclaim to be producing replicas of real-world societies, just the development of an *in-silico* method of studying societal activity and developing theory. In addition, and as noted by Epstein and Axtell (1996), their work was ultimately restricted by the computational powers of the time and theoretical knowledge of a modelling approach that was very much in its infancy. Haklay *et al*., (2001) later present their own ABM, STREETS, aimed at simulating the behavioural aspects of pedestrian movement and conclude that ABM is highly applicable to the field of retail planning and that the further development of models populated with socioeconomically representative agents could benefit the wider field of urban planning more generally.

O'Sullivan (2008) later surveys the range of applications and approaches encompassed by ABMs and their implications on the domain of geographical information science. The author points to what he refers to as the problem of *equifinality*, or "the fact that many models could be built that would match with empirical observations equally well" (O'Sullivan, 2008:546). Measuring the representational accuracy of an ABM, or any model, is, according to the author, impossible due to the likelihood that those same results could be replicated by very different models. Similarly, Kowarik (2012) and Premo (2008, 2010), in their discussions of ABMs in archaeology, point out that it must be remembered that models do not represent the past itself, but rather the modellers idea of the past (PREMO 2008). This is a point worth remembering but, this author feels, not a limitation of ABM. 'Equifinality' is characteristic of complexity (Batty & Torrens, 2005) and it is the stochasticity inherent within ABMs that makes them useful tools for idea exploration. It is generally understood that models represent a simulated past or future and come with probabilities of occurrence and levels of accuracy, one must simply take care when interpreting and distributing the results.

O'Sullivan *et al*., (2012:111) point out that the "bulk of academically orientated [ABM] work to date" focuses on "simple abstract models" that aim to explore the wider collective implications of individual agent's decision-making, a somewhat redundant comment given the evolutionary progress of ABM – and almost every other scientific approach - and the need to walk before running. The authors reference several studies that appear to demonstrate ABM's continued development and movement away from "simple abstract models", from Schelling (1969; 1978) to Axelrod (1997) to Cetin *et al*., (2002) and Batty (2005). The author would add to this list the more recent work of Dawson *et al*. (2011), Silverman and Bijak (2013), Crooks and Wise (2013), Heppenstall *et al*. (2014), Malik *et al*. (2015), Hawe *et al*. (2015) and Wise and Cheng (2016) as examples of the continued development and improvement of ABM and its increasing inclusion of social theory and its increasingly sophisticated representations of agents that can logically consider space and develop spatial relations.

In discussing the modelling of emergency situations, Gonzalez, (2009) suggests that a multi-method approach may be appropriate. The author states that because a simulated environment may not require the same level of autonomy and complexity, if any, as the agents being modelled, other model types could be used to represent objects, events and the dynamics of the environment, such as a DES package, and then combined with an ABM of agents within the emergency simulation. Increasingly, researchers are using different modelling paradigms for different parts of their simulation models. For example, Schieritz & Grosler (2003) used both SD and ABM methods to model the emergent structures within supply chains. The authors found that, despite the practical problems of combining different software environments, the combination of methods did reduce the *a priori* complexity of the model. Further, Lättilä *et al*. (2010) examine five different models that combine SD and ABM methods and conclude that the use of such hybrid simulation models can produce more accurate and reliable Expert Systems (ES). Similarly, Bobashev *et al*. (2007) found that a hybrid ABM-equation-based model (EBM) can dramatically reduce computational demand and run time, and allows for easier mathematical analysis of emerging structures generated by the ABM.

Many studies now utilize ABM in conjunction with one or more other modelling methodologies. For example, Birkin & Wu (2012) argue that microsimulation models (MSM) and ABM are complementary approaches whose benefits – MSM's stochastic, rule-based policy focus and ABM's emphasis on emergent behaviours – can reduce either methodology's limitations. Researchers are increasingly turning to ABM to 'agentise' their models. For example, Gonzalez (2012) proposes a crisis response simulation architecture whereby a discrete-event simulation (DES) models the crisis environment and entities, and the response organisation is modelled using ABM. Wu *et al*., (2008) combine MSM and ABM to model the future population changes in the city of Leeds, UK.

Further, the relatively recent linking of ABM with GIS provides researchers with the ability to model emergent behaviour within the spatial domain, as well as the temporal domain (Torrens & Benenson, 2004). Much of the identified research has focused on temporal analysis of, for example, disease propagation (Kaplan *et al*., 2002), hospital patient influx after a disaster (Hoard *et al.*, 2005), evacuation (Pel, Bliemer & Hoogendoorn, 2012), health equipment delivery (Aaby *et al.*, 2006), and logistics during crises responses (Tako & Robinson, 2012). However, work by, for example, Crooks and Wise (2001; 2013) and Fikar *et al.* (2018), has highlighted the potential for the integration of geospatial analysis in emergency modelling.

There are valid criticisms of the transparency and reproducibility of many ABMs, however it is argued here that the alternative methods suffer from similar problems. All computer simulation methods have epistemological and methodological problems (see: Boudon (1965) and Padioleau (1969) for early discussions that still hold true fifty years later). The increasing use of empirical data to support the building of ABMs will improve the stability and reproducibility of results and, in conjunction with the publication of code and use of open source licenses, improve the understanding of how ABMs are constructed, minimising the view that they are "black box" models. In relation to emergency modelling, ABMs may be better suited when compared to mathematical models as ABMs present more opportunities for interaction, participation and co-creation with stakeholders who may lack advanced mathematical skills. The modelling process as well as the outputs of such a participatory modelling approach – the approach taken within this thesis and outlined in Chapters 6 and 7 – can improve the understanding of the situation being modelled and aid the communication of that understanding (Taylor, Coll Besa & Forrester, 2016).

Ultimately, as with most research, there are multiple methodological opportunities open to the researcher whose use could be argued for. ABM is not a replacement for SD, DES or SDSS modelling and that is not being argued here. There are many examples where an SD or SDSS approach will efficiently solve a problem and the use of ABM would not be suitable (Borshchev & Filippov, 2004). It would be sensible for modellers to choose the best tool for the job, not the one they have a vested interest in or one that is in vogue and may be more prudent to utilise multiple modelling techniques. The use of multi-paradigm model architectures – for example SD and DE sub-models that interact with an ABM (Großler & Schieritz, 2005) – is increasingly common and could be more appropriate in many instances (*ibid*) and represent a powerful tool to address complexity (Taylor, Coll Besa & Forrester, 2016).

2.4 KEY THEMES & GAPS IDENTIFIED IN THE LITERATURE

The literature reviewed demonstrates the current state of research into vulnerability, ABM, GIS and the cross-discipline work that incorporates all three.

Findings from this literature review have demonstrated the breadth of vulnerability analysis and the continued desire to quantify vulnerability and the many methodologies employed. However, the review revealed various widespread methodological limitations. Past work on measuring and mapping vulnerability was found to suffer from five main problems:

1. the focus on population concentrations within known hazard zones and not entire populations, potentially omitting vulnerable populations.
2. it has been limited by scale – either too large to uncover local-level nuances or too insular to allow for useful comparisons at a country or larger level, often utilizing site-specific data or indicators.
3. the focus on income as the key variable for measuring vulnerability, deprivation or resilience.
4. the reliance on proprietary data and/or methodologies.
5. the limited inclusion of accessibility within the measurement of vulnerability, despite the recognition of its importance.

The review found a plethora of large-scale (country to near-global) attempts to assess vulnerability with a focus on relative measurements of vulnerability based predominantly on the economic aspects of life and idiosyncratic views on indicator weighting. Few studies that took account of social aspects of vulnerability (health, well-being and support) were found to be a realistic examination of vulnerability on a local scale using an indicator-based approach. Limited quantitative research was found that combined geo-demographic analysis of vulnerability and hazard mapping to produce a composite vulnerability index at a national scale with a resolution smaller than county or region level.

A lack of integration between academic analyses of vulnerability and governmental and non-governmental policy was also noted (Mustafa *et al.,* 2011), with the requirements, scale, complexity and enquiry method required by both such parties are often at odds (*ibid*). Researchers across many disciplines have developed their own conceptual models of vulnerability, often addressing similar problems and processes, but using different terminologies and scales. The existence of different conceptualizations and languages used to discuss vulnerability has become problematic, causing conceptual confusion around vulnerability research, particularly within interdisciplinary work. It is demonstrated here that the diversity within the conceptualisations and definitions of vulnerability is a reflection of the scope of valid perspectives within the complex and integrated socio-environmental system, and that it is essential to accept this diversity when applying a vulnerability perspective.

The review found that much of the emergency response literature focuses on supply-chain logistics and operations management within large-scale international response efforts. NGO-academic partnerships were found to be limited. However, interest in computational models of emergency relief operations was found to be growing within academic literature and the NGO sector. It is believed this is due to their risk-free nature and the proliferation and growing value of data recording, storing and analysis software, as well as the push for greater accountability and outcomes measurement within the sector as a whole.

A growing trend of framing emergency relief modelling in terms of vulnerability and capacity was also noted, but as noted with geospatial analysis more broadly, data scarcity is a major limitation of modelling work and there remains scant literature that is concerned with real-world case studies and work that is theoretically grounded and empirically validated.

Findings from this literature review have demonstrated the breadth of ABM analysis and the continued desire to integrate fully ABM and GIS and the many methodologies employed. However, the review revealed various widespread methodological limitations and gaps within the work, namely the limited work into fully integrating and utilising geospatial data in ABMs and the even more limited work within the context of emergency/disaster relief.

The distinct spatial nature of emergencies makes them perfect for geospatial analysis and as such a diverse collection of studies is available. However, the work the emergency response and management domain aims to undertake is complicated by myriad cascading endogenous and exogenous factors and almost all studies noted that technical limitations, namely data quality, quantity and integration, and up-to-date and interoperable systems and datasets, remain major constraints to the proliferation and use of GIS within emergency management and relief operations. Much of the quantitative academic work examined focused on the (comparatively) data-rich area of logistics and operations management, with project management, decision-making and supply-chain optimization analyses favoured. A growing trend in the vulnerability and capacity framing of emergency relief modelling was also noted. However, despite the increase in research over recent years, there remains scant literature that is concerned with real-world case study examination, and theoretically grounded and empirically validated modelling.

Researchers are increasingly turning to participatory modelling to bridge this data gap and gain a greater understanding of the phenomenon under consideration and the processes involved through interaction with local stakeholders, beneficiaries, and domain experts. Simple, easy-to-understand models designed in collaboration with the stakeholders have proven to be useful tools for emergency responders. Increased NGO-academic collaboration that can validate these models using real-world case studies could greatly improve the research and its impact.

However, this review found that NGO-academic partnerships are scarce and applied research is limited. In addition, no work was found that examined NGO emergency response operations with a vulnerability focus. It is hoped that this thesis will address this gap within the literature.

ABM was chosen as the primary modelling approach as response efforts are characterised by complex relationships between responders and beneficiaries with poorly defined feedback loops that are difficult to quantify with pure mathematics or with conventional economic modelling techniques. ABM has been shown to be a useful tool for evaluating the complexity of social, environmental, and development policy issues (Taylor, Coll Besa & Forrester, 2016). Response efforts focus on inherently nonlinear systems where responder policies or decisions can have disproportionate and unpredictable impacts on beneficiaries. An ABM is an effective way of exploring the behaviour of such complex systems as it allows for the integration of multiple theories regarding the phenomenon under investigation and heterogeneous agents within the model, such as relief distribution units or refugees, that can be assigned multiple decision-making strategies and can act independently to solve a common goal and modify their behaviour over time. This creates a virtual simulation of the micro-level decision making and the emergent impacts on the macro-level system(s) (Holland, 1992) and the consequences of user-defined policy decisions (Comfort, 2004).

The primary focus of many emergency relief ABMs is the optimisation of logistics networks and the pre-positioning of resources (Turner *et al.*, 2011) and the simulation of post-disaster situations and response management (Sobiech, 2008). However, the majority of past emergency response and relief ABMs have been abstract examinations of situations or over-simplified models. Many models also stop short of modelling the entire relief and resources network, particularly the flow of resources down to the individual, which has been identified as the most problematic element within such networks (Turner *et al.*, 2011). Few studies were identified that incorporated GIS fully with most favouring a systems view, and fewer studies still were found to take account of, for example, population demographics or elements of vulnerability (Turner *et al.*, 2011). To the author's knowledge, only Crooks and Wise (2011, 2013) have fully incorporated ABM and GIS to assist emergency relief and response efforts.

In terms of emergency and humanitarian modelling, the focus of this thesis, few ABMs were found that attempt to model an actual event, a finding also noted by Menth (2016). Focus was found to be on the "planning" and "pre-preparedness" stages, with past emergencies used to calibrate models and replicate real events, and then used to determine optimal response procedures after the fact (Hawe *et al*., 2012). While experimentation and examinations of theoretical frameworks is useful, grounded and applied models that examine real-world events are essential to enhance understanding and progress the use of ABM within emergency management and humanitarian logistics. Further, at present, there is only a limited understanding of the impacts of relief distribution strategy changes on the end-to-end supply of emergency supplies and management (Anon, 2018). This thesis aims to address this and several other identified gaps in the literature by presenting an applied, empirical, and geospatial model developed in cooperation with humanitarian responders and built upon theoretical frameworks and event information developed in participation with the same responders.

3 METHODOLOGY: STAKEHOLDER ENGAGEMENT

Introduction	Literature Review	**Stakeholder Engagement**	Methodology OSVI	Results OSVI	Stakeholder Engagement	Methodology Model	Results Model	Discussion	Conclusion
Ch. 1	Ch. 2	**Ch. 3**	Ch. 4	Ch. 5	Ch. 6	Ch. 7	Ch. 8	Ch. 9	Ch. 10

"In terms of scale, complexity and duration, [the Gloucestershire floods] is simply the largest peacetime emergency we've seen."

~ Tim Brain, Chief Constable of Gloucestershire

3.1 STAKEHOLDER ENGAGEMENT & CASE STUDY SELECTION

The BRC works throughout the UK, with offices in 60+ locations. Flood related response work has been undertaken by personnel at most offices at some point in the past. The level of researcher-sponsor engagement that the EngD engagement provided gave ample opportunities to learn about response work from BRC staff and volunteers. However, the project required quantitative data on response efforts and obtaining such data was difficult, even impossible, in many cases. In light of this, and following discussions with BRC staff, it was decided to focus on the county of Norfolk. This decision was twofold: although the BRC has not responded to a specific flood event in Norfolk, the county has a large at-risk area and local BRC staff were actively working with County Council and Environment Agency to prepare for future flood events, and the BRC actively works with a number of highly vulnerable groups in the county who could require extra response efforts following a flood. It was decided that a number of projected flood scenarios would be examined, and a range of generalised response strategies modelled based upon institutional BRC experience, best practices and institutional learning, and information from the wider literature.

Mid-way through the project and following a focus group meeting and a data search on the BRC's internal servers (previously unavailable), suitable information was found for the response efforts following the 2007 floods across Gloucestershire, Herefordshire, Worcestershire, Oxfordshire, Berkshire and South Wales could be used for model testing. After further research and discussions with BRC staff, and the discovery of accurate figures on resources distributed and response timing, it was decided to focus on examining and modelling the response efforts that took place in the county of Gloucestershire. A combination of financial reports, IFRC bulletins, and first responder notes were obtained that, when combined with participatory modelling guidance, could be used to recreate response efforts in Gloucestershire. More information is provided in section 6.2.

The case studies examined would be classified as 'large-scale' under Gad-el-Hak's classification (an emergency which either affects an area of at least $10km^2$ in size, or affects at least 100 individuals, or both) and were classified as 'serious' by the UK Government. In this paper, we use the generic 'impact' and geographic scale dimensions and the classification system used by ConOps when referring to events. This is to maintain applicability within the BRC's lexicon and to ensure usability and understanding of the model by the BRC and other UK emergency responders.

3.1.1 STUDY AREA ONE: NORFOLK

Norfolk is a low-lying English county with an extensive coastline – 93 miles. Norfolk has a lengthy history of coastal and riverine flooding, ranging from the North Sea flood of 1953 to several less extensive, but still damaging, flood events occurring over the past half century. It is estimated that 100,077 properties in the county are at risk from flooding, with the areas of Norwich, King's Lynn and Great Yarmouth highlighted at particular risk (Carroll, 2012). It is an area with a near-equal rural/urban divide with an aged population and a low population density – 160 people per square kilometre (compared to the UK average of 407). Norfolk has limited accessibility options despite being one of the largest counties in the UK: it has no motorway, direct access to only three primary ‘A’ roads (A11, A12, A47), only one major railway station and has only two NHS hospitals with accident and emergency facilities (Norfolk & Norwich University Hospital and Queen Elizabeth Hospital).

The BRC runs an office in Norwich, the main city in Norfolk. The BRC provides a range of service to Norfolk and the surrounding counties, including event first aid and ambulance support, mobility aids, older people outreach, support at home, and support in emergencies.

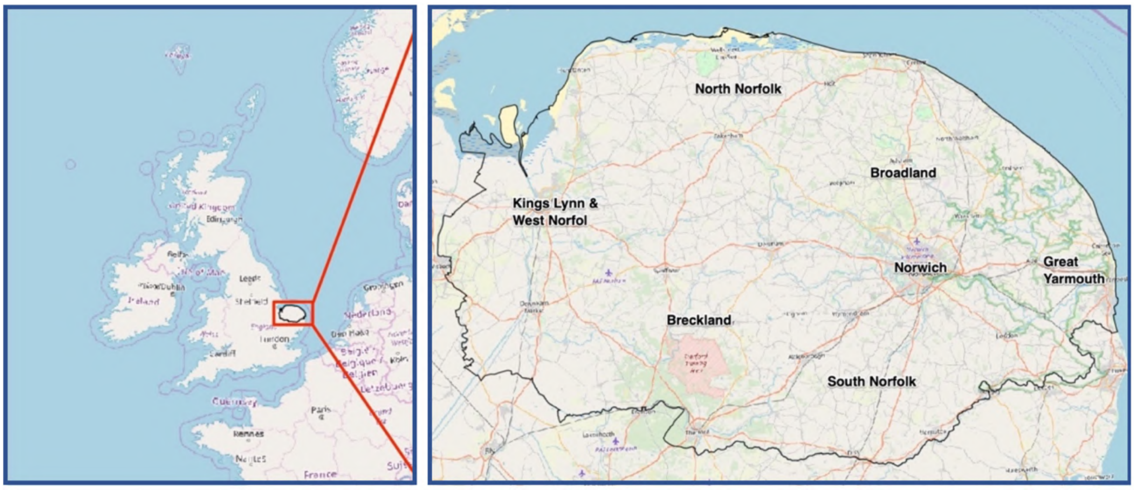


Figure 9: Study area map showing the location of the county of Norfolk and its major urban areas

Figure 10: Images of floods across Norfolk (AFP/Getty©, Albanpix©)

3.1.2 STUDY AREA TWO: GLOUCESTERSHIRE

Gloucestershire is a county in South West England, with a population of 623,094 and a mid-to-low population density – 287 people per square kilometre (compared to the UK average of 407 and Norfolk average of 160) (Gloucestershire County Council, 2016). A large proportion of the county is built upon the River Severn floodplain and much of the county's populated areas have a low-lying topology and are at risk from fluvial flooding. Unlike Norfolk, Gloucestershire has an extensive transport network and ample accessibility options: it has direct access to the M5 motorway, seven 'A' roads (A38, A40, A48, A417, A424, A429, A436), 9 railway stations, and 10 NHS hospitals (two with accident and emergency facilities: Cheltenham General Hospital and Gloucestershire Royal Hospital).

In 2007, Gloucestershire suffered severe flooding during a series of floods that affected much of the UK between June and July 2007, with a record 78mm of rain falling in 12 hours. 350,000 people were left without clean water for 14 days after the Severn Trent Water's Mythe Water Treatment facility was flooded and 48,000 people were without electricity when the Castle Mead electricity sub-station was damaged by flood waters. 10,000 motorists were stranded on the M5 motorway overnight, 2,000 people were evacuated to rest centres, and 500 were stranded at the county's railway stations. In total, 3,966 houses were flooded, 500 businesses and 22 schools. Three people died.

The BRC responded to the 2007 flood events in the following ways: providing evacuation assistance, Ambulance support, the provision of bottled water, hygiene kits, and food parcels, emergency rest centre support (practical and emotional), and the provision of blankets and duvets/sleeping bags. The BRC was tasked with water distribution and the overall management of the remaining supply of water during the 14-day period where mains water was unavailable.

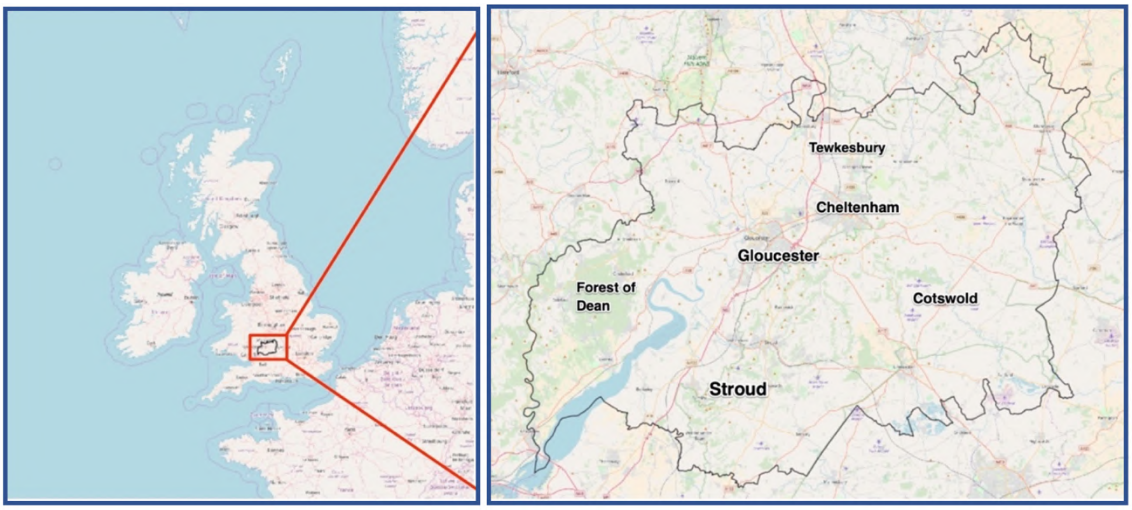


Figure 11: Study area map showing the location of the county of Gloucestershire and its major urban areas

Figure 12: Aerial images of floods across Gloucestershire in 2007 (BSG/NERC©)

3.2 THEORETICAL FRAMEWORK

After initial consultation with BRC staff and volunteers it became necessary to define key terms and establish a theoretical framework to provide a general representation of these key terms in relation to the goals of the project as well develop an understanding of the way socio-economic and place-based factors influence both vulnerability and the performance of humanitarian response efforts.

Initial talks and engagement with BRC staff and volunteers started by examining the widely accepted and simplified mathematical expression for risk proposed by (Laska & Morrow, 2003):

$$Risk = Hazard \times Vulnerability$$

Focus group discussions led us to modify this expression of risk and incorporate elements such as *coping capacity, exposure, adaptive capacity, susceptibility* and *deficiencies in preparedness* to better represent BRC's understanding and interests. The following simplified equation was produced, where risk *(R)* is the product of hazard *(H)* multiplied by vulnerability *(V)*, which in turn is the sum of exposure *(E)* and adaptive capacity *(AC)*:

$$R = H \times V\,(E + AC)$$

This formulation was then expanded upon to incorporate the determinants present with the OSVI for the calculation of each element. In the following equation, hazard (*H*) is the function of magnitude *(M)*, frequency *(F)* and proximity *(P)*; and vulnerability *(V)* is the product of exposure *(E)* and adaptive capacity *(AC)*:

$$R = H(M, F, P) \times V\,(E[X_1 \dots X_4] + AC[Y_1 \dots Y_4])$$

Exposure *(E)* is the product of determinants ($X_1 \dots X_4$) represented within the OSVI as: individual *(I)*, household and community *(HC)*, settlements and structures (*SS*) and asset exposure *(A)*. Similarly, adaptive capacity (*AC*) is the product of determinants (Y_1 ... Y_4): environmental (*En*), social (*So*), economic and equity *(EE)*, and physical and technical (*PT*).

During focus group discussions, it was made clear that BRC staff and volunteers felt that, in addition to vulnerability being the product of exposure *(E)* and adaptive capacity *(AC)*, it should also be subdivided in to two distinct forms: social vulnerability *(SoV)* and situational vulnerability *(SiV)*, represented as follows:

$$V = SoV + SiV$$

It was felt that this better represented the kinds of vulnerability that BRC staff and volunteers encounter during emergency situations. Discussions led to the following definitions:

> Social Vulnerability: The differing level of exposure to hazards and access to resources, and the coping capacity of individuals or groups.
>
> Situational Vulnerability: Vulnerability due to context specific stressors (*e.g.* proximity to hazard, hazard return period, event timing).

The definition of vulnerability that is used throughout this study is: vulnerability results from the socio-economic and geo-physical conditions that make parts of society susceptible to damage or disruption (modified after Clark *et al*., 1998; Blaikie *et al*., 2005; Müller *et al*., 2011).

One of the specific contributions of this research is the consideration of situational factors – here defined as exogenous and contextual factors in the hazard-affected areas and the amplification of vulnerabilities due to those context specific stressors – within the OSVI and subsequently the model and examination of performance within the humanitarian response. Situational factors can rarely, if ever, be modified by responder agencies, such as the BRC, but their impact can be managed if the agency prepares (Kunz & Reiner, 2012).

Following the agreement of the above definitions and representations of key terms and relationships, it was decided to situate them within a vulnerability and humanitarian response context and incorporate the decisions and graphically represent them in the theoretical framework to describe the influence of, and relationships within, vulnerability on humanitarian response procedures (see Figure 13). This required the inclusion of development and emergency response elements and procedures as well as a consideration of their spatial and temporal context.

BRC staff and volunteers provided guidance and outlined key stages of development, including exposure analyses, disaster risk reduction (DRR) strategies and community partnerships. This can be seen in the *Resilience, Prevention & Governance* section of Figure 13. A response matrix was produced that aimed to present the various stages of emergency response procedures across multiple scales, as well as the related resources and the timescales involved. The matrix was based upon BRC procedures and past experience, and was designed, revised and finalised over the course of a meeting with BRC *Emergency Response and Management* personnel. The full theoretical framework was produced collaboratively over the course of three focus group sessions. The finalised theoretical framework (Figure 13) was presented to BRC staff during a model workshop.

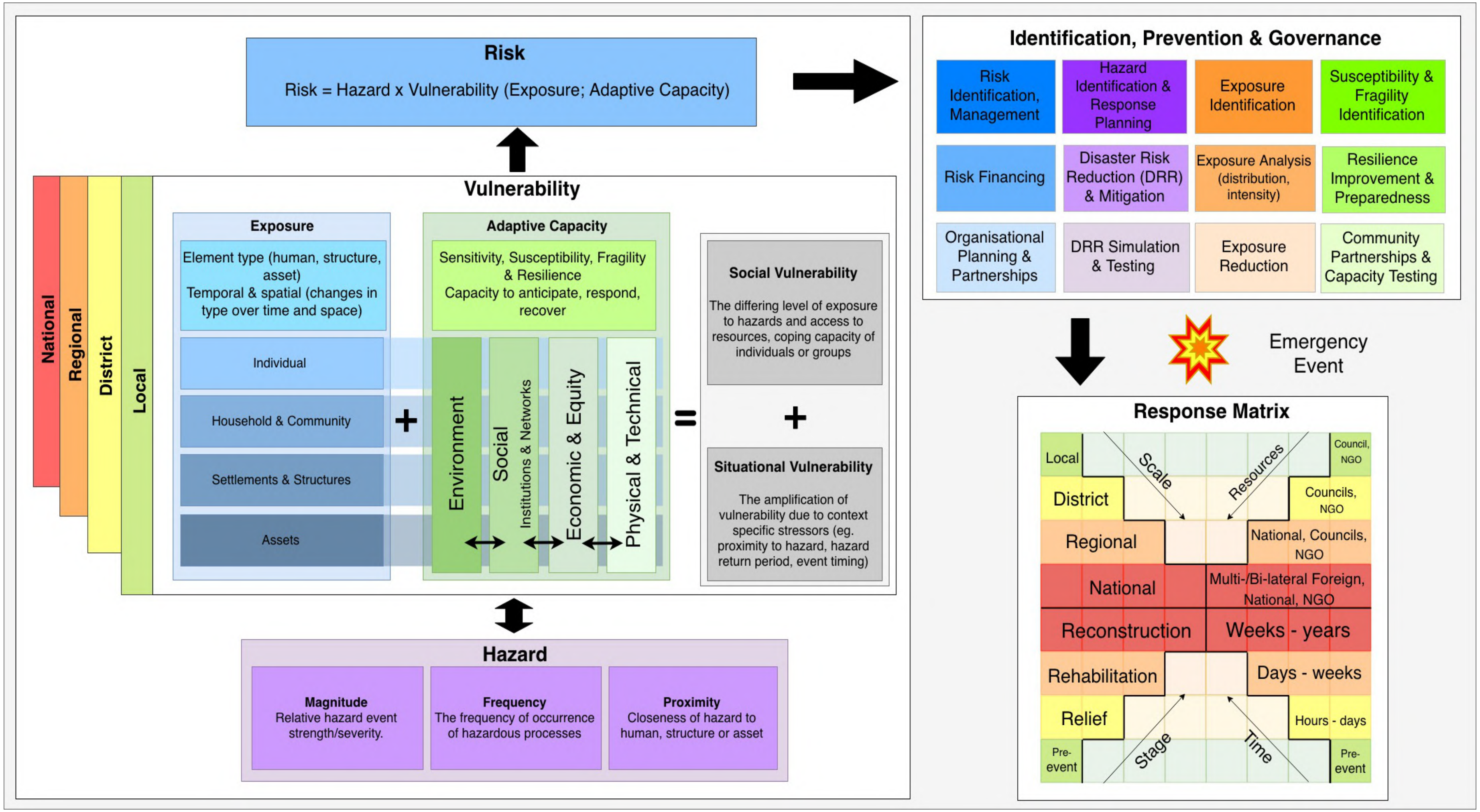


Figure 13: Visual representation of Theoretical Framework

3.3 METHODOLOGICAL FRAMEWORK

To understand better and test the relationships between the influencing factors of vulnerability (both endogenous and exogenous) and the performance of BRC emergency response efforts, a conceptual methodological framework was developed in conjunction with BRC *Emergency Response and Management* personnel. The goal of designing the framework was twofold:

1. It would help to determine key emergency response stages, BRC response procedures, and the factors that affect problem identification, decision making, and operational response procedures. These elements could then be incorporated into the framework.
2. It would give stakeholders and users a full overview of the complex emergency management process, helping them to see where the OSVI and model sit within this process, namely the OSVI as a major contextual input and the model as part of the decision-making stage.

As seen in Figure 14, the OSVI is one of the inputs in the framework. Alongside road and emergency networks, hazard maps and weather maps, the OSVI makes up the contextual analysis input. The goal here is to give users all available information on the environment of interest. In addition to the contextual analysis, the model takes capacities and capabilities analysis as input. These are primarily made up of organisation dependent factors, such as available resources and staff, time restrictions and skills, and beneficiary requirements. These contextual inputs combine to give a situational overview to the user. The goal here is to give the user the relevant information needed to answer questions such as: what is happening and who is affected?

This information is then used within the decision-making process. This process is made up of two main interlocking elements: event assessment and the model. This process takes in to consideration key organisational response processes and programmes such as stock and staff management and IT and communications. The decision-making process then assists the response efforts, as outlined in Figure 14. The model sits within the wider organisational event assessment sphere and is one part of a complex structure and decision-making process.

In a business setting, the methodological framework as well as the theoretical framework, would be evaluated by measuring the value it creates or saves (either in monetary terms or personnel time) (Goldsby & Rao, 2009). However, in a humanitarian setting, the performance or effectiveness of a framework is instead measured against its ability to meet the needs of beneficiaries, be it the timely delivery of items that are needed, the quantity of relief items delivered within a set time or budget, or the safety and survivability of those affected. The model presented is designed to assist performance measurement and aid the measurement of outputs/outcomes. By testing a range of response strategies under a given scenario, the model makes it possible to test the effectiveness (are beneficiaries' needs met?) and efficiency (are services delivered in a timely manner?) of those strategies. The primary outcomes of the model are envisioned to be the successful provision of relief and the reduction in vulnerability. Secondary outcomes are likely to be an increase in skills and understanding and a greater appreciation for data and the greater examination of past experiences and lessons learned. The finalised methodological framework (Figure 14) was presented to BRC staff during a model workshop.

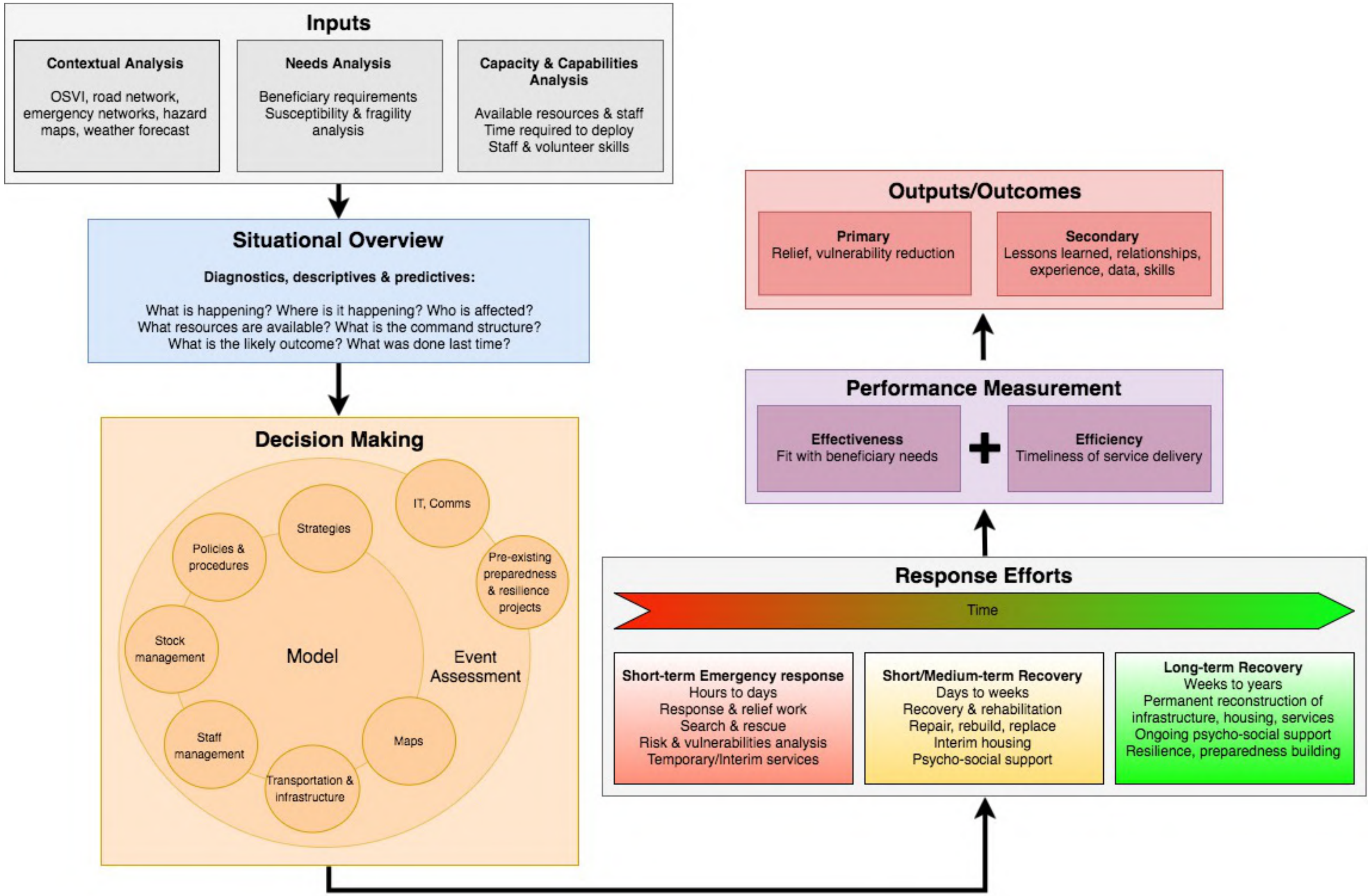


Figure 14: Visual representation of Methodological Framework

4 METHODOLOGY: OSVI[19]

Introduction	Literature Review	Stakeholder Engagement	**Methodology OSVI**	Results OSVI	Stakeholder Engagement	Methodology Model	Results Model	Discussion	Conclusion
Ch. 1	Ch. 2	Ch. 3	**Ch. 4**	Ch. 5	Ch. 6	Ch. 7	Ch. 8	Ch. 9	Ch. 10

"GIS is a technical innovation as important to the spatial sciences as was the invention of the microscope to the biological sciences."

~ Abler, 1987: 303

4.1 DATA COLLECTION, ORGANIZATION & EXAMINATION

To examine social vulnerability (and later synthesise populations within the model) socio-economic data were collected from the 2011 UK Census, as well as from the Neighbourhood Statistics Service, the General Lifestyle Survey, and the Indices of Multiple Deprivation; and accessibility data (accessibility to health facilities, schools and major towns and cities *etc.*) were collected from the Department of Transport. Census data provided by the UK Government are usually done so in a clean, well-structured and error-free format. However, downloading data at the granular level required by this project for the entire UK required over 100 files to be downloaded and collated. Records were harmonised (all records had entries that allowed for cross-referencing, but not all records had the same entries) and data were cleaned, checked and validated against known entities to ensure the validity of the final dataset. The final database was enhanced with additional related data, namely georeferences to improve mapping, and attribute tags were added to improve the management of the database.

[19] This chapter is adapted from: Garbutt, Ellul & Fujiyama. 2015 Mapping Social Vulnerability to Flood Hazard in Norfolk, England. *Environmental Hazards* Vol. 14 No. 2 pp. 156-186.

4.1.1 GEOGRAPHY & MAP DATA

Choosing the correct level of Census geography is essential to highlighting the real patterns and issues within large governmental datasets. It can be detrimental to simply choose the smallest Census tract available. When looking at fine resolution geographies, particularly Output Area (OA) and postcode level, confidentiality becomes a problem as data supplied is likely subjected to rounding to ensure anonymity when dealing with, for example, instances of violent or sexual crime or users of mental health services. In addition, choosing a level of geography such as postcodes results in a vast increase in the level of investigation and calculation required, adding strain to the GIS produced (for example, there are 2.5 million postcodes in the UK compared to 171,372 Output Areas). Conversely, choosing a medium-large geography, Medium Super Output Area (MSOA) or Local Authority (LA), would speed up investigation and allow for easier integration of health and crime data, but reduce the applicability of results at a community/neighbourhood level, as a single vulnerability score would be produced for in excess of 15,000 people.

Examination of the different geography products available led to the decision to use the Lower Layer Super Output Area (LSOA) boundaries for final analysis and visualisation (see Figure 2). LSOA have a minimum population of 1,000, with an overall mean of 1,500, providing a sufficiently fine-grain detail to examine vulnerability at a community level. In addition, key data sources, namely ONS Census, readily supply data at the LSOA level and the resultant LSOA-based OSVI would be easily compared to the English Indices of Deprivation (IMD) and Experian's MOSAIC classification (see section 5.2). There are 539 LSOA in Norfolk, 34,753 throughout England and Wales.

This project takes full advantage of the open source community and utilises a wide range of open source digital maps supplied by the Ordnance Survey (OS) and Office for National Statistics (ONS) and key service location data provided by OpenStreetMap (OSM). It was hoped that OSM road data could be utilised for routing purposes. However, when OSM road data was compared to OS OpenData data, a significant number of roads, particularly local residential streets and small country tracks, were either missing or significantly misaligned and lacking metadata required for robust routing. Thus, it was decided to use an Ordnance Survey MasterMap Integrated Transport Network (ITN) road dataset, freely available from the Ordnance Survey under their OpenData™ initiative to develop a routable road map.

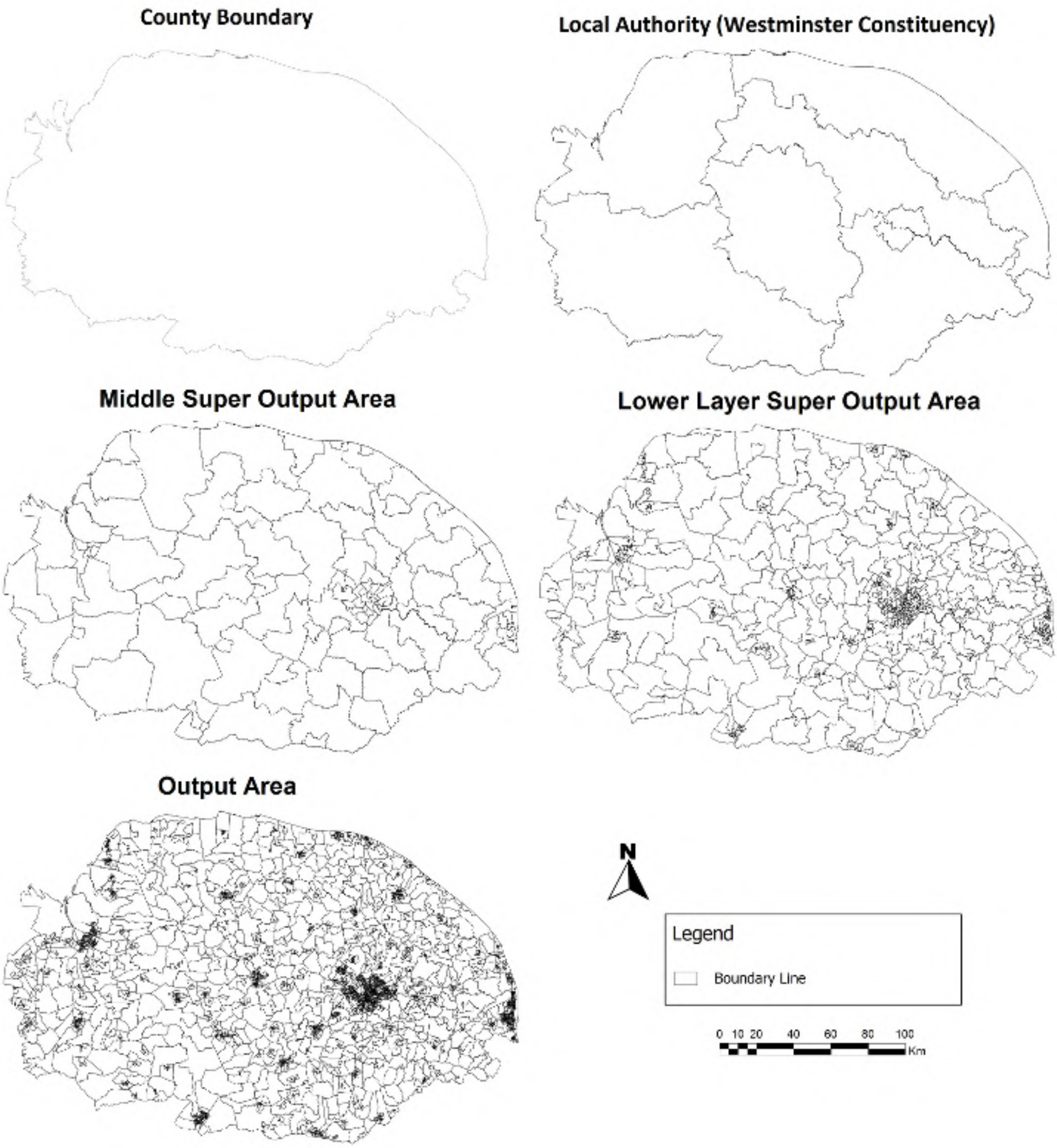


Figure 15: Boundary Line geography comparison

4.1.2 FLOOD DATA

UK flood data, specifically information pertaining to flood affected areas and flood defences, is freely available via the Environment Agency's (EA) website. It was decided that, for this project, the type of flooding (tidal, fluvial or ground) was not required for analysis, just the knowledge that a certain area was or was not within a flood zone. However, it was decided to plan for the 'worst case scenario' and utilise the EA 'extreme flooding' scenario: 0.1% (1 in 1,000) or greater chance of happening each year (see Figure 3). In other words, flooding in these areas has a low probability of occurring, but a potentially high impact on those in those areas. It was not possible, using the freely available EA flood data, to use flood depth data as an indicator for the severity of the flood as the data is not available. Thus, the flood zone used in the analysis assumes a constant blanket level of risk. Ideally this would be improved upon in future research by using flood depth data to more accurately gauge impact/risk. In addition, the LSOA Centroids, which represent a summary single reference point of how the population at census time was spatially distributed and grouped within that LSOA, were utilised to define key populated areas within each area and were utilised within accessibility analysis and as part of a hazard indicator. Exposure is defined as the assets/values located in the flood-prone (or general hazard-prone) area (IPCC, 2012) and so the use of Centroids as markers of the density of the population and built environment allows for the exposure component of flood risk to be considered within the larger vulnerability index. This is in contrast to other studies, including the SVI (Cutter *et al*., 2000), where socially vulnerable households are highlighted irrespective of their presence within a hazard zone and so must be combined with hazard and exposure data separately to capture potential risk.

Flood Zone	Definition
Zone 1 Low Probability	Land having a less than 1 in 1,000 annual probability of river or sea flooding.
Zone 2 Medium Probability	Land having between a 1 in 100 and 1 in 1,000 annual probability of river flooding; or land having between a 1 in 200 and 1 in 1,000 annual probability of sea flooding.
Zone 3a High Probability	Land having a 1 in 100 or greater annual probability of river flooding; or Land having a 1 in 200 or greater annual probability of sea flooding.
Zone 3b The Functional Floodplain	This zone comprises land where water has to flow or be stored in times of flood. Local planning authorities should identify in their Strategic Flood Risk Assessments areas of functional floodplain and its boundaries accordingly, in agreement with the Environment Agency.

Table 7: definition of Environment Agency flood zones used (taken from Ministry of Housing, Communities & Local Government, 2019)

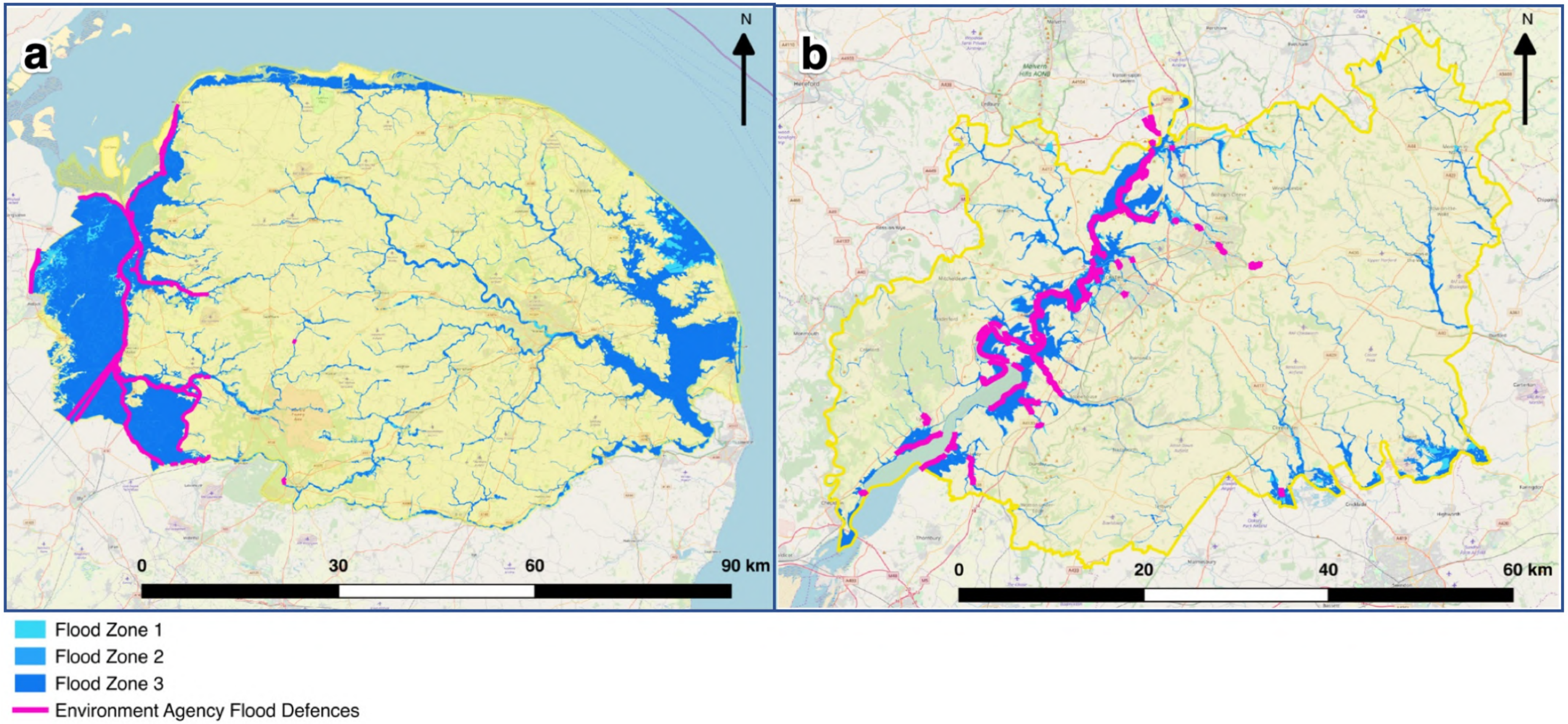


Figure 16: Flood Zone extent for (a) Norfolk and (b) Gloucestershire

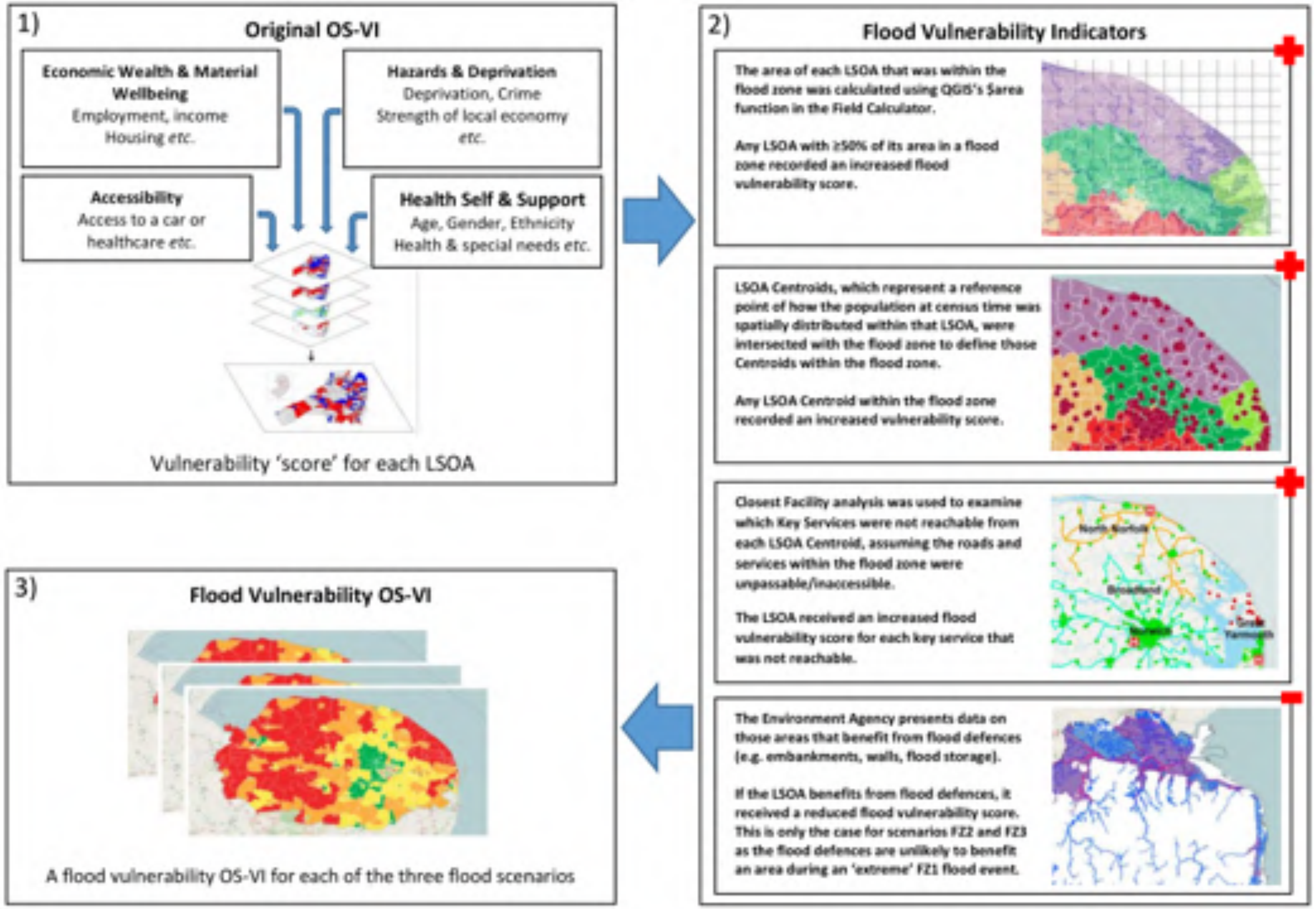


Figure 17: Flow chart outlining the methodology used to develop the flood vulnerability OSVI

4.2 IDENTIFICATION OF VULNERABILITY INDICATORS

It is widely accepted that vulnerability analysis requires the identification of conditions that make people and places vulnerable (White, Kates & Burton, 2001; Anderson & Woodrow, 1989), a measure of societal resilience to identified hazards (Blaikie *et al*., 1994; Hewitt, 1997), and the integration of ‘localised’ exposure potential (Kasperson & Kasperson, 2001; Cutter, *et al*., 2000). The OSVI was constructed with these three assertions (place-based vulnerability, resilience, exposure) at its core.

The OSVI was designed to be indicative, not comprehensive. The selection of indicators had two controlling factors: 1) justification of its relevance to the measure of vulnerability based upon extant data/literature and; 2) the availability of open source data presented at an appropriate geography that is of consistent quality. Although there is no agreement on a single set of vulnerability indicators within the wider literature, there is agreement that vulnerability stems from elements related to economic and material wealth, health, institutional support, accessibility and the presence of hazards (Bruneau *et al.*, 2003; Gunderson, 2009).

Initially, more than 100 variables were collected from the data sources listed above. Through extensive literature analysis, focus group discussions with experts from NGOs and community groups affected by flooding, and testing for multicollinearity among variables, a ‘short list’ of 77 key vulnerability indicators was produced that met the controlling factors. Further discussions, as well as factor analysis that facilitates replication of variables at different spatial scales, reduced the list to a set of four category elements, which are further divided into sub-categories and finally 53 proxy variables and their respective indicators (see Table 1). The OSVI database was prepared as a full England and Wales dataset and filtered for the Norfolk and Gloucestershire case studies herein.

Category	Sub-category	Variable	Indicator[a]	Supporting reference
Economic Wealth and Material Well-being	Employment and Income	49+ hours work week	% of LSOA residents working 49+ hours per week	Tierney, Lindell, and Perry (2001), Dwyer, Zoppou, Nielsen, Day, and Roberts (2004), Lucas, Tyler, and Christodoulou (2009), O'Sullivan, Mulgan, Ali, and Norman (2009), and DCLG (2011)
		Working age unemployed	% of LSOA residents unemployed (economically active)	
		Never worked	% of LSOA residents who have never worked	
		Retired	% of LSOA residents who are retired	
		Working age claiming a Key Benefit	% of LSOA working-age residents claiming a Key Benefit	
		Median household income	% of LSOA households with below-average median income	
	Housing	Central heating	% households in LSOA with no central heating	Morrow (1999), Haki and Akyurek (2004), and Cutter et al. (2003)
		Caravan	% of LSOA whose only accommodation is a caravan	
		One-person households	% of one-person households in LSOA	
		Elderly one-person households	% of one-person households whose occupant is aged 65+ in LSOA	
		Persons per bedroom	% of households in LSOA with more than 1.5 persons per bedroom	
		Residents of communal establishments	% of LSOA residents permanently living in Communal Residences	
Health, Self and Support	Age	Young	% of LSOA residents aged under 16	Schneiderbauer (2007), Haki and Akyurek (2004), Cutter et al. (2003), and O'Sullivan et al. (2009)
		Elderly	% of LSOA residents aged 65+	
		Median age	% of LSOA residents aged above the LSOA median age	
	Gender	Female	% of LSOA residents who are female	Wisner, Blaikie, Cannon, and Davis (2004), Haki and Akyurek (2004), Cutter et al. (2003), and Enarson and Morrow (1998)
	Ethnicity/Race	Non-white	% of LSOA residents who are non-white	Morrow (1999) and O'Sullivan et al. (2009)

Category	Sub-category	Variable	Indicator[a]	Supporting reference
	Health and Special Needs	Working age Incapacity Benefit claimants	% of LSOA residents of working age claiming Incapacity Benefit	O'Sullivan et al. (2009), Morrow (1999), and DCLG (2011)
		Bad health	% of LSOA residents reporting bad and very bad health	
		Limited actions	% of LSOA residents reporting limited actions due to long-term health problems/disability	
		One-person households in bad health	% of one-person households whose occupant reports a long-term health problems/disability	
		Prevalence of unhealthy children	% of children in LA classed as unhealthy (underweight + overweight)	
		Adult mental health service access	LA with adults accessing mental health services above average	
	Education	Low qualifications	% of LSOA residents with less than five GCSEs awards or equivalent	Morrow (1999), Cutter et al. (2008), and DCLG (2011)
		No qualifications	% of LSOA residents with no qualifications	
	Language	English language	% of LSOA residents who cannot speak English well or at all	O'Sullivan et al. (2009), Peguero (2008), Chen et al. (2007), and Trujillo-Pagan (2007)
	Lone Parents	Lone parent households (LPH)	% of LSOA households classed as LPH	Morrow (1999), Bianchi and Spain (1996), Cutter et al. (2008), and DCLG (2011)
		LPH + full-time employment	% of LPH in LSOA where parent is employed	
		LPH + dependent children	% of LPH in LSOA with dependent children	
		Female + LPH + full-time employed	% of LPH in LSOA where parent is female and in full-time employment	
		Female + LPH + unemployed	% of LPH in LSOA where parent is female and unemployed	

Category	Sub-category	Variable	Indicator[a]	Supporting reference
	Carers	Unpaid Care 50 + hours/ week	% of LSOA residents providing care in excess of 50 hours per week	O'Sullivan et al. (2009) and Cutter et al. (2008)
		Unpaid Care 20–49 hours/ week	% of LSOA residents providing care between 20 and 49 hours per week	
	Dependent Children	Three or more dependent children	% of LSOA households in LSOA with 3+ dependent children	O'Sullivan et al. (2009) and Cutter et al. (2008)
		Unemployed with dependent children	% of LSOA households with dependent children where head of household is unemployed	
		Households with one person with LTH and dependent children	% of LSOA households with dependent children where one person has long-term health problems/disability	
Hazards and Deprivation	Presence of Flood Hazard	Centroid Flood Zone	LSOA Centroid within flood zone	Cutter et al. (2008)
		≥50% of LSOA area in flood zone	≥50% of LSOA area in flood zone	
	Deprivation Dimensions	Two or more deprivation dimensions	% of LSOA households with two or more deprivation dimensions	DCLG (2011)
		IMD Score ≥ 50% of max. UK score	LSOA with IMD Score ≥50% of max. score	
		IMD Score ≥ 50% of max. Norfolk score	LSOA with IMD Score ≥50% of max. score	
	Crime	Crime rate	LA reporting a crime rate (5-year average per 1000 population) above national average	DCLG (2011)

Category	Sub-category	Variable	Indicator[a]	Supporting reference
	Strength of Local Economy	Local unemployment	% of LSOA residents unemployed	Norris, Stevens, Pfefferbaum, Wyche, and Pfefferbaum (2008), Cutter et al. (2008), and Van Zandt et al. (2012)
		Individual insolvencies	LA with individual insolvency rate above national average	
		Total bankruptcies	LA with bankruptcy rate ≥50% of 5-year national average	
		House repossessions	LA with house repossessions rate (4-year average per 1000 houses) above national average	
		Landlord repossessions by area	LA with landlord repossessions rate (4-year average per 1000 houses) above national average	
Accessibility	Access to a Car	No car	% of LSOA households with no access to a car	O'Sullivan et al. (2009)
	Access to Infrastructure	Hospital beds	LA with hospital beds per 1000 population below national average	Cutter et al. (2008)
		Car access to a food store	LSOA with car drive time to a food store above national average	
	Access to Health care	Car access to a hospital	LSOA with car drive time to a hospital above national average	Norris et al. (2008) and Auf de Heide and Scanlon (2007)
		Car access to a GP	LSOA with car drive time to a GP above national average	
		LSOA Centroid cut off due to flood zone	LSOA Centroid unable to reach closest hospital due to being cut off by flood zone	

Note: GCSE, General Certificate of Secondary Education.
[a]Unless otherwise stated, each indicator is 'above average': either 'above England and Wales average' or 'above Norfolk average' depending on OS-VI being examined.

Table 1: Full list of OSVI variables/indicators

4.3 DEVELOPMENT OF A VULNERABILITY INDEX

The design of the OSVI was based upon the methodology developed by Cutter *et al*., (2000) and Cutter *et al*., (2003) (and subsequently modified by many, including Wu *et al*. (2002) and Koks *et al*., (2015)). A vulnerability 'score' was produced for each of the 539 Lower Layer Super Output Areas (LSOA) of Norfolk. All indicators were normalised, translated into scale-free relative frequencies per LSOA and reduced to a binary format: with zero representing no vulnerability and one representing the presence of vulnerability. The indicator for each vulnerability variable is based upon the average figure for that variable within England and Wales as a whole *i.e*. for the variable 'percentage of population of LSOA aged 16 or under'. If the result is above the national average, the LSOA is assigned a binary vulnerability score of one for that variable, or if the result is below the average, it is assigned zero. It was felt that the use of an average for each vulnerability indicator (both national and county) offered a suitable measure of potential vulnerability by representing a baseline whereby those below the average are arguably more vulnerable than those above the baseline. OSVI results were ranked (LSOA with the lowest cumulative vulnerability score ranked 1 and the highest score ranked 539), divided into four vulnerability ratings: low, low-moderate, moderate-high and high, and mapped (see Figure 6).

It was decided that a transparent and easy to understand indicator system would be best, given the intent to use the system outside of academia. While a plethora of weighting methods exist that are subjective or reliant upon data analysis, such methods do not adequately reflect the priorities of decision makers (Cutter *et al.,* 2010; Esty *et al.,* 2005). As such, an equal-weighting system was utilised for the OSVI, but team leaders from the consulting NGO were provided with an interactive 'dashboard' whereby they could define the weightings used for the calculation of each vulnerability category so that they could produce an index that represents the priorities of their department.

Two separate OSVI were produced; one based upon variable averages for England and Wales as a whole and one that examines Norfolk in isolation. This was done to provide information on vulnerability in Norfolk in relation to that of

England and Wales but also to identify vulnerability within Norfolk under a local context. The intention of the National OSVI was to present the vulnerability of Norfolk in relation to England and Wales, not in context to England and Wales. What the presented National OSVI does not show is the rating of any given Norfolk LSOA in relation to the other 34,214 LSOA in England and Wales. Only Norfolk LSOA were ranked. It was out of the scope of this project to produce an entire National OSVI. Although several variables were processed at the national level, several key variables, namely those relating to flooding and accessibility, could not be processed to the extent necessary within the given timeframe. The Local OSVI was created using average figures for Norfolk only. This localised OSVI provided a more place-based examination of vulnerability.

4.4 ACCESSIBILITY ANALYSIS

As stated in the Literature Review, access to key services is an important aspect of vulnerability and the loss of capabilities that accompany limited access to key services is well known (Miller, 2003). The UK Government states that 30 minutes is a 'reasonable' time to access a key service (DfT, 2004). Thus, to gain a greater understanding of accessibility within Norfolk, key services within the study area, including hospitals, GP surgeries, large food stores and schools, were mapped using data from OSM, and travel time to these key services was calculated.

Travel time to a hospital was chosen for analysis not due to the potential increased demand for hospital access caused by the flood event – there is little evidence in the UK to suggest that flooding leads to an increase in hospital demand in the immediate aftermath of a flood (Bennet, 1970; Floyd & Tunstall, 2004; Tunstall *et al.*, 2006) – but due to the vital health, wellbeing and social care services that hospitals provide to the rural and largely elderly communities within the study area (Hoard *et al.*, 2005). Any reduction or disruption to these services due to reduced service provision as emergency response work takes priority (Kazmierczak & Kenny, 2011) and routine social care personnel respond to those impacted by the floods (WHO, 2002) or the loss of service due to hospital closure or damage (Greater London Authority, 2013; WHO, 2002) or reduced accessibility due to restricted transport options or damaged transport systems

(Aday, 2001; Morath, 2010; WHO, 2002), could exacerbate pre-existing community vulnerabilities, health concerns and the stresses of flooding (Hajat *et al.*, 2005). In addition, the BRC provides several hospital-related services, including transport to and from hospital for those with restricted mobility and accessibility.

Service Area and Closest Facility analysis was undertaken using QGIS and the routing metadata within an Ordnance Survey ITN road dataset (see Figures 4 and 5). It was assumed all journeys started at the LSOA Centroid and were taken in a car travelling at the maximum speed allowed. The impedance was time and the fastest routes were calculated. Analysis was repeated under flooded conditions where it was assumed that, under the ‘worst case scenario’, all roads within the flood zone would be impassable and that key services would likely be damaged or inaccessible. Thus, roads and key services within the flood zone were restricted. Accessibility results fed into the OSVI, with any LSOA registering travel time to a key service above the average receiving a score of one and all others a score of zero. A case study example of those LSOA that were unable to reach a hospital due to the flood zone restrictions is presented.

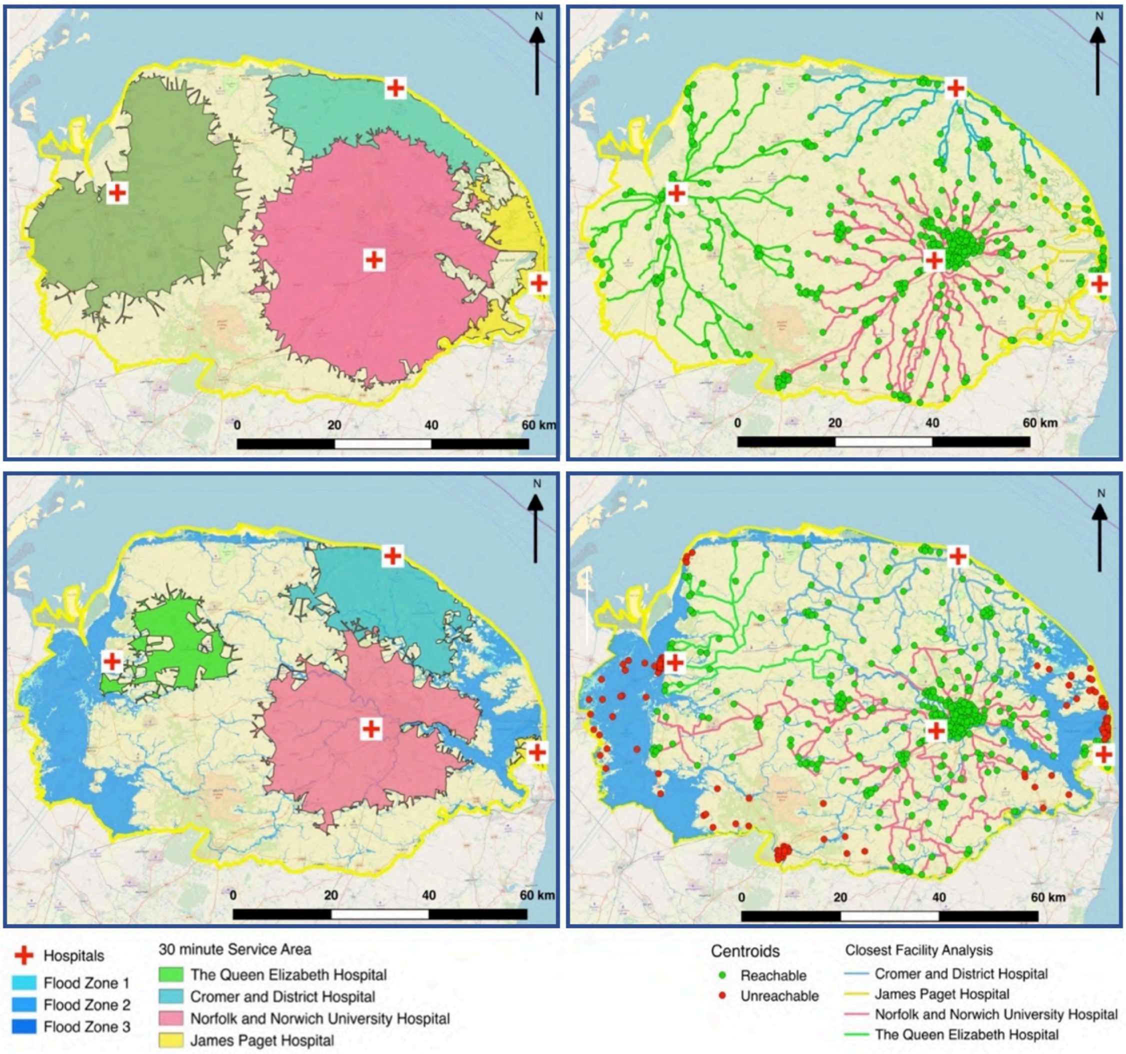


Figure 18: Closest Facility & Route Analysis: Left (a) Service area – 30 minutes travel time from hospitals under non-flooded conditions and (b) Service area – 30 minutes travel time from hospitals under flooded condition. Right (a) Closest facility analysis to nearest hospital under flooded conditions.

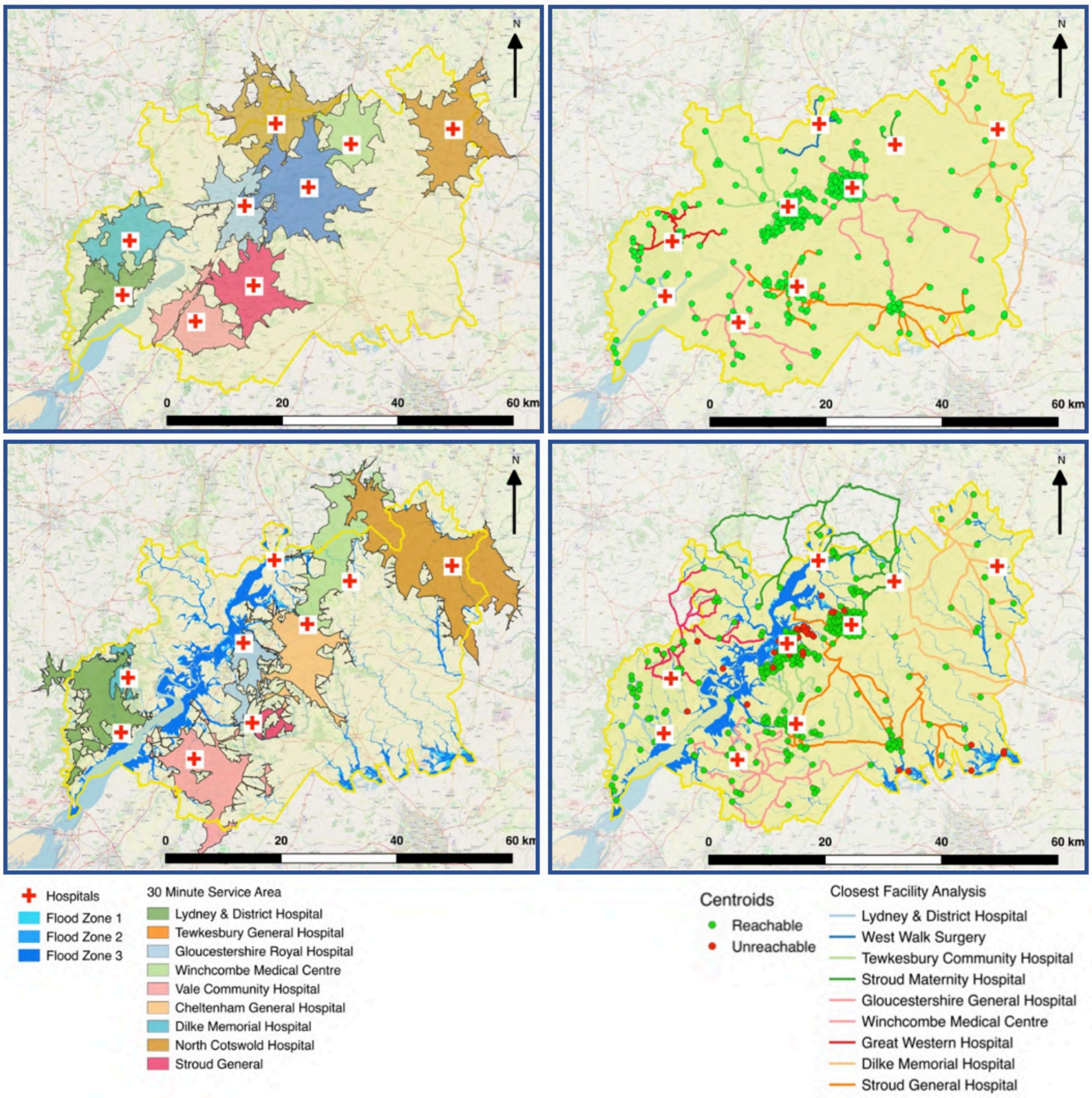


Figure 19: Closest Facility & Route Analysis: Left (a) Service area – 30 minutes travel time from hospitals under non-flooded conditions and (b) Service area – 30 minutes travel time from hospitals under flooded condition. Right (a) Closest facility analysis to nearest hospital under flooded conditions.

4.5 VISUALIZATION

OSVI results were ranked (LSOA with the lowest cumulative vulnerability score ranked 1 and the highest score ranked 539 [Norfolk] or 373 [Gloucestershire]), divided into four vulnerability ratings and, following discussions with NGO sponsors and beneficiaries, visualised in the near-universal and easily understood traffic light style graduated symbology that allows for quick interpretation and is widely recognised within risk and emergency management sectors (see: Cabinet Office, 2010):

1. *low* vulnerability (1-134; 1-92);
2. *low to moderate* vulnerability (135-269; 93-185);
3. *moderate to high* vulnerability (270-404; 186-279);
4. *high* vulnerability (405-539; 280-373).

As is, areas rated *high* indicate areas with a relative higher level of vulnerability because a high number of assessed variables were above average for that LSOA in the National or Local OSVI, suggesting that that LSOA is in a more vulnerable state relative to the average national or county LSOA. Similarly, areas rated *low* indicate areas with a relative lower level of vulnerability and suggest that LSOA is in a less vulnerable state relative to the average national or county LSOA.

4.6 VALIDATION

The creation and validation of a social vulnerability index has several constraints. Besides the limitations discussed in the Literature Review, namely the varied conceptualisations and difficulty in finding empirical evidence about social vulnerability, the creation of the OSVI was largely constrained by data related issues. The typical data problems related to socio-economic indicators (see: King, 2001) such as data availability, quality, gaps, infrequent updates, data decay and normalisation were all present during the development of the OSVI. Cartographic and data representation effects were also acknowledged: challenges related to spatial resolution, level and scale, and potential heterogeneous representation of units and generalisation or stereotyping (see, for example: Meentemeyer, 1989; Blake & Openshaw, 1995; Silverman *et al*., 2013; Turner & Penn, 2002; Fekete, Damm & Birkmann, 2010; Brien *et al*., 2004 for extensive documentation of these effects).

The majority of studies that examine the creation of social vulnerability indices acknowledge that validation of the index is necessary, but not all attempt it (Oulahen *et al*., 2015; Bakkensen *et al*., 2017). Of those that do attempt validation, most use statistical analysis, such as sensitivity and uncertainty analysis (Wu, Yarnal & Fisher, 2002) or random simulation tests of the index through Monte Carlo tests (Gall, 2007), to assess robustness by altering variables or weightings used in index construction (see Schmidtlein *et al*., (2008), Fekete (2009), Oulahen *et al*., (2015b), Eakin & Bojórquez-Tapia (2008), Tate (2012) and Bakkensen *et al.*, (2017) for discussions on statistical validation of social vulnerability indices) and the use of proxies (Schneiderbauer & Ehrlich, 2006). However, as with other such social indicators, accuracy and validity assessment are stymied by the complexity and multidimensionality of contributing factors and the lack of a variable to which indices can be fully validated against – there is no directly observable vulnerability phenomenon to measure or a device to measure it (Schmidtlein *et al.*, 2008; Tate, 2012). Many researchers have attempted to validate social vulnerability indices with independent proxy data, namely mortality (Gall, 2007), economic losses (Schmidtlein *et al.,* 2008) and built environment damage (Burton, 2010), and household surveys (Fekete, 2009). These studies have had limited success (Tate, 2012).

An alternative approach to index validation that few studies rely upon is the use of expert researchers or local practitioners in the production and calculation of vulnerability indices (Emrich & Cutter, 2005; Greiving *et al.*, 2006; Oulahen *et al*., 2015; Fekete, Damm & Birkmann, 2010). The choice of vulnerability indicators used is generally guided by data availability (in terms of access but also scale, resolution and timeframe) or statistical validity (Tate, 2012). Internal validation of indices, or the examination of how changes in index construction affect modelled results, is rare (*ibid*), but rarer still are studies that present their index to local practitioners for validation or incorporate practitioner feedback throughout the construction of the index (Oulahen *et al.*, 2015). If an index is created that is intended to guide local planning or policy making, then those who are involved in making such decisions and those who may use the index should be consulted at multiple stages of its construction (*ibid*). The opinions of local experts, first responders, council members or residents are important given their domain knowledge and experience and can provide guidance on variable inclusion, the scale of analysis, subjective decisions such as weighting, and provide context to outputs (Oulahen *et al.*, 2015; Schmidtlein *et al.*, 2008; Zvoleff & An, 2014).

The access to practitioners offered by the EngD project (as outlined in section 1.1) presented the opportunity to develop a highly participatory and iterative approach to index creation. Focus groups and discussions were held regularly, and feedback was systematically factored in at all stages of the creation of the OSVI: choice of scale, variable and indicator selection, weighting, visualisation *etc*. This external validation process, combined with the provision of supporting literature for all index variables and indicators and reliance upon the OECD guide to constructing composite indicators (OECD, 2008), ensured the creation of a conceptually coherent and robust composite index.

5 RESULTS: OSVI

Introduction	Literature Review	Stakeholder Engagement	Methodology OSVI	**Results OSVI**	Stakeholder Engagement	Methodology Model	Results Model	Discussion	Conclusion
Ch. 1	Ch. 2	Ch. 3	Ch. 4	**Ch. 5**	Ch. 6	Ch. 7	Ch. 8	Ch. 9	Ch. 10

"In a very real sense, social vulnerability mapping reveals disparities that make a difference when it comes to the capacity of residents and households to respond, mobilize resources, and bounce back from natural or other types of disasters."

~ Zandt et al., 2012:51

This chapter[20] presents the results of the OSVI analysis. Data are presented separately for each of the case study areas and then the similarities and differences between the two are discussed. Focus is on the demographics of vulnerability, and the impact of flooding and accessibility on the results. The OSVI is then compared to similar indices. Finally, the OSVI is customised for different BRC Services and the results are presented.

5.1 THE OPEN SOURCE VULNERABILITY INDEX

5.1.1 STUDY AREA ONE: NORFOLK

As can be seen in Figure 20 and Figure 21, the National and Local OSVI display a similar vulnerability distribution. No significant trend was noted that could explain the changes between the two OSVI. Both OSVI present vulnerability within Norfolk as following a general radial pattern around the major urban areas, namely the city of Norwich, with vulnerability high within the urban centre and decreasing outward. A low vulnerability 'ring' can be seen to encircle Norwich, representing the relatively affluent suburbs of Norwich.

[20] The following chapter is adapted from: Garbutt, K., Ellul, C. & Fujiyama, T. 2015 Mapping Social Vulnerability to Flood Hazard in Norfolk, England. Environmental Hazards Vol. 14 No. 2 pp. 156-186.

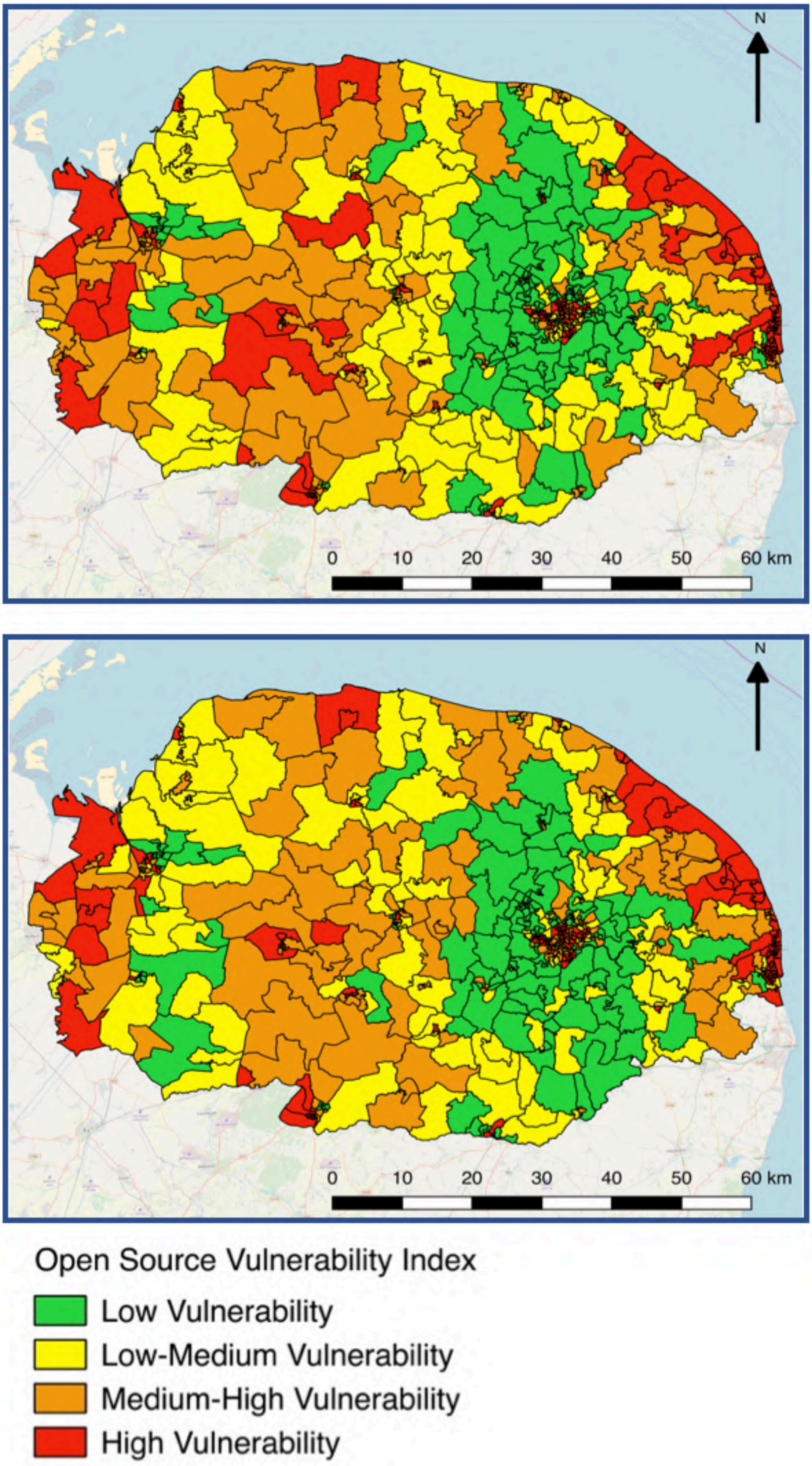


Figure 20: (a) Local OSVI and (b) National OSVI)

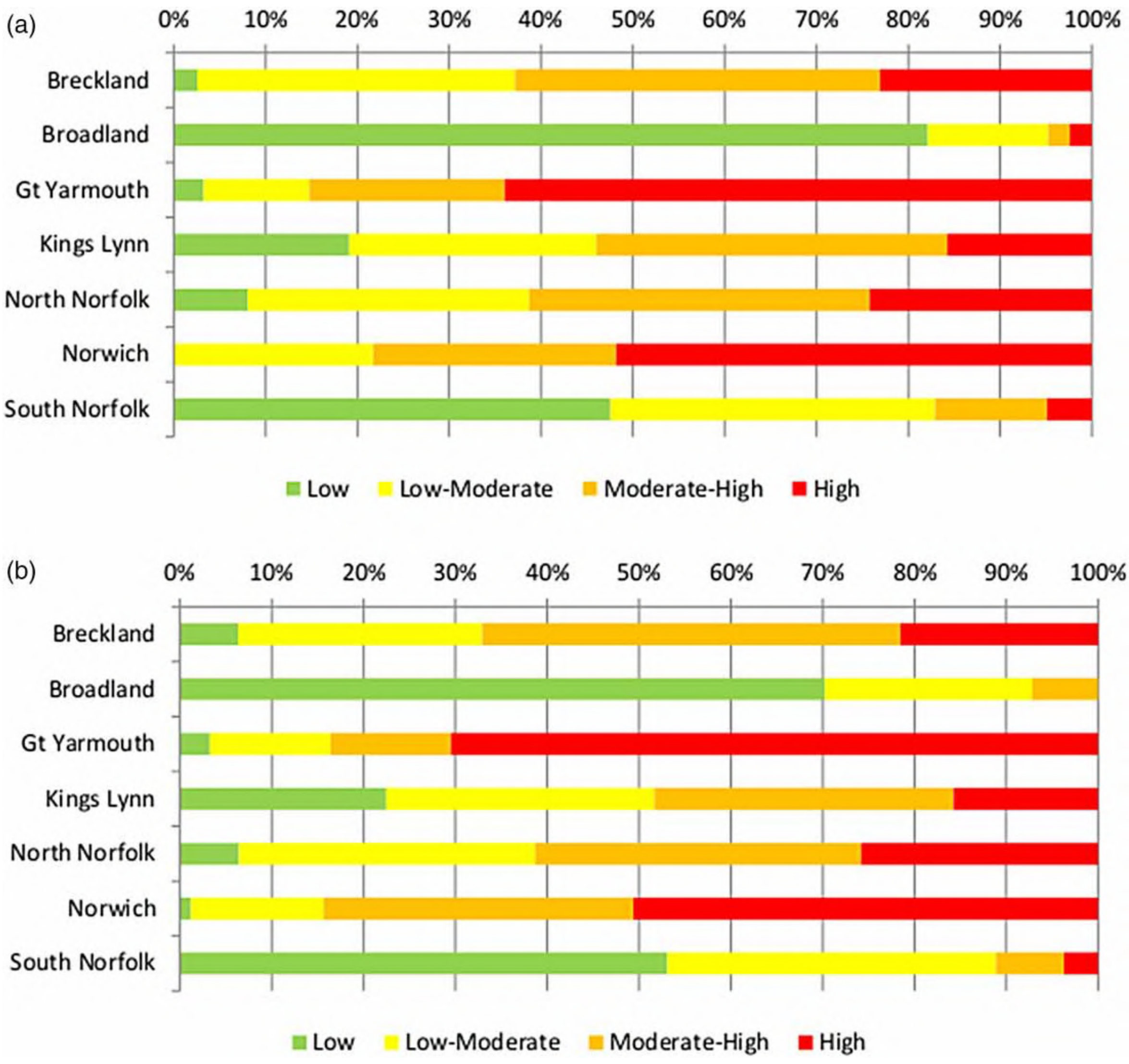


Figure 21: (a) Proportion of each LA in local OSVI by OSVI rating and (b) proportion of each LA in national OSVI by OSVI rating.

The OSVI scores range from 12 (low vulnerability) to 45 out of 53 (high vulnerability) for the full National OSVI, with a mean score of 24, and a range of 6 to 45 out of 53 for the Local OSVI, with a mean of 22. With the exception of two LSOA, the most vulnerable LA is Great Yarmouth, with approximately 85% of LSOA in both indices rated high or moderate-high. Topping off the list as the most vulnerable LSOA is Southtown & Cobholm in Great Yarmouth (E01026635), with a vulnerability score of 45 out of 53 in both indices. This is expected given the area's deprived economy and housing, as well as the general poor health of residents and the presence of a flood hazard across 25% of its area. In comparison, the least vulnerable LA is Broadland, with 91% and 86% of LSOA in that area rated low or low-moderate in the National OSVI and Local OSVI respectively. The least vulnerable LSOA within the National OSVI was Town

(E01026945) in South Norfolk with a score of 12 out of 53. Sprowston Central (E01026556) in Broadland is the least vulnerable LSOA in the Local OSVI, with a vulnerability score of 6 out of 53.

Table 8 shows the variables that contribute the most to the vulnerability scores recorded within the England & Wales OSVI. As can be seen, all 539 LSOA within Norfolk recorded a drive time to a food store in excess of the national average. This was not unexpected given the study areas rural geography, but does represent a major source of vulnerability, particularly given the elderly nature of the area's population (390 LSOA recording above average elderly populations) and its poor health and mobility (366 and 326 LSOA recording above average number of residents reporting limited actions and long-term health problems/ disability respectively).

The LSOA with a high vulnerability rating are characterised by a disproportionate mix of urbanized towns or cities, 70%, compared to rural towns or villages, which account for just 30%. In comparison, the urban-rural divide within those LSOA with a low vulnerability rating is roughly equal, 49% to 51%. For those areas with a low-moderate or moderate-high rating, the urban-rural divide is approximately 40%/60%. Norwich, which is entirely urbanised, recorded only one LSOA with a low vulnerability rating within the National OSVI, with 73% of Norwich LSOA recording moderate-high or high ratings.

Rank	Total number of LSOA (out of 539) recording variable	Variable
1	539	LSOA with car drive time to a food store above average
2	537	Percentage of lone parent households in LSOA with dependent children above average
3	534	Percentage of LSOA residents providing care between 20 and 49 hours per week
4	390	Percentage of LSOA residents aged 65+ above average
5	374	Percentage of LSOA households with below average median income
6	372	Percentage of LSOA residents who are female above average
7	371	Percentage of LSOA residents with no formal qualifications above average
8	366	Percentage of LSOA residents reporting limited actions due to long-term health problems/disability
9	326	Percentage of one-person households whose occupant reports a long-term health problems/disability
10	322	Percentage of LSOA residents providing care in excess of 50 hours per week
11	313	Percentage of LSOA residents working 49+ hours per week
12	309	Percentage of LSOA households with two or more deprivation dimensions

Table 8: Variables contributing most to the vulnerability score

5.1.2 STUDY AREA TWO: GLOUCESTERSHIRE

As can be seen in Figure 22, the National and Local OSVI display a similar vulnerability distribution. As with Norfolk, no significant trend was noted that could explain the changes between the two OSVI. Unlike Norfolk, no radial vulnerability pattern around the major urban areas, with vulnerability high within the urban centre and decreasing outward as the areas become more rural, was noted in Gloucestershire. However, a Northwest/Southeast divide is visible, with vulnerability increasing the further Northwest one travels towards the Welsh border.

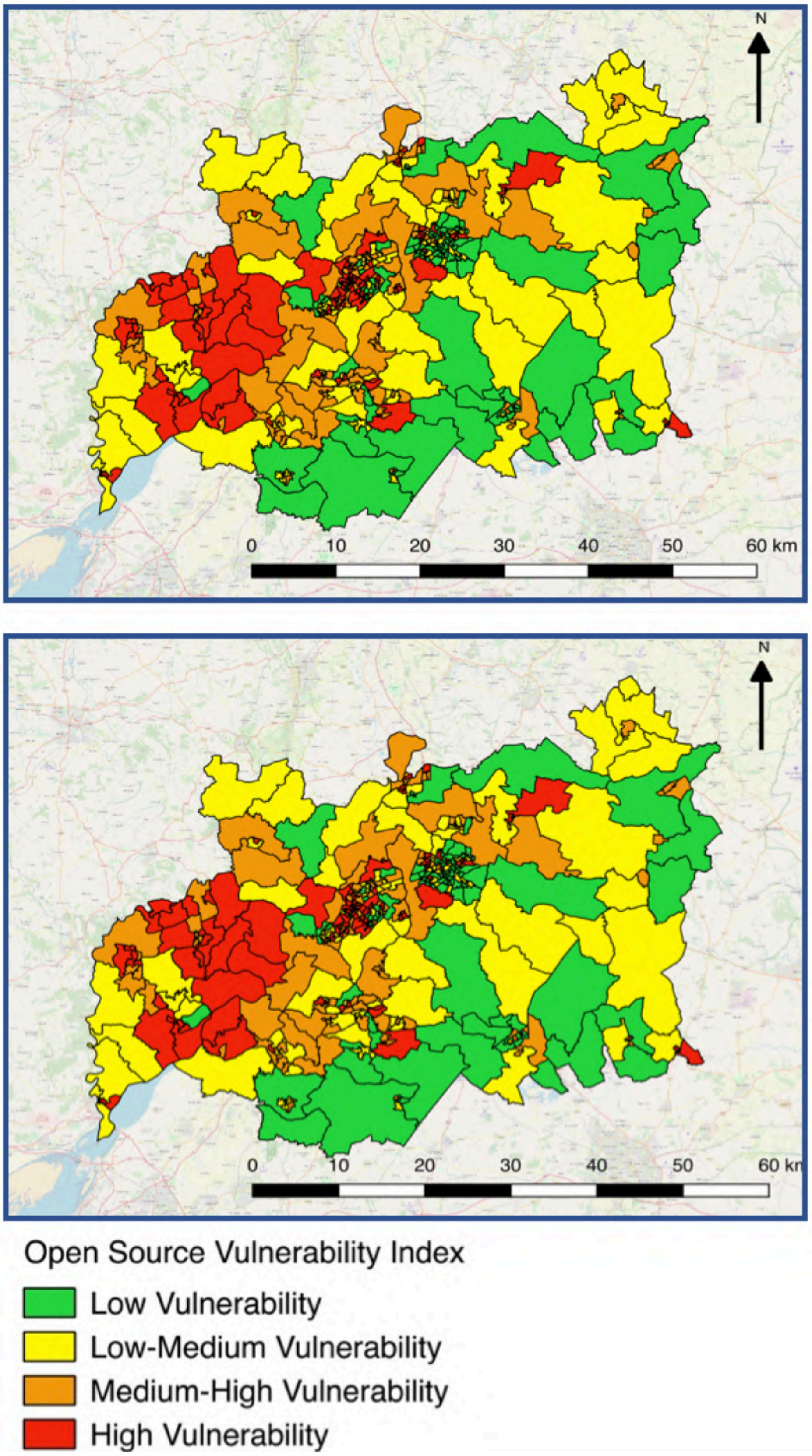


Figure 22: (a) Local OSVI and (b) National OSVI)

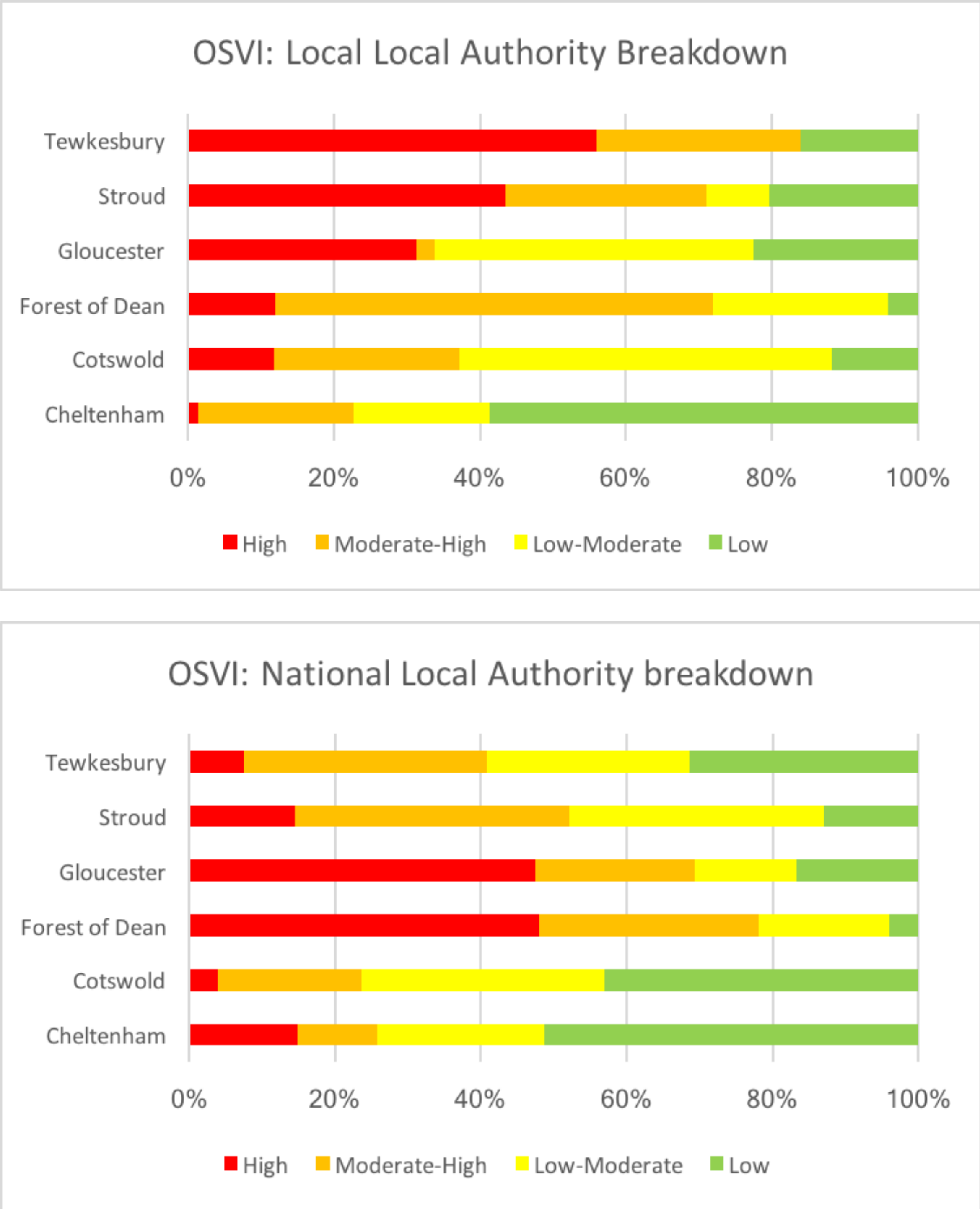


Figure 23: (a) Proportion of each LA in Gloucestershire local OSVI by OSVI rating and (b) proportion of each LA in national OSVI by OSVI rating.

The OSVI scores range from 8 (low vulnerability) to 33 out of 53 (high vulnerability) for the full National OSVI, with a mean score of 17, and a range of 0 to 6 out of 53 for the Local OSVI, with a mean of 1. The most vulnerable LA in the National OSVI is Forest of Dean, with approximately 74% of LSOA rated high or moderate-high, this reduces slightly to 71% in the Local OSVI. In the local

OSVI, Tewkesbury is the most vulnerable, with 84% of LSOA in the LA rated high or moderate-high. Topping off the list as the most vulnerable LSOA in the National OSVI is Gloucester 005B, with a vulnerability score of 33 out of 53. This was expected given that 10 Gloucester districts are in the most 10% deprived nationally within the IMD and the LA in general area has a deprived economy and housing sector and the presence of a flood hazard across 25% of its area. In comparison, the least vulnerable LA in the National OSVI is Cotswold, with 77% of LSOA in that area rated low or low-moderate, followed closely by Cheltenham, with 72% of LSOA in that area rated low or low-moderate. Cheltenham is also the least vulnerable LA in the Local OSVI, with 78% of LSOA in that area rated low or low-moderate. The least vulnerable LSOA within the National OSVI was Cheltenham 013E and Cheltenham with a both recording a score of 8 out of 53. In comparison, 68 LSOA in the Local OSVI recorded 0 out of 53.

Table 9 shows the variables that contribute the most to the vulnerability scores recorded within the National OSVI. As can be seen, all 373 LSOA within Gloucestershire recorded a lower than average number of hospital beds, higher than average house repossessions and lower than average qualifications. Although these factors were not unexpected, they do represent a major source of vulnerability, particularly given the combination of an expanding elderly population in the county, 3% of the population withdrawing from the labour market due to an illness or a disability, and limited access to a car, variables which were found to coexist in several areas and could further entrench economic and social vulnerabilities in these communities (Li, 2013).

LSOA with a high rating were characterised by above average levels of lone parent households with dependent children, households that have two or more Deprivation Dimensions, residents with no qualifications or fewer than five GCSE awards or equivalent, levels of long-term unemployment, and residents who report bad or very bad health. These variables were similarly highlighted in the Norfolk analysis.

Rank	Total number of LSOA (out of 373) recording variable	Variable
1	373	Local Authority with hospital beds per 1000 population below national average
2	373	Local Authority with house repossessions rate above (4-year average per 1,000 households) above national average
3	373	Percentage of residents with less than five GCSE awards or equivalent
4	315	Percentage of households in LSOA with Lone Parent aged 16-74 with Dependent Children
5	265	Percentage of those in LSOA of working age that are Unemployed
6	259	Percentage of residents in LSOA aged above the national median
7	243	Percentage of one person households where person has long-term health problems/disability above UK average
8	236	Percentage of residents aged 65+ above national average
9	234	Percentage of households in LSOA with Dependent children in household above national average
10	219	Percentage of those in LSOA that are Retired

Table 9: Variables contributing most to the vulnerability score

5.2 RURAL AND URBAN VULNERABILITY

A rural/urban divide within vulnerability was noted. Accessibility has already been shown to be impacted by an area's rural or urban characteristics, with flooding further exacerbating rural area's limited accessibility. However, the link between an area's rural/urban make-up and its vulnerability is not as clear. A predominantly rural area's vulnerability appears to be more changeable. For example, North Norfolk, which is 85% rural, recorded approximately 40% *low* or low-moderate ratings; whereas South Norfolk, which is 68% rural, recorded approximately 80% low or low-moderate ratings. However, predominantly urban areas were found to be dominated by high vulnerability ratings. For example, Great Yarmouth, which is 64% urban, recorded approximately 80% high or moderate-high ratings and Norwich, which is completely urbanised, recorded approximately 75% high or moderate-high ratings. This implies that high vulnerability in an area is to some degree related to its urban extent: increased urban space leads to higher levels of vulnerability. However, not all urban areas are equally vulnerable, nor are the underlying vulnerabilities the same. More work is needed to uncover the relationship between rural/urban extent and the factors that influence vulnerability.

The LA of Norwich, which represents the only major city in Norfolk and the most populous region, demonstrates the rural/urban divide of vulnerability well. Within Norwich, the majority of LSOA are rated either moderate-high or high within both OSVI. This high vulnerability urban pattern (Figure 24) is similar amongst both OSVI and is a phenomenon noted within the literature whereby urban centres throughout the world are found to have high rates of vulnerability, as well as deprivation, and are often surrounded by more affluent suburbs with considerably lower levels of vulnerability (Erskine, 2010; Gartner, 2011; Musterd & Ostendorf, 2013). This is evidenced by the two LA that encircle Norwich, Broadland and South Norfolk, both recording much lower levels of vulnerability within both OSVI (Figure 24).

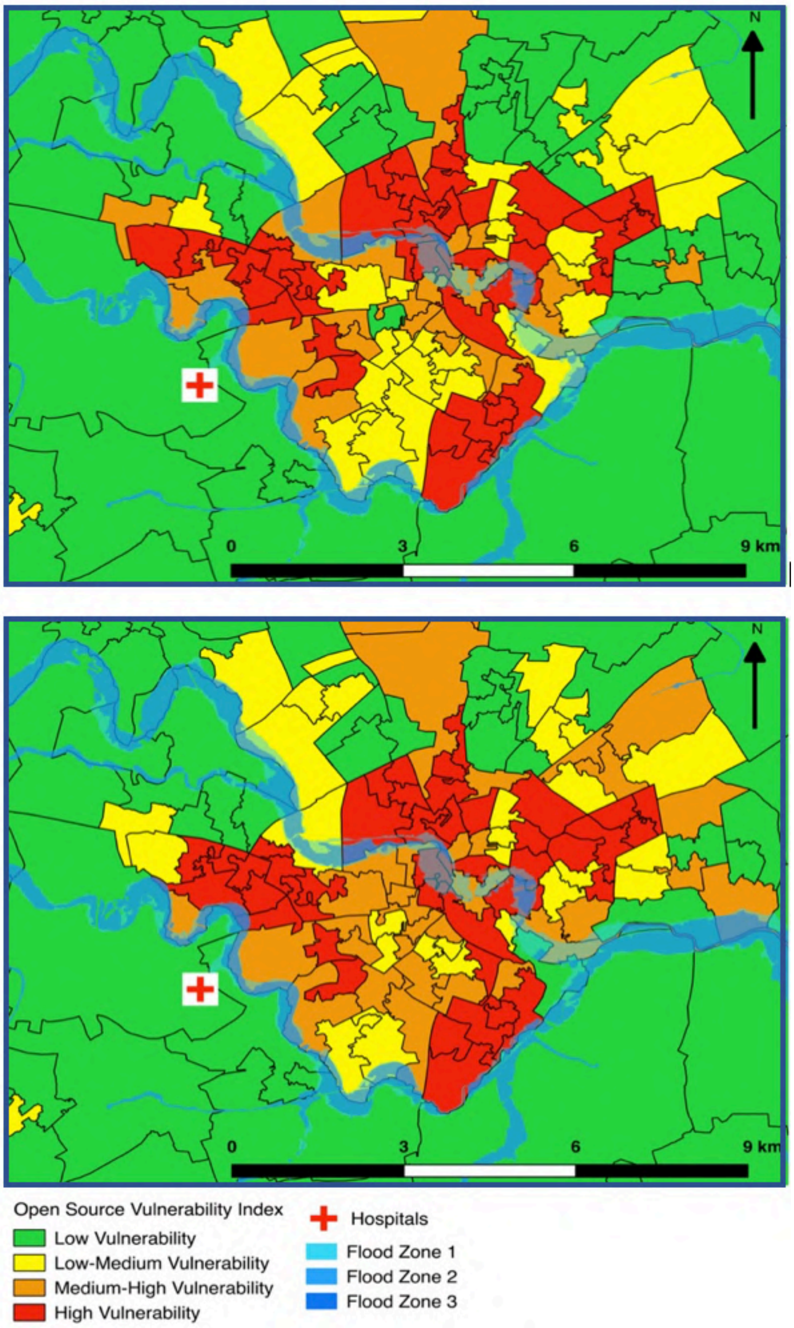


Figure 24: (a) Local OSVI Norwich City detail and (b) National OSVI Norwich City detail

As in the Norfolk case study, LSOA with a high vulnerability rating in Gloucestershire are characterised by a disproportionate mix of urbanized towns or cities, 67% and 76% OSVIL and OSVIN respectively, compared to rural towns or villages, which account for just 33% and 24%. However, in comparison to the Norfolk case study where the urban-rural divide within those LSOA with a low vulnerability rating is roughly equal, 49% to 51% OSVIL and OSVIN respectively, in Gloucestershire the divide is 84/16% and 78/22% for the OSVIL and OSVIN respectively.

For those areas with a low-moderate or moderate-high rating, the urban-rural divide is approximately 70%/30%. Like Norwich, Cheltenham and Gloucester are both entirely urbanised, however the OSVI breakdown is quite different. Whereas Norwich recorded only one LSOA with a low vulnerability rating within the National OSVI, with 73% of Norwich LSOA recording moderate-high or high ratings, 59% and 52% of Cheltenham and LSOA recorded a low vulnerability rating, in the National and Local OSVI respectively. As with the entirely urbanised area of Norwich, both Cheltenham and Gloucester are characterised by above average levels of lone parent households with dependent children, rates of unhealthy (both underweight, overweight or obese) children, working age unemployed residents, residents with low qualifications, and one-person households where the person has long-term health problems/disability.

In comparison, Cotswold is the most rural local authority, with 74% of LSOA classed as 'rural'. As expected, the area is characterised by higher than average number of residents aged 65+ and a higher than average median age. More surprisingly, these characteristics are combined with a higher than average number of residents working in excess of 49 hours per week. This suggests residents are working later in life, possibly due to pension reductions and increasing living costs, a trend noted nationally (Office for National Statistics, 2016; McPhail, 2013).

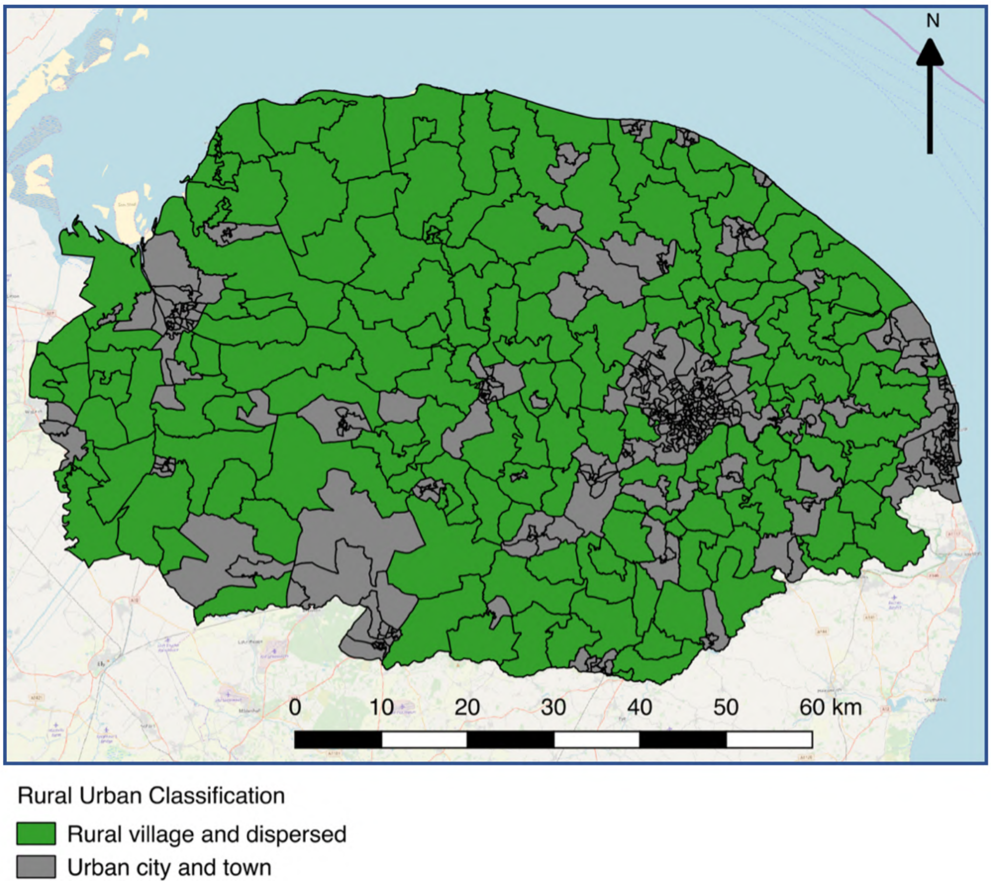


Figure 25: Norfolk Rural/Urban Makeup

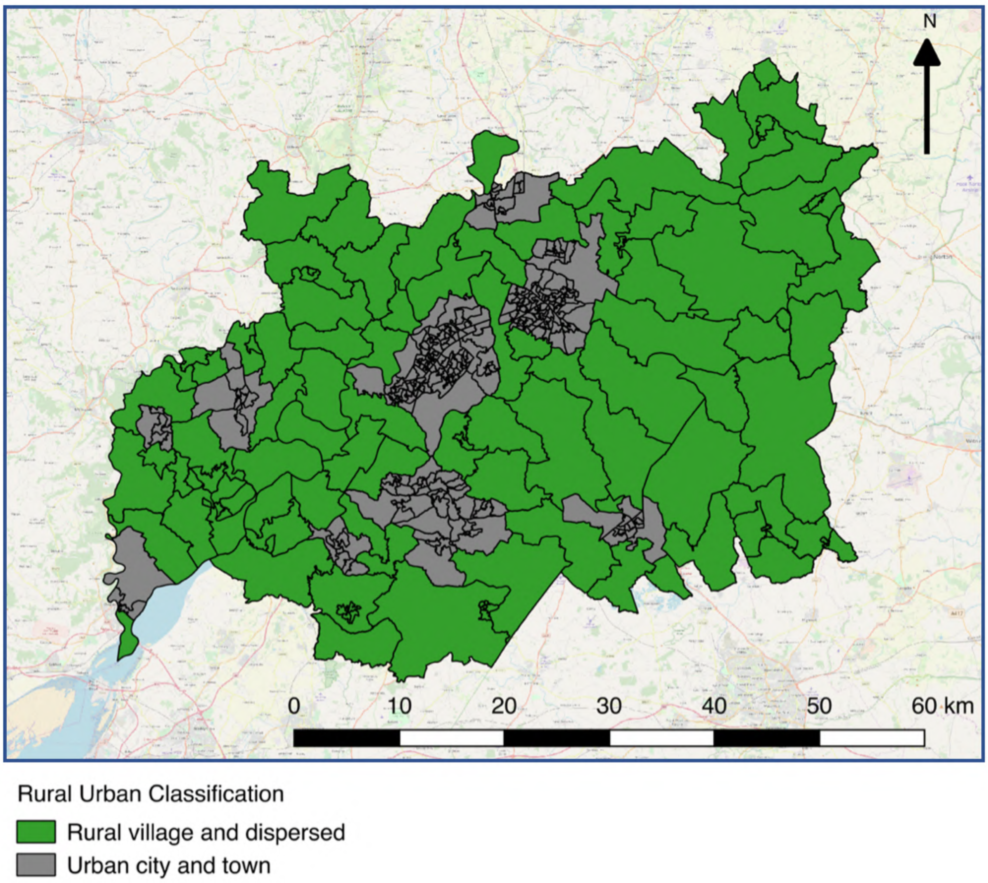
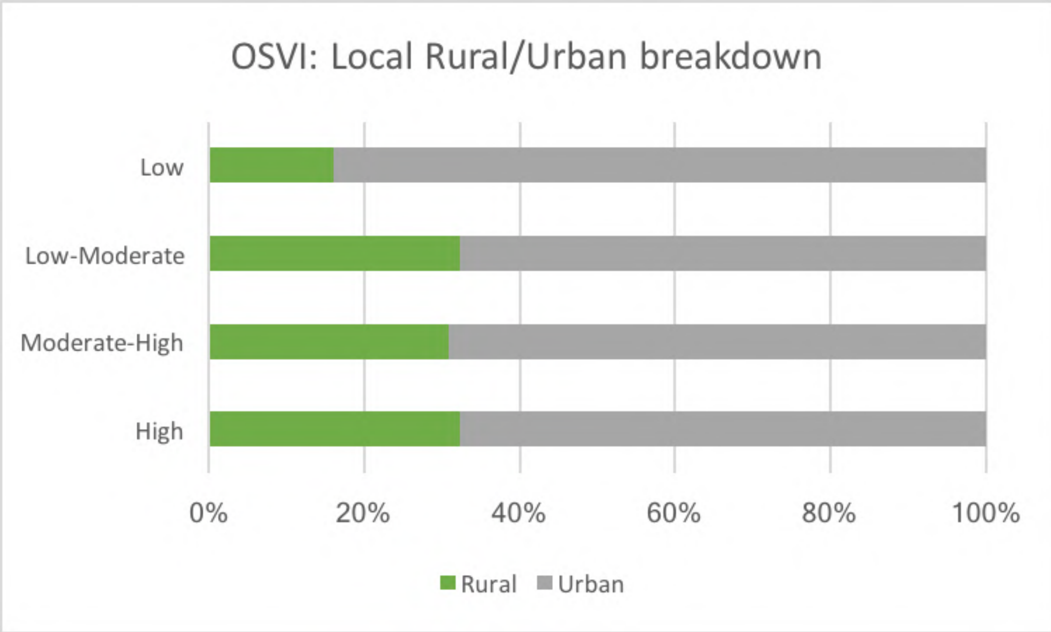


Figure 26: Gloucestershire Rural/Urban Makeup



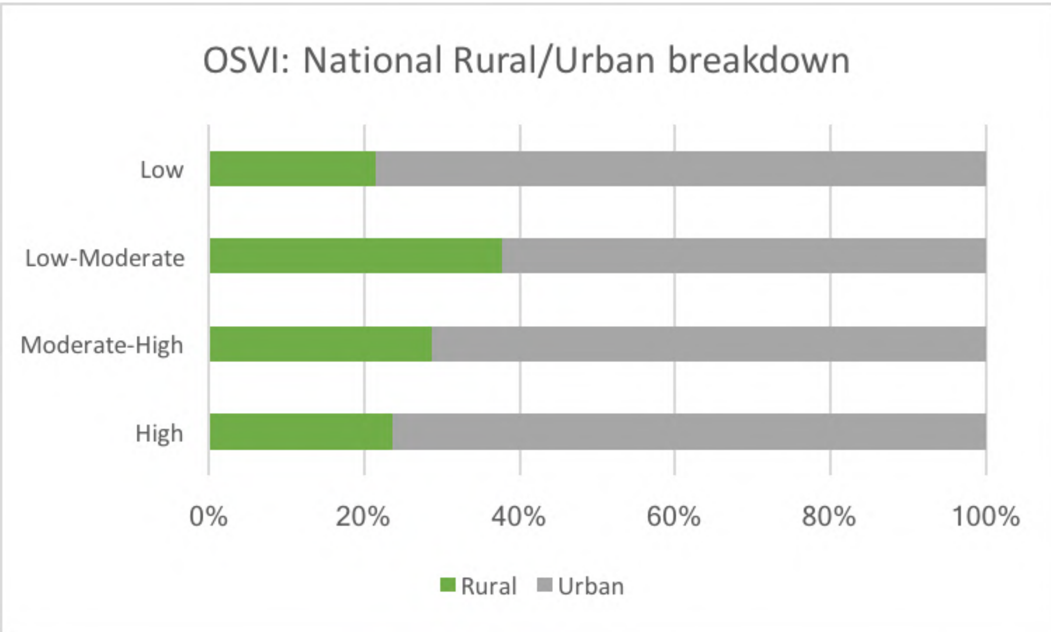


Figure 27: (a) rural and urban breakdown of each LA in Gloucestershire by OSVI Local rating and (b) rural and urban breakdown of each LA in Gloucestershire by OSVI National rating and

5.3 IMPACT OF FLOODING ON VULNERABILITY

Approximately 43% and 26% of the total population of Norfolk and Gloucestershire respectively live in areas with one or more flood indicators, indicating a high exposure to flooding in both study areas. This is also illustrated in Figure 30 and Figure 32 which clearly show that flood prone areas have a higher than average share of the aggregated high socially vulnerable population as highlighted in the OSVI.

In total, 277 of 373 LSOA (74%) in Gloucestershire were found to be impacted by flooding, compared to 30% in Norfolk: 46 LSOA were cut off from hospitals during the flood scenario (compared to 110 in Norfolk); 8 had more than 50% of their area within the flood zone (compared to 57 in Norfolk); and 13 LSOA Centroids were within the flood zone (compared to 33 in Norfolk). Only 1 LSOA recorded all three flood risks: Stroud 003C.

Excluding those within the urban centres of Norwich and Gloucester, the major clusters of LSOA with a high vulnerability rating can be seen loosely to match those areas with greater exposure to the flood zone (see Figure 32). Great Yarmouth in East Norfolk and Kings Lynn and West Norfolk account for 75% of those areas that received a high vulnerability rating and are impacted by flooding in Norfolk. In Gloucestershire, the Forest of Dean in the East of the county 74% of LSOA recorded a high or moderate-high vulnerability rating, despite only 8% of the area's land being covered by flood zone. This is likely due to the area's OSVI being dominated by above average levels of lone parent households with dependent children, rates of unhealthy (both underweight, overweight or obese) children, residents with low qualifications, and households with three or more dependent children. 40% and 37% of those LSOA with a high or moderate-high vulnerability rating were impacted by flooding in some way, compared to just 20% and 22% of those with a low or low-moderate rating in the National and Local OSVI respectively. Further, 79% and 90% of those LSOA with the majority of their area within the flood zone recorded a high or moderate-high vulnerability rating in the National and Local OSVI respectively.

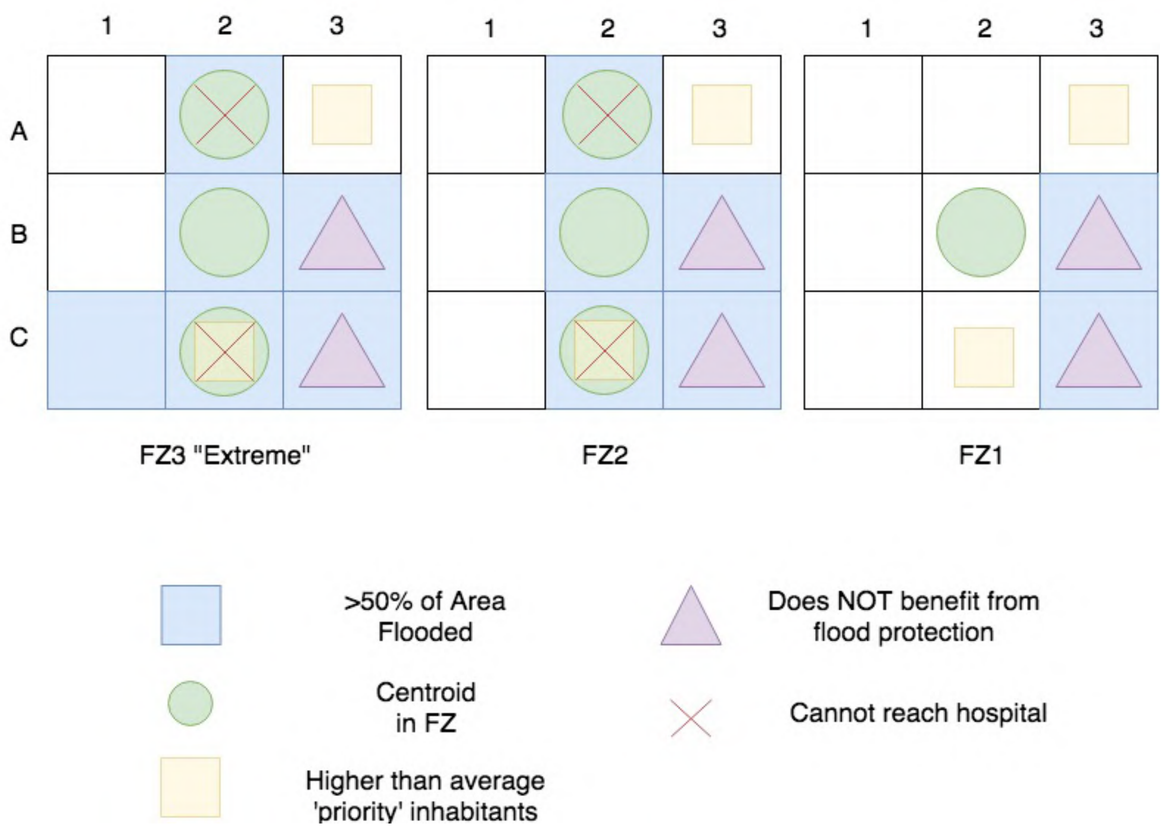
Broadly speaking, those LSOA impacted by flooding were characterised by above average: households where the household reference person is aged 65 and over, households where no adult works and have dependents, households lacking central heating, lone parent households with dependent children, and above average insolvency rates. This is particularly concerning given the potential hazards of flooding and the added stressors of age, dependents and economic recovery.

Gloucestershire analysis was undertaken late in the project timeline. Lessons were learned from the Norfolk analysis and additional flood analysis was undertaken for the Gloucestershire analysis. A 'Cumulative Flood Score' (CFS) was determined for each LSOA in Gloucestershire (see Figure 28). This analysis was later used to determine the impact of flooding on different response strategies (see chapter 9.2.1). The Norfolk flood analysis added one point to the OSVI score of each LSOA if more than 50% of that area was covered by flood zone, or if the area's Centroid was in a flood zone, or if key services were unreachable due to the flood zone, as well as subtracting one point if the area benefitted from Environment Agency flood defences (see Figure 17). In comparison, the CFS for each LSOA was calculated by summing the following factors:

- +1 if >50% of the LSOA area is in flood zone 1.
- +1 if >50% of the LSOA area is in flood zone 2.
- +1 if >50% of the LSOA area is in flood zone 3.
- +1 if the LSOA Centroid is in the flood zone.
- +1 if the LSOA is NOT in an area benefiting from Environment Agency Flood Defences and is in an area at risk of flooding.
- +1 if Closest Facility analysis determines that the LSOA Centroid can NOT reach a hospital.
- +1 for each 'priority' grouping (as defined in consultation with BRC staff and volunteers)
    - +1 for a higher than average number of elderly individuals.
    - +1 for a higher than average number of disabled individuals.

- +1 for a higher than average number of individuals with bad or very bad health.
- +1 for a higher than average number of individuals with limited actions due to a long-term health problem/disability.
- +1 for a higher than average number of one-person households.

This analysis gives every LSOA in Gloucestershire a CFS between 0 and 11 (0-6 for flood factors, 0-5 for 'priority' grouping factors). See Figure 31 for a map displaying the CFS for each LSOA in Gloucestershire.



FZ Score

	1	2	3
A	0	3	1
B	0	2	2
C	1	4	2

FZ Score

	1	2	3
A	0	3	1
B	0	2	2
C	0	4	2

FZ Score

	1	2	3
A	0	0	1
B	0	1	2
C	0	1	2

Figure 28: Example Cumulative Flood Score (CFS) Diagram

Flood Impact Score (FIS)				
Indicators	**LSOA**			
	1	**2**	**3**	**…**
LSOA Centroid is in the flood zone	1	0	0	…
LSOA is in flood zone but is **NOT** in an area benefiting from Environment Agency Flood Defences	0	1	0	…
Closest Facility analysis determines that the LSOA can **NOT** reach a hospital	1	1	0	…
>50% of the LSOA area is in flood zone 1	1	1	1	…
>50% of the LSOA area is in flood zone 2	1	1	0	…
>50% of the LSOA area is in flood zone 3	1	0	0	…
Total:	**5**	**4**	**1**	**…**

Priority Resident Score (PRIOS)				
Indicators	**LSOA**			
	1	**2**	**3**	**…**
Higher than average number of elderly individuals	1	0	0	…
Higher than average number of individuals with bad or very bad health	1	0	1	…
Higher than average number of individuals with limited actions due to a long-term health problem/disability	1	0	1	…
Higher than average number of one-person households.	1	1	0	…
Higher than average number of households with dependent children	1	0	1	
Total:	**5**	**1**	**3**	**…**

Cumulative Flood Priority Score (CFPS)				
	LSOA			
	1	**2**	**3**	**…**
Cumulative Total (FIS + PRIOS = CFS):	10	5	4	…

Table 10: Example Cumulative Flood Priority Score (CFPS)

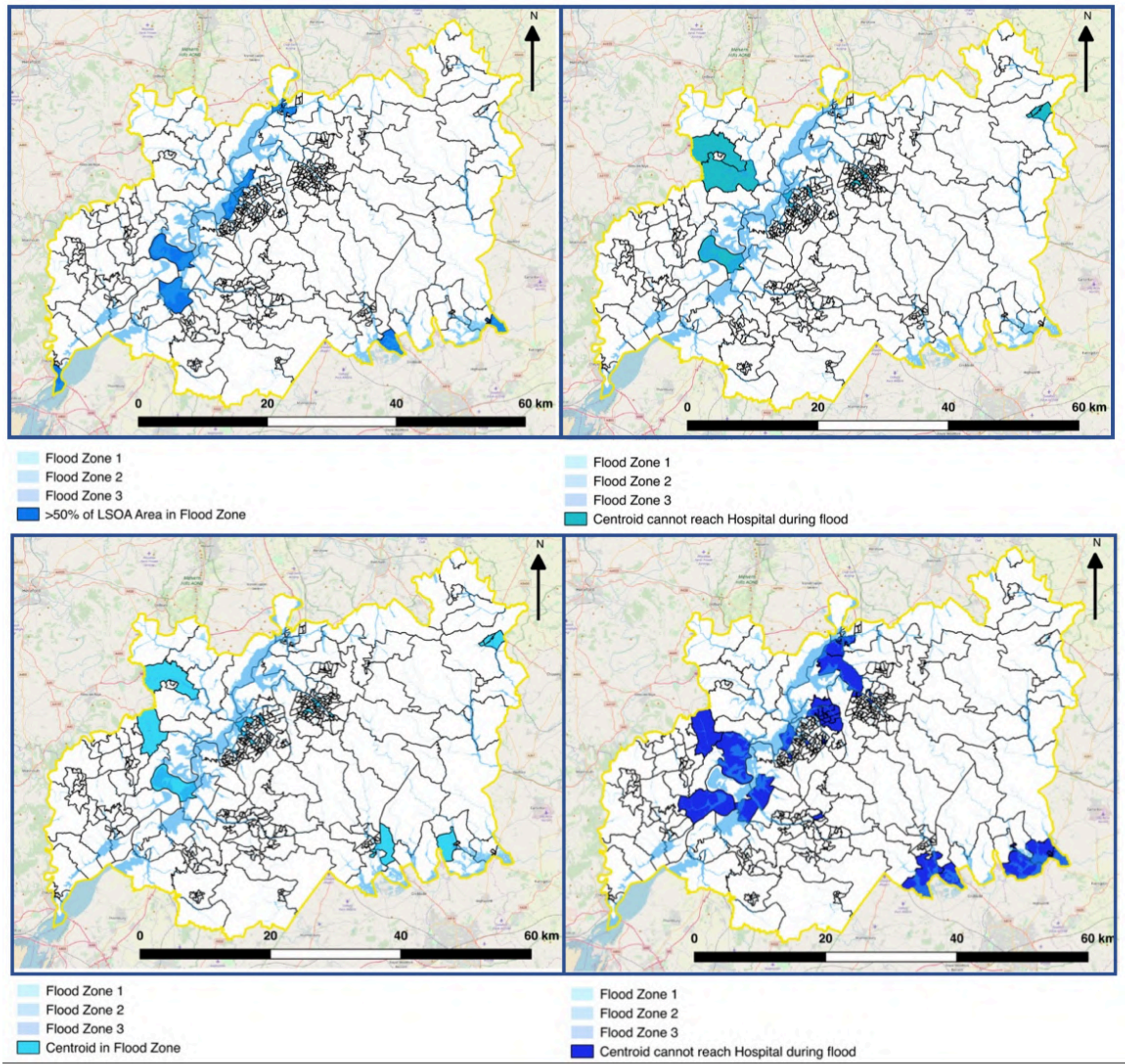
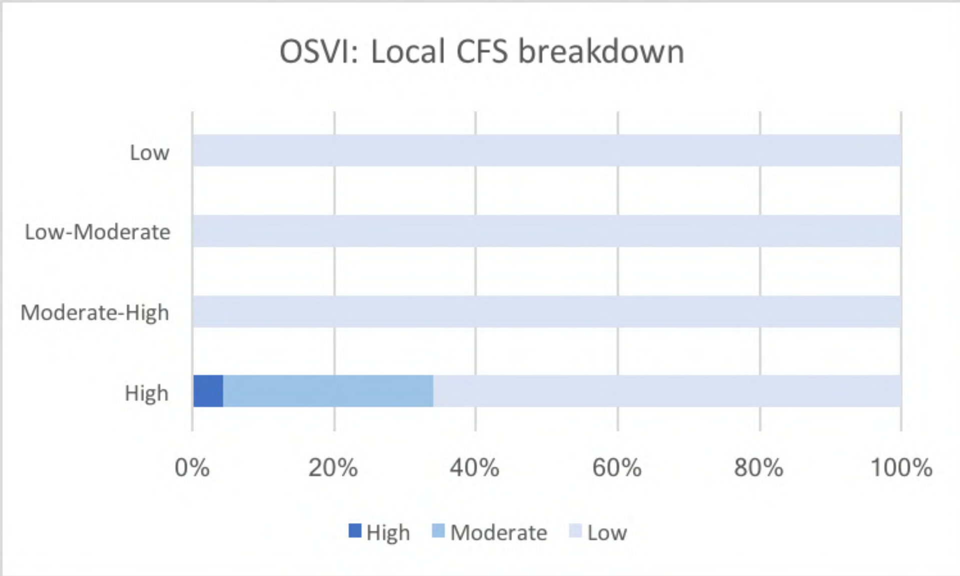


Figure 29: Gloucestershire CFS rating

As can be seen in Figure 30, only LSOA that recorded a high vulnerability rating in either National or Local OSVI recorded high CFS scores. In comparison, no LSOA with a low rating in either the National or Local OSVI recorded moderate or high CFS scores. This further suggests an underlying causal relationship between proximity to the hazard and socio-economic and health vulnerabilities – a trend noted by other authors (see: Alexander, 1993; Blaikie *et al*., 1994; Watts & Bohle, 1993) – although the relationship remains unclear and further study is needed.



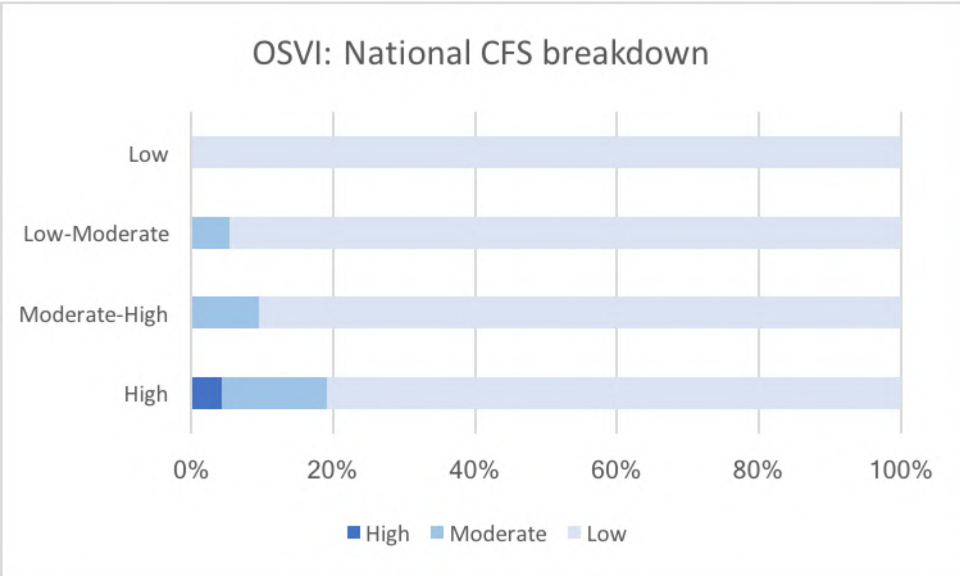


Figure 30: Gloucestershire CFS Breakdown by OSVI Rating

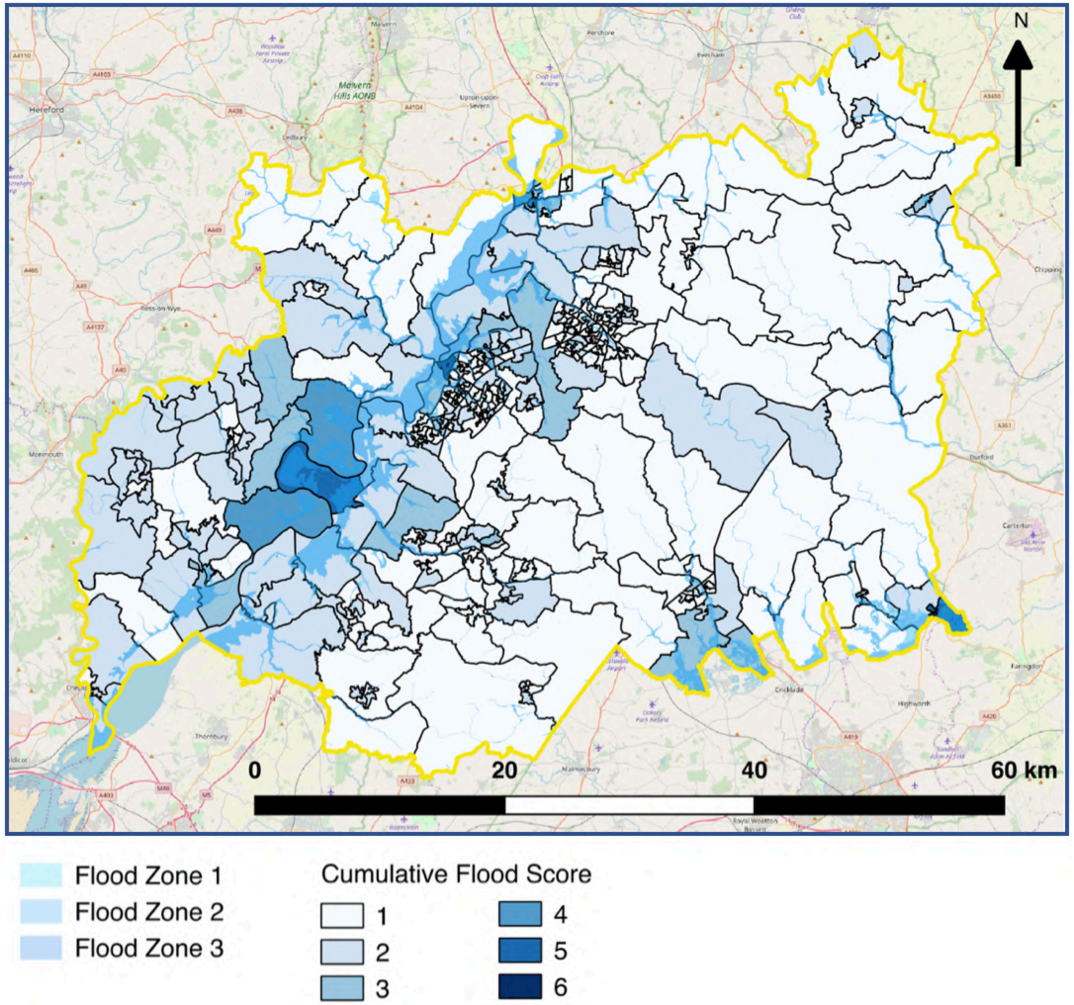


Figure 31: Gloucestershire Cumulative Flood Score Map

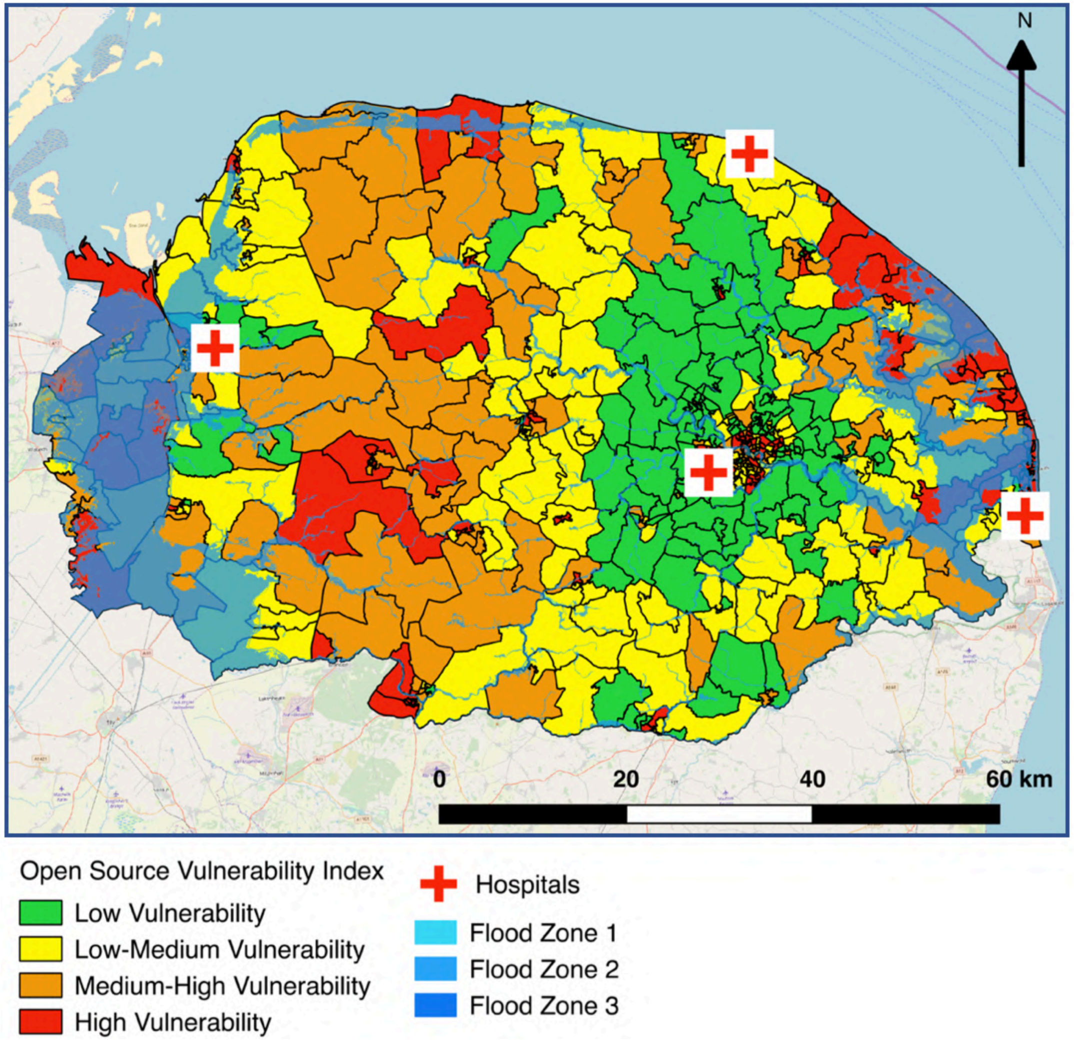


Figure 32: OSVI: Vulnerability Index under FZ3 'extreme flood' scenario featuring flood data overlay

5.4 IMPACT OF ACCESSIBILITY ON VULNERABILITY

Accessibility analysis found that travel time to a hospital in normal, non-flooded, conditions in Norfolk ranged from 1 to 62 minutes (see Table 11). Norwich was the most accessible area in terms of drive time, with most key services reachable within an average of 12 minutes. Breckland and Gt Yarmouth were the least accessible LA: travel time ranged from 19 to 62 minutes, with an average of 41 minutes in Breckland; and 90% of LSOA recorded travel time in excess of 30 minutes in Gt Yarmouth. The LSOA Suffield Park (E01026778) in North Norfolk recorded the lowest drive time under both 'normal' and 'flooded' scenarios, just 1 minute. In Gloucestershire, under the same conditions, the average drive time to a hospital was 10 minutes, with a range of 1 minute to 52 minutes (see Table 12). The majority of LSOA could reach key services in under 30 minutes.

Under the flood scenario, when all roads within the flood zone were restricted, 110 of 539 LSOA could not reach a hospital, 38% of these were in Kings Lynn and West Norfolk. 150 LSOA recorded travel times in excess of 30 minutes during normal conditions. This increases to 179 during flooded conditions, or 289 when LSOA with no access are included. 236 LSOA recorded no change in travel time. The LSOA with the largest change in travel time between 'normal' and 'flooded' conditions, and subsequently the longest overall travel time, was Watlington in Kings Lynn and West Norfolk (E01026722), which saw an increase of 104 minutes: from 22 to 126 minutes.

Accessibility in Norfolk is largely controlled by the rural/urban makeup of each area. 50% of Norfolk LSOA are listed as rural, with 59% of those listed as being dispersed or in a sparse setting. Travel time to a hospital in rural LSOA increased by 62% from an average of 29 minutes during non-flooded conditions to 47 minutes during the flooded scenario. For urban LSOA, travel time increased by 29% from an average of 17 to 22 minutes.

Scenario	Analysis	
'Normal'	Centroids located in FZ	N/A
	LSOA unable to reach hospital	N/A
	Drive time to hospital <30 minutes	405
	Drive time to hospital >30 minutes	134
	Drive time to hospital >60 minutes	0
	Shortest journey	1 minute
	Longest journey	52 minutes
	Average drive time	12 minutes
FZ3	Centroids located in FZ	33
	LSOA unable to reach hospital	110
	Drive time to hospital <30 minutes	150
	Drive time to hospital >30 minutes	188
	Drive time to hospital >60 minutes	91
	Shortest journey	1 minutes
	Longest journey	126 minutes
	Average drive time	35 minutes

Table 11: Norfolk Closest Facility Analysis Summary

In comparison to Norfolk, the rural/urban makeup of Gloucestershire does not appear to control accessibility. This was expected due to the predominantly urban makeup of the county compared to the predominantly rural makeup of Norfolk. However, the increases in travel time from 'normal' conditions to flooded were orders of magnitude more in Gloucestershire compared to Norfolk. Travel time to a hospital in rural LSOA increased by 325% from an average of 12 minutes during non-flooded conditions to 51 minutes during the flooded scenario. For urban LSOA, travel time increased by 444% from an average of 9 to 49 minutes.

Scenario	Analysis	
'Normal'	Centroids located in FZ	N/A
	LSOA unable to reach hospital	N/A
	Drive time to hospital <30 minutes	361
	Drive time to hospital >30 minutes	12
	Drive time to hospital >60 minutes	0
	Shortest journey	30 seconds
	Longest journey	51 minutes
	Average drive time to hospital	12 minutes
FZ3	Centroids located in FZ	14
	LSOA unable to reach hospital	59
	Drive time to hospital <30 minutes	229
	Drive time to hospital >30 minutes	85
	Drive time to hospital >60 minutes	17
	Shortest journey	30 seconds
	Longest journey	101 minutes
	Average drive time to hospital	22 minutes

Table 12: Gloucestershire Closest Facility analysis statistics by flood scenario

Comparative analysis found that average travel time to a hospital across Norfolk as a whole under flooded conditions increased by 52%, from an average of 23 minutes to 35 minutes. Norwich was again the most 'accessible' area, with average travel time remaining at 12 minutes and all LSOA available to reach a hospital. In comparison, Kings Lynn and West Norfolk saw the largest travel time increase: recording a 223% increase from an average of 21 to 68 minutes. In addition, 48% of Kings Lynn and West Norfolk LSOA Centroids could not reach a hospital. Gt Yarmouth remains the least accessible LA, with 57% of Great

Yarmouth LSOA unable to reach a hospital during flooded conditions and the local hospital, the James Paget University Hospital, largely cut off by the flood zone (see Figures 4 and 5). The number of LSOA in Great Yarmouth without reasonable accessibility increases to 90% when those with travel time over 30 minutes are included.

Gloucestershire analysis was undertaken following the decision to calibrate the ABM using a reasonably well documented BRC response case study. Subsequently, given the lessons learned from the Norfolk analysis, additional analysis was undertaken. For example, it was decided to examine the impact of ‘edge effects’ on accessibility analysis. Norfolk’s closest facility analysis was limited to within the Norfolk county boundary and to key services within the county only. For the sake of comparison, the same was done for Gloucestershire accessibility analysis. However, to examine ‘edge effects’ better, closest facility analysis was not restricted to within the Gloucestershire county boundary and key services within the surrounding areas were included. It was felt that this would provide a more realistic examination of accessibility. For example, residents of the Cotswold LSOA of 005B are much closer to the accident and emergency Great Western Hospital in Swindon but restricted accessibility analysis requires residents travel twice the distance to the Stroud General Hospital, a minor injuries hospital, or three times the distance to the Cheltenham General Hospital, an accident and emergency hospital. Table 13 outlines the changes in travel times and Centroid access under both restricted and unrestricted analysis. It can be seen that unrestricted analysis allows more Centroids to reach key facilities due to the ability to reroute outside of the county and, if closer, route to the Great Western Hospital in Swindon, an Accident and Emergency hospital nine miles outside the Gloucestershire county line. As would be expected, under the ‘normal’ scenario, travel time decreases in the unrestricted analysis. Similarly, as would be expected, travel times and the number of Centroids unable to reach a key service increase as the severity of the flood zone increases, and unrestricted values are lower than restricted.

Scenario	Analysis	Restricted Analysis	Unrestricted Analysis	% change
'Normal'	Average drive time	12 minutes	9 minutes	-25%
	Shortest journey	30 seconds	30 seconds	0
	Longest journey	51 minutes	41 minutes	-19%
	Unable to reach hospital	0	0	0
FZ1	Average drive time	15 minutes	13 minutes	-13%
	Shortest journey	30 seconds	30 seconds	0
	Longest journey	85 minutes	61 minutes	-31%
	Unable to reach hospital	34	28	-17%
FZ2	Average drive time	22 minutes	18 minutes	-18%
	Shortest journey	30 seconds	30 seconds	0
	Longest journey	89 minutes	67 minutes	-24%
	Unable to reach hospital	44	38	-13%
FZ3	Average drive time	22 minutes	18 minutes	-18%
	Shortest journey	30 seconds	30 seconds	0
	Longest journey	101 minutes	77 minutes	-23%
	Unable to reach hospital	59	44	-25%

Table 13: Comparison of Travel Time and Centroid Access under Restricted and Unrestricted Routing Analysis

Table 13 shows a comparison of the restricted routes available under the FZ3 scenario and unrestricted routes available under the same FZ3 scenario. It can be seen that some routes that were previously unable to reach a hospital under the restricted analysis can navigate outside of the county and around the flood zone to reach a hospital.

5.5 INDEX COMPARISON

When both the National and Local OSVI are compared, there is little variation within the overall distribution of the vulnerability scores. No significant trend in the changes of vulnerability ratings was determined. Between both OSVI the range in vulnerability scores was +/-12 and only one instance of an LSOA vulnerability rating changing by more than one gradation *i.e.* from a low to high was found. Instead most changes were subtler, with the vulnerability rating changing by only one gradation *e.g.* from moderate-high to high. The vulnerability rating of Bowthorpe (E01026794) in Norwich increased from a low-moderate rating in the National OSVI to a high rating in the Local OSVI and represents a change in vulnerability score of +/-3, suggesting the LSOA is far more vulnerable within a local context than it is relative to the rest of England and Wales. Examination of the area's underlying vulnerability variables found this was due to the LSOA having above average unemployment amongst working age residents as well as above average claimants of working age benefits, residents with low qualifications and households with female lone parents in full-time employment within the Local OSVI. This highlights the level of detail and the local-level context that the OSVI can reveal.

The findings from the OSVI correspond very closely to oft-cited poverty and deprivation maps produced by, for example, the information services group Experian (Experian, 2014). In particular, ~80% of those areas with a high OSVI rating fall within those Local Authorities highlighted within the Experian maps (Rogers, 2012) as having the greatest overall risk of poverty, the largest instances of child poverty, and the largest proportion of households whose income is less than 60% of the median for England – all seen as indicators of vulnerability (Noble *et al.*, 2000; Hills, 2012; Whelan & Bertrand, 2005).

The pattern of vulnerability displayed within the OSVI: a general radial configuration with vulnerability decreasing with distance from major urban areas, was found to differ from the pattern of deprivation displayed in the Index of Multiple Deprivation 2010 (IMD), a LSOA level measure of deprivation produced by the University of Oxford for the UK Government's Department for

Communities and Local Government (McLennan *et al.*, 2011). Contrary to the OSVI, the IMD ranking within major urban areas, such as the city of Norwich, and several of the coastal LSOA within the flood zone are characterised by relatively low deprivation. Similarly, many of the suburban areas with *low* OSVI ratings record high deprivation ratings within the IMD. Although the OSVI and IMD are measuring different concepts – vulnerability and deprivation respectively – the working definitions of the two concepts and the indicators being measured are deemed sufficiently similar to warrant comparison. The differences in the display of vulnerability and deprivation is undoubtedly due to the methodological differences between the two indices and, in particular, the IMD's focus on income and employment deprivation and its exclusion of hazards and accessibility measures as well as the equal weighting of categories within the OSVI compared to the subjective weightings of domains within the IMD. Combined, the Income Deprivation Domain and the Employment Deprivation Domain within the IMD are weighted to account for 45% of the overall IMD score. An examination of the variables within these domains, all of which relate to families claiming forms of tax credits or claimants of unemployment-related benefits amongst working age residents, explains why areas along the coast that are characterised by retired populations whose age and economic status likely excludes them from those key IMD indicators record a relatively low IMD ranking, yet score a high OSVI rating. In addition, indices like the IMD more often than not focus on predominantly urban concerns, such as unemployment, benefits claimants and poor housing, to the detriment of rural concerns such as social isolation and accessibility (see: Farrington & Farrington, 2005; OCSI, 2012; Preston & Rajé, 2007).

We see the OSVI as a complementary tool to the IMD. The OSVI is more inclusive, considering a broader range of economic as well as social indicators that address vulnerability in both urban and rural areas, and provides greater local context than the IMD, highlighting potential vulnerability hotspots.

In an international context, the findings from the OSVI compares to those produced by social vulnerability analyses for other areas, including the United States (Cutter *et al*., 2013) China (Zhou *et al*., 2014) the United Kingdom (Tapsell *et al*., 2002; Fielding & Burningham, 2005) Israel (Felsenstein & Lichter, 2014) and Germany (Alexander Fekete, 2009). The study presented here differs from previous studies due to its focus on using a wide array of small-scale, household-level data. In scope, focus and methodology, the OSVI and the findings presented, are comparable to the work of Koks *et al*. (2015) who focused on assessing flood risk management (FRM) strategies and combining the presence of flood hazard, exposure and a social vulnerability index to examine flood vulnerability in Rotterdam, Netherlands. Whereas Koks *et al*. (2015) were able to examine social demographics at a smaller scale (postcode level, approximately 20 households), their study relies upon just eight variables, compared to the 53 variables in the OSVI. The findings from the OSVI correspond very closely to those of Koks *et al*. (2015), namely the substantial share of the study population that can be defined as socially vulnerable and the heterogeneous nature of this group, a detail the authors note is often missed in FRM studies. In addition, the oft reported correlation that highly vulnerable people are more likely to live in flood-prone areas is found in the analysis of the OSVI, but, as found by Koks *et al*. (2015), the relationship appears less significant. The reason behind this is believed to be the differences in housing markets: for example, in the US property prices are often much lower in flood-prone areas and so attract lower income and often more vulnerable individuals (Bin & Landry, 2013). In comparison, the price differential between houses in and out of flood-prone areas is less prominent in the UK and The Netherlands (Jongman *et al.*, 2014). In addition, Bin and Landry (2013) found that actual experience of a flood affects house prices greatly, suggesting those flood zones that represent a high risk but low occurrence may see little discount in pricing.

5.6 BRC SERVICES & CATEGORY WEIGHTINGS

It was decided to work with multiple BRC departments, such as the Recovery and Response and Independent Living departments, to define the weightings used for the calculation of each vulnerability category so that the index represents the priorities of each service provided by these departments.

Through discussions with BRC staff a number of weightings were chosen for each of the four VI categories. These weightings, presented in Table 6, are used to represent the potential perceived importance of each category to the work undertaken by each BRC service and were applied to the relevant category. The full customised VI was then calculated for each of the seven BRC services.

For example, for the Transport Support service, which provides transport to those affected by crisis for medical appointments and essential daily needs, measures of accessibility were deemed very important, followed by measures of health and the support available. As such, the Accessibility and HSS categories were assigned 80% of the total VI score, 55% and 25% respectively. The remaining 20% was equally split between the remaining EWMW category (10%) and HD category (10-%).

The resultant BRC service vulnerability maps (see Figures 16 and 17) are designed to highlight LSOAs whose vulnerability rankings change from those presented in the two overall VI and which may be of interest to BRC service managers during planning. For example, under the Transport Support weightings scenario, a clear rural/urban divide is apparent whereby rural LSOAs are ranked high on the vulnerability scale and urban centres ranked low. This is in opposition to the general pattern within the full VI and such knowledge could be utilised to focus the service's activities within these rural areas.

In contrast, under the Independent Living weightings scenario, those LSOAs ranked high are within the major urban areas of Norfolk, namely Norwich, Great Yarmouth and Kings Lynn. This suggests that those who may require support at home are likely to live within an urban environment and as such the advertising of the service could be focused in such areas to increase service uptake.

BRC Services	Service Description	Category Weightings			
		Economic Wealth and Material Wellbeing	Health, Self and Support	Hazards and Deprivation	Accessibility
Fire & Emergency Support	The BRC helps people cope after a fire or other emergency, providing practical and emotional support.	5%	5%	45%	45%
Support in Emergencies	The BRC supports people affected by emergencies both in the UK and abroad – from natural disasters such as floods and fire to terrorist attacks.	10%	25%	35%	30%
Independent Living	The BRC provides support at home, transport and mobility aids to help people when they face a crisis in their daily lives.	45%	45%	5%	5%
Support at Home	The BRC offers short-term practical and emotional support at home to help people regain their independence.	50%	30%	10%	10%
Transport Support	The BRC offers support to people affected by crisis by providing transport for medical appointments and essential daily needs.	10%	25%	10%	55%
Mobility Aid	The BRC lends wheelchairs and other independent living aids.	10%	40%	35%	15%
Hand, Arm, Shoulder Massage	The BRC offers hand, arm and shoulder massage to promote wellbeing for people who need support at home and to relieve stress in emergencies.	25%	50%	5%	20%

Table 14: BRC Services Descriptions & Category Weightings[21]

[21] These weightings do not represent the views of the BRC with regards to the importance of aspects of vulnerability and are used for demonstrative purposes only to test the OSVI.

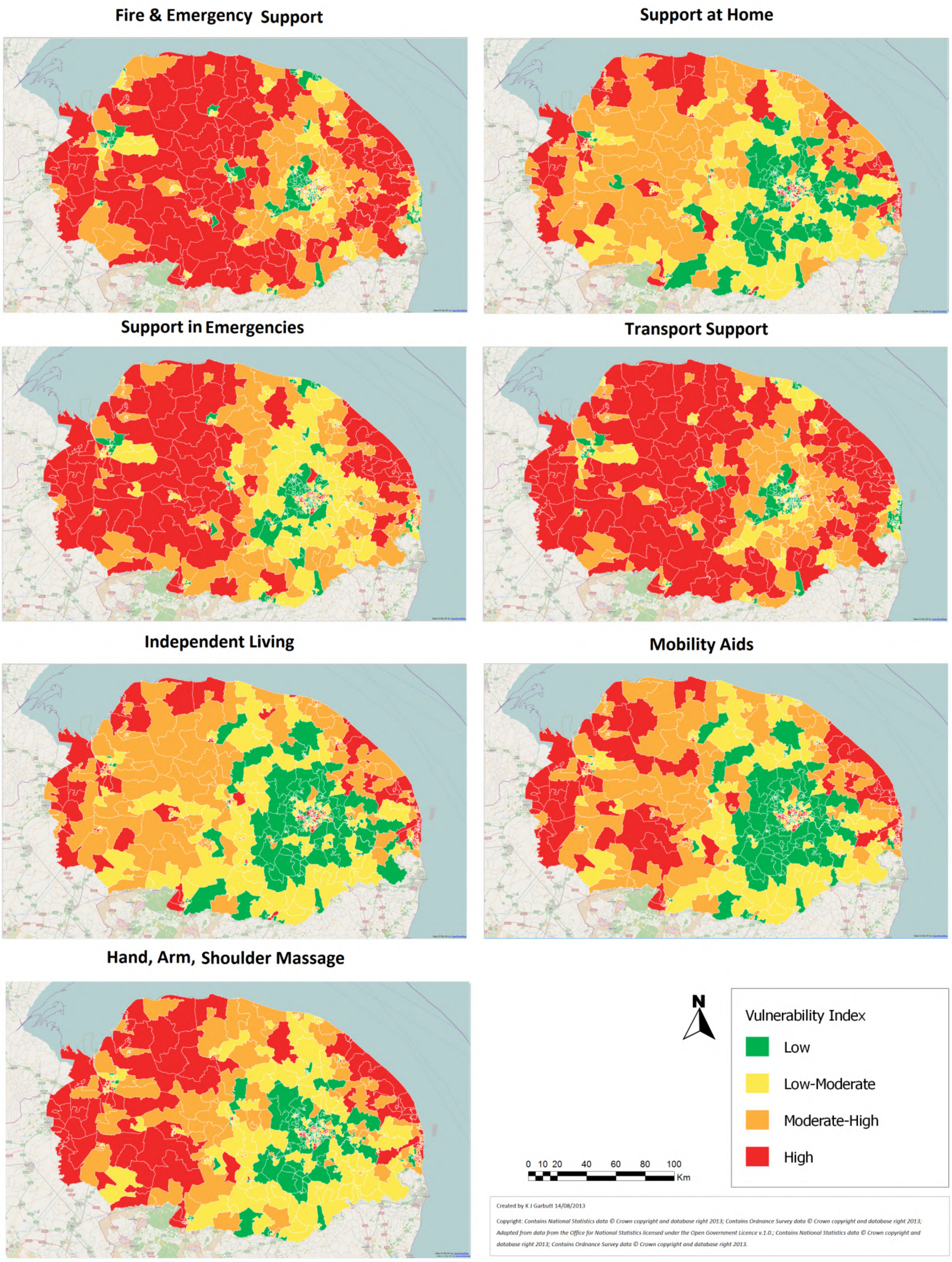


Figure 33: National OSVI with BRC weightings

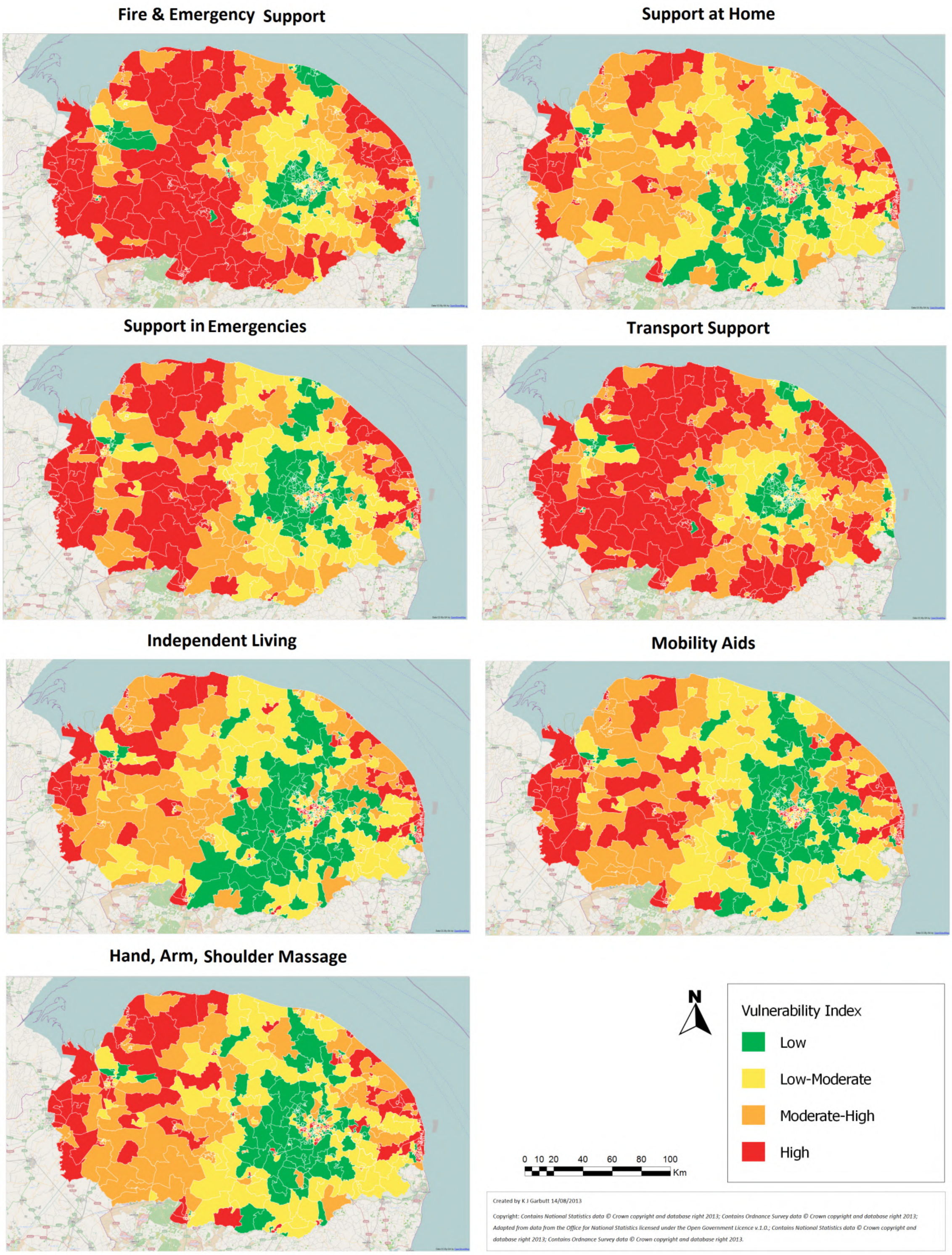


Figure 34: Local OSVI with BRC weightings

5.7 RESULTS: OSVI - SUMMARY

Both the Local and National OSVI present vulnerability within the case study county of Norfolk as following a general radial pattern around the major urban areas, namely the city of Norwich, with vulnerability high within the urban centre and decreasing outward. A low vulnerability 'ring' can be seen to encircle Norwich, representing the relatively affluent suburbs of Norwich. A positive correlation between the urban extent of an area and its level of vulnerability was noted ($r = 0.9$). Similarly, high vulnerability areas were found to be disproportionately impacted by flooding (proportionality index = .692), with flood affected areas more likely to be composed of elderly, sick and poor individuals. Accessibility analysis revealed access to healthcare to be severely disrupted by flooding, further exacerbating the identified social vulnerabilities of those in high risk flood zones.

There have been few examinations of comparative indicators of social vulnerability that incorporate measures of accessibility and flood risk. Fewer studies still have integrated a broad spectrum of vulnerability indicators available at the national level but with a resolution that allows for the representation of local-level vulnerability. Further, limited attention has been paid to the use of open source data and technology, with proprietary sources preferred. The approach presented here addresses these limitations.

The index produced draws considerable influence from Blaikie *et al*'s (1994) Pressure and Release (PAR) Model, in particular the "unsafe conditions" phase of the model, by directing attention to the physical factors and human actions (or inactions) that can create unsafe conditions within communities but also Cutter *et al*'s (1996; 2008) hazards of place model by focusing explicitly on place vulnerability within the OSVI, particularly relative local vulnerability within the Local OSVI. The inclusion of both vulnerability indicators and a measure of risk potential via the flood hazard zone within the OSVI provides a comprehensive picture of social vulnerability and allows for the examination of the interaction between socio-economic and biophysical vulnerabilities.

The OSVI provides context to environmental hazards and offers a means of assessing social vulnerability through the use of readily available and fully open source data and software. Unlike many vulnerability indices, the OSVI incorporates flood risk as well as the loss of capabilities and the importance of key services (health facilities, for example) through the measurement of accessibility when determining an area's level of social vulnerability (Figure 7). The OSVI was designed at the national level, with data for all proxy indicators available across the entirety of England and Wales, but case study analysis has focused on two counties, Norfolk and Gloucestershire, to maximise the depth of examination and calibration.

The goal of this project was to utilise free and readily available secondary data to produce a tool that could be used by local councils or NGOs to identify communities that may require added assistance before, during or after a flood event. This methodological approach provides a mechanism whereby quality data on core drivers of vulnerability can be used to create a vulnerability index that provides information at a national level but at a sufficiently fine resolution so as to identify pockets of vulnerable communities. The methods used are scalable and adaptable and the project's reliance on open source data and technology significantly reduce the associated costs and allow all parties involved to easily coordinate and share information, potentially improving local knowledge and reducing vulnerability (Trujillo, Ordones & Hernandes, 2000).

The OSVI is the first step in imagining a dynamic and customisable platform that can provide added context to complex situations and the targeting of resource and service allocation; be it the provision of programmes to address an identified vulnerability stressor or the location of new facilities to improve accessibility. Future work will focus on further refining the variables and indicators used as well as examining the underlying dimensions of social vulnerability and risk and its changes over space and time.

6 METHODOLOGY: STAKEHOLDER ENGAGEMENT

Introduction	Literature Review	Stakeholder Engagement	Methodology OSVI	Results OSVI	**Stakeholder Engagement**	Methodology Model	Results Model	Discussion	Conclusion
Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5	**Ch. 6**	Ch. 7	Ch. 8	Ch. 9	Ch. 10

"NGOs can often play a more powerful role using the results of research than can the research community itself."

~ Delisle et al. 2005: 5

This chapter outlines the stakeholder engagement and participatory modelling approach used to identify the requirements and parameters for the model. Problem identification and project conceptualisation is outlined, followed by the data collection and scenario development processes. The end of this chapter presents the results of this engagement process, which provides the foundations and requirements for the development of the Agent Based Model (ABM) described in Chapter 7.

6.1 ENGAGEMENT APPROACH

As stated in section 3.1, the EngD process and the level of engagement with the BRC that it supported provided ample opportunities to interact with BRC staff and volunteers. A participatory or conference modelling approach was utilised (described in more detail in section 6.2) whereby stakeholders and beneficiaries (BRC staff and volunteers) with domain knowledge assisted in the project development and modelling process through a series of semi-structured and unstructured interviews, focus group and workshop sessions, as well as practical demonstrations and presentations. Despite the level of engagement during the EngD process, sampling for these sessions was pragmatic, with participants often chosen out of convenience. Due to the time-sensitive work being done by BRC staff and competing schedules of all involved, it was often difficult to schedule group sessions and staff often had to cancel at the last minute. It is possible that this sampling led to bias in session outcomes and should be addressed in future work.

A five-step participatory research approach was used (see Figure 35) that combined stakeholder and modeller consultation at multiple stages to aid knowledge transfer, frame the project and define requirements and preferences, and build consensus on next steps.

Figure 35: Participatory modelling approach utilised – the green highlighted sections will be discussed in this chapter and remaining sections will be discussed in *Chapter 6: Methodology: Model Development* (approach adapted from Ritzema et al., (2010))

Step 1. Problem identification

At this starting stage, high level requirements are gathered for the project. Preliminary unstructured discussions were held with BRC staff members from the GIS-DT and Emergency Planning Team supporting the project and later semi-structured focus groups were held with other BRC stakeholders from multiple teams including the International and Data Governance Teams to explore the identified problem. Organisation- and project-specific requirements and restrictions were identified (see Chapter 3 and section 6.2) as well as ideal goals, objectives, and outputs. Technical and academic project guidance was provided to BRC staff through relevant literature and examples of similar projects during discussions. Mutual feedback was given, and stakeholders suggested appropriate internal data resources and contacts for step two. The full problem identification process is described in full in section 6.2.

Step 2. Data collection

Multiple semi-structured interviews (in person and over phone) were held with stakeholders identified in step one. Discussions focused on outlining the data requirements for model building and strategy development and identifying potential sources of data within the BRC (reports, receipts, personal accounts *etc*) and retrieving said data. Those consulted often assisted data collection through database searches or contacting related parties from regional BRC offices on the researcher's behalf. The full data collection and preparation process is described in full in section 6.3.

Step 3. Scenario Development

BRC stakeholders from the Emergency Planning Team as well responders from the Norfolk and Gloucestershire regional offices assisted in the development of the model's scenarios. At this stage, detailed requirements are agreed for the remaining tasks, and an in-depth understanding of model behaviours and parameters is developed. Multiple formal semi-structured and informal unstructured discussions (in person and telephone) and focus groups were held over six months across multiple sites. Stakeholders provided their preferences for scenario parameters and provided feedback and guidance on the data collected in step two, as well as recommendations for further data collection. Guidance on model design, as well as example models, was presented to stakeholders and the limitations and requirements for steps four and five were outlined. The full scenario and strategy development process is described in full in section 6.4.

Step 4. Model development

Model development was as participatory as possible. Stakeholders from multiple teams were engaged through regular formal and informal model presentations at key development stages. These presentations allowed for stakeholders to consult on the modelling process and provide feedback as well as outline practical and technical requirements. In addition, informal workshops and feedback sessions provided a space to test how the model runs under strategies being developed and how users interact with it. Amendments were made to the model onsite where possible so stakeholders could see the modelling process and see changes and improvements being made. Workshops were often ad hoc, with attendees determined by who was available when model development had reached a key stage. Although opportunistic, the process was deemed a success as it allowed development to progress in a timely manner and all interested teams were included at some point. Model development was the longest process and involved extensive testing, strategy integration, and calibration and validation through knowledge transfer and examination from stakeholders. The full model development process is described in full in Chapter 7.

Step 5. Outputs, lessons learned and future work

Outputs, consultation and lessons learned workshops were held with BRC stakeholders who had been a part of the previous steps, as well as managers and other interested parties who had learned about the work. Model outputs were presented in formal structured sessions, and discussions were held to gain feedback from potential users. Model outputs were quantitatively evaluated and interpreted, but also examined and validated by stakeholders to ensure that they align with the requirements set out in step one, as well as the values and perceptions of the. The goal was to present a scientific model that is both accurate and useful, but also represents the experiences, insights and assumptions of stakeholders (Burkhard *et al.*, 2005). The potential use of the model by the BRC and others was discussed as well as potential future work during a formal end-of-project meeting with key project supporters. The full model evaluation and discussion process is described in full in Chapters 8 and 9.

6.2 PROBLEM IDENTIFICATION

As outlined above (section 4.6), the input from domain experts and project stakeholders helped to guide the creation of the OSVI and validate the results. This process was deemed successful and staff at the BRC were happy to collaborate and become involved in the research. Given this willingness, and to address the issue of limited interaction and knowledge exchange amongst modellers and researchers (see Literature Review section 2.3.2), it was decided to utilise a participatory approach to project design and development. The exchange of knowledge between NGOs like the BRC and other interested parties, such as local councils and community groups, is critical to glean a better understanding of the management of emergency situations. Participatory, or conference, modelling/research and knowledge exchange programmes have provided a new approach to overcome the problem of data scarcity within several planning areas (Ritzema *et al.*, 2010). As discussed above (section 6.1), a participatory modelling approach that includes stakeholders and beneficiaries, and their tacit understanding of local conditions, allows researchers to concentrate on the modelling process (Argent & Grayson, 2003) and allows for a common understanding to be achieved and systems of management to be developed (Loucks, 2006). The goal should be to develop simple models designed in collaboration with the stakeholders (Berkhoff, 2007). The effectiveness of models, the utility of their outputs and their wider adoption, is dependent on those that use the model: stakeholders, decision-makers, users (Bennett *et al*., 2013). In the example here, the BRC is the intended user and thus a qualitative consideration of their needs as well as a quantitative understanding of the index and model is essential for the adoption and further use and development.

As the EngD process requires researchers to spend 50% to 75% of their time working with their industry sponsor, this offered an important opportunity for a participatory design process to be undertaken towards model development and evaluation. It was possible to embed on site with the BRC at their London head office and work closely with BRC staff and volunteers to gain a better understanding of the BRC's working requirements, ensure the development of the index and model are framed appropriately, gather user feedback, and test the model with BRC staff and with BRC case studies[22].

6.2.1 EPISTEMOLOGICAL FRAMEWORK DEVELOPMENT

The simulation model process starts with an examination of the phenomenon the researcher is interested in. In this instance, changes in vulnerability during a flood event is the phenomenon of interest. Most models begin as a process flowchart: a description of the expected elements within the model and their relationships[23]. The dimensionality of the model space must also be decided: two-dimensional grid, or three-dimensional world. Then, the logic of the model must be set out, usually graphically using Unified Modelling Language (UML) or in the form of "pseudo-code"[24]. This is then translated into a programming language and programmed into an ABM toolkit (see section 7.2).

To aid conceptualisation of the model, an epistemological framework was created (Figure 36). This framework aids model development and understanding by outlining the theories, processes, and inputs that will feed into the model, as well as their interactions, on an abstract level. As can be seen in Figure 36, several key theories and methods are included in the conceptualisation and feed into the overall framework by providing relevant data and informing the model frameworks. For example, vulnerability theory and related concepts, such as risk and adaptive capacity, provide an understanding of the phenomenon under

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[22] Additionally, in July 2016, a successful application for a UCL Advances Knowledge Exchange and Enterprise Funding grant was submitted. The grant supported a six-month full-time secondment to the BRC, running from October 1, 2016.

[23] See Gilbert (2008) and Barthelemy & Toint (2012) for a description of the process of setting up an ABM project.

[24] UML (Unified Modeling Language) is a group of standardized graphical notations used for describing and designing primarily object-oriented software systems that has been proposed as a suitable tool for describing ABMs graphically (*e.g.*, (Bersini, 2012; Siebers & Aickelin, 2010)). In addition, ODD (Overview, Design concepts, Details) is an effort to standardize and publish descriptions of ABMs with the goal of promoting reproduction (Grimm *et al.*, 2006).

examination and will guide data collection and input as well as the participatory modelling process. Similarly, modelling methods and Geographic Information Systems (GIS) are listed as the processes involved with both methods feeding directly into the model development process. Empirical data collected will guide the development of the theoretical and conceptual frameworks and the computational model itself: the model is designed to support the theories and data that are available. Further, participatory modelling will guide all aspects of model development, offering a level of validation and verification at all stages. The framework presented is not explicitly cyclical, but feedbacks are present within the relationships between the theory-data-model development domains. Without a firm understanding of the theories surrounding the phenomenon under examination (*i.e.* vulnerability) the modeller cannot appropriately determine the empirical data that is needed or the modelling processes that will be required. However, data availability and the modelling process can guide the selection of methods and associated theories.

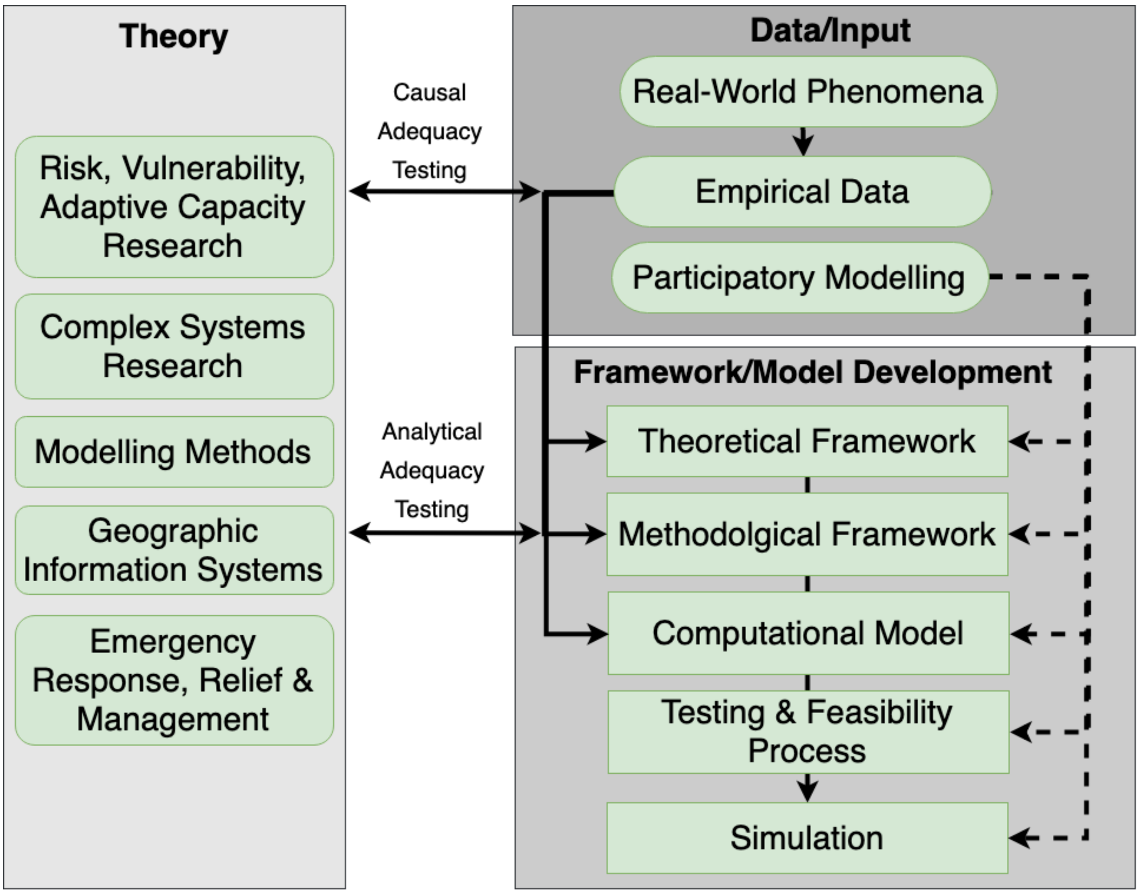

Figure 36: Epistemological Framework (adapted from Rossiter *et al.* (2010) and McKelvey (2002))

The Epistemological Framework (Figure 36) was utilised in initial meetings with BRC staff and volunteers when discussing the project. The Framework helped non-experts to understand the modelling process at an abstract level and elements were discussed, explained and adapted where necessary.

6.2.2 HIGH LEVEL REQUIREMENTS GATHERING

An informal framing session to capture the formal requirements was held at the beginning of the modelling process between the researcher, supervisors and interested BRC staff. Talks led to a network of contacts throughout the wider BRC organisation and a series of semi-structured face-to-face, telephone and e-mail interviews were undertaken over the course of six months. This process allowed for knowledge of the project to be disseminated throughout several departments, regional offices and levels of the BRC and a wider network of potential project participants. In addition, shadowing of BRC staff and volunteers across a number of BRC offices, including the London headquarters and the regional offices of Norfolk, Oxford and Cumbria, were undertaken to discuss potential uses of the model by national and regional response teams, and determine potential future developments.

This consultation and engagement process continued throughout the entire project timeframe and was loosely structured as follows:

1. Familiarisation with BRC procedures and processes.
2. Identification and engagement with stakeholders, likely users and interested parties.
3. Engagement and shadowing.
4. Data collection.
5. Index development, refinement and adaptation.
6. Index presentation, demonstration, and assessment.
7. Scenario and strategy development.
8. Model framework development.
9. Participatory modelling and feedback.
10. Model testing, further consultation, refinement and adaptation.

11. Model presentation, demonstration, and assessment.

The following objectives were agreed:

- In collaboration with the BRC staff, determine a set of performance indicators to measure effectively the modelled outputs and outcomes. These indicators should be used to examine and compare modelled response strategy performance under multiple scenarios.
- Guided by BRC staff, develop a testing and feasibility framework to examine the model's potential effectiveness and performance within future domestic BRC responses and rigorously test the newly developed scenarios and strategies.
- Develop, in conjunction with BRC staff and volunteers, a vulnerability model framework to outline and better understand the modelling process, including inputs, interactions and feedbacks, calculations, and outputs. This framework should better explain the model process to BRC users with no formal modelling experience.
- Actively test and develop the model with BRC staff and volunteers. A participatory approach to modelling should be undertaken whereby the expected end-users are active modellers, focusing development and improving the applicability and marketability of the model.

Informal semi-structured and unstructured focus group sessions were conducted throughout the modelling process. Due to the time sensitive work being done by BRC staff and competing schedules, sampling for these sessions was pragmatic, with participants often chosen out of convenience. Each session focused on a different theme as the model developed:

1. Model focus: inputs, goals, parameters, procedures.
2. Scenario and strategy development, data availability.
3. Framework development.

These sessions were informal and open-ended discussions aimed at gathering the required views, expectations and needs for successful model development. “Whiteboard sessions” were held where participants freely contributed all concerns and ideas for the model, including its ultimate usefulness, data requirements and potential sources of said data, and thoughts on framework and strategy development. Over the course of the sessions these thoughts and suggestions were summarised, and key components agreed upon, such as a precise list of model inputs, the scenarios and strategies to be tested, and outlines for each of the frameworks. Where interested staff and volunteers could not attend a focus group session, due to scheduling problems, telephone and e-mail conversations were carried out to ensure all voices were heard.

Focus group sessions gave stakeholders the opportunity to engage with one another and share information and lessons learned from past experiences and this information was then summarised and where possible backed up by data (event reports, commodity orders *etc*.) that was made available to the group and wider network. Focus group sessions proved invaluable to the process of model development, validation and verification, as well as for gaining a greater understanding of what the BRC does and does not do during flood emergencies and the key variables to model.

6.3 DATA COLLECTION & PREPARATION

6.3.1 MAP DATA

Much of the data that was used to create the OSVI was used as input data for the model, (see section 4). The environment component of the model consists of three main location and event inputs: boundaries and areas; hazards; and the road network. Map data, including road data and flood zone data was updated. Newer versions of this data were made available by the Ordnance Survey and Environment Agency during the creation of the OSVI (2013) and the development of the model (2016). Updated data featured information on newly built roads and buildings, as well as flood defences. This data was supplemented with BRC specific data, namely the types of resources that would be available during flood responses and the location of regional offices, as well as additional population and hazard information for demand identification and routing (see Table 15 for an outline of the data used). Each data type will be discussed in greater detail.

BOUNDARIES

Boundary data within the model is made up of several interlinking shapefiles, including a simple county boundary line that marks the extent of the study area, an area file containing electoral and administrative information, an area file containing demographics data and the OSVI, and a population-weighted Centroid file that links all the above information to single points within each LSOA that represent the spatial distribution of that area's population. During simulations, boundary lines are used to restrict movement of agents (agents remain within the county at all times) and information held within the boundary areas are used during decision-making (OSVI ratings, number of affected households, for example).

HAZARDS

Hazards data in the model is represented by the Environment Agency's flood maps. Each study area has three flood zone maps representing the probability of river and sea flooding, ignoring the presence of defences. In addition, areas benefiting from flood defences are visualised. Flood information is utilised within the calculation of the Flood Impact Score and the Cumulative Flood Priority Score as well as routing – under some scenarios the road network is restricted based upon flood rating.

Data Type	Description
Administration	*Ordnance Survey Boundary-Line* data were used to produce county boundary extents and local authority zones (LA, LSOA)
Demographics	The final OSVI dataset was used. In addition, data collected from the *2011 UK Census* was used to determine population makeup and location.
Road Network	*Ordnance Survey Open Road* data was used to build the model network for routing. The data includes classification information on: motorways, A-roads, B-roads, road classification, road name, primary route information, and motorway junction information.
Buildings	*Ordnance Survey Open Map – Local Buildings* data was used to map private and business buildings to determine likely population dispersal during a flood event and give an estimate of likely 'affected persons'.
Hazard Area	*Environment Agency* flood zone extents were used to map those areas likely affected by flooding under different scenarios and used in conjunction with the road network and buildings data to determine likely 'affected persons' and a flood classification for each road segment.
NGO Resources	The BRC provided information on facility location and type; stock quantity, location and refresh rate; staff/volunteer count, working patterns and location; vehicle number, type and location.
Hospital Locations	Taken from NHS data and mapped to closest road segment.

Table 15: Data types and description of data used during model development

ROAD NETWORK

The road network utilised within the model is built upon the Ordnance Survey MasterMap Integrated Transport Network (ITN) road dataset. The road network was clipped to restrict agent movement to within the study area. The road network was prepared for routing. This included identifying and removing unconnected road segments, or 'dangles', present after clipping (see Figure 37) and checking all segments and nodes connect.

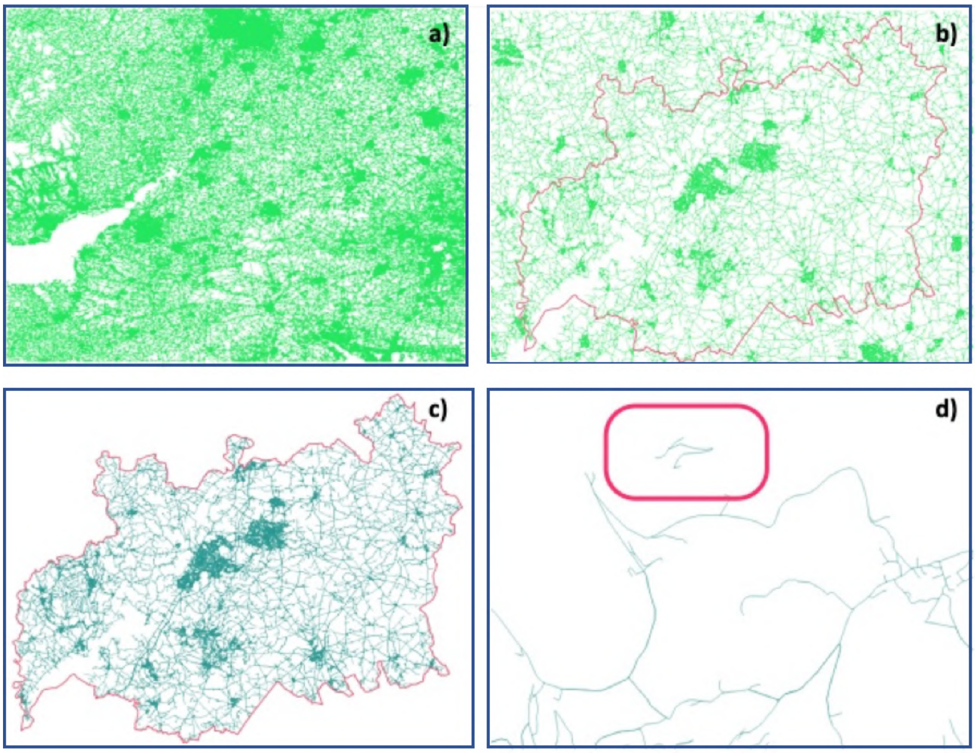

Figure 37: Road data preparation. (a) full UK road network (green); b) road network (green) with Gloucestershire boundary line (red); (c) road network clipped to those within the boundary; (d) 'dangles' (unconnected lines) highlighted and removed.

The final model scans the road network to determine major and minor roads and tests that all nodes are connected to the complete network and that it is suitable for routing before the routing algorithm runs but preparing the network in advance speeds up model runs.

Additional features can also be added to the model if a particular environmental feature is of interest or is believed to play a significant role in response work. For example, additional transport and infrastructure features, such as traffic estimates and travel times, rights and restrictions, and variable speed restrictions, can also be added. Such information adds to the realism within the model and may lead to an improvement in results, but the cost of including this data must be examined. This is discussed further in section 9.4.

In an ABM, an agent's actions and decisions depend partly on what it observes in its environment. Thus, all entities within the model that are required for decision making, such as the road network the agents move along, must be suitably detailed and represented at an appropriate level (Sato & Takahashi, 2010). These entities can be active (various types of interactive agents) and passive, with limited if any behaviours, usually road networks (Hall & Virrantaus, 2016). However, most emergencies, especially large natural events like the kind under investigation, involve a certain level of destruction and so the environmental entities in a model must contain attributes which can be modified to reflect this (Hawe *et al.*, 2012). To this end, the impact of flooding was factored into the entity that the agents would interact with most: the road network. The road network used was updated to include destruction information, with each road segment classified depending on the impact of the flood events being investigated.

The impact of flooding was determined for each road segment in both the Gloucestershire and Norfolk road networks. The road network was intersected with each flood zone and then each road segment was classified depending on the flood zones impact (see Figure 38):

- Green: road segment has multiple connections and is not directly impacted by the FZ.
- Yellow: road segment has restricted or limited connectivity.
- Orange: road segment is unreachable, or segment is only reachable from roads entirely cut off by FZ.
- Red: road segment is entirely within FZ and/or has no unflooded connectivity.

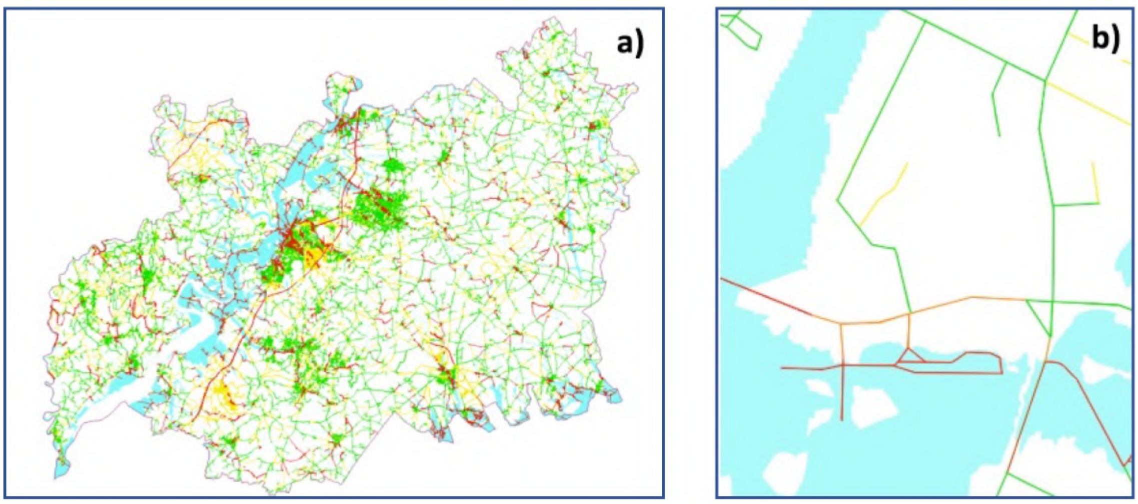

Figure 38: (a) Map of Gloucestershire showing complete road network with flood impact score for each road segment; (b) Detail of road network with flood impact score.

Following flood impact analysis on the road network it was necessary to update the location of Centroids to ensure they are accessible for routing regardless of the flood impact network being used. Centroids were 'snapped' to their nearest road segment in QGIS. Where nearest road segment was on a part of the network that could not be reached, the Centroid was re-snapped to a road segment that was connected to the wider road network and was within the same LSOA (see Figure 39). Centroids were used for 'goal' locations when routing. In addition, newly generated 'affected' population data was merged to the Centroids.

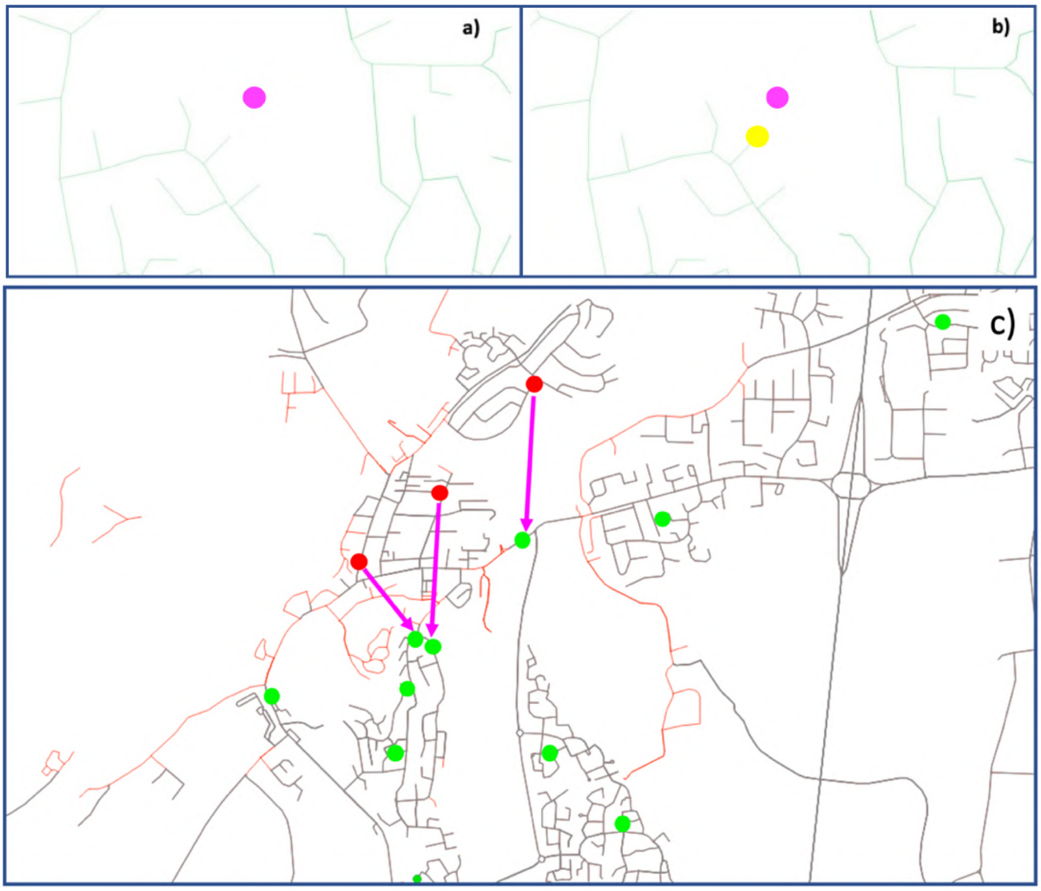

Figure 39: (a) Original location of Centroid (pink dot); (b) New location of Centroid (yellow) after being 'snapped' to the closest road network line (green dot); (c) In instances where the Centroid was on a piece of road network completely cut off due to flood waters (red road segments), the Centroid was moved from its original position (red dot) to a non-flooded road segment (grey) within the same LSOA to a new position (green dot)

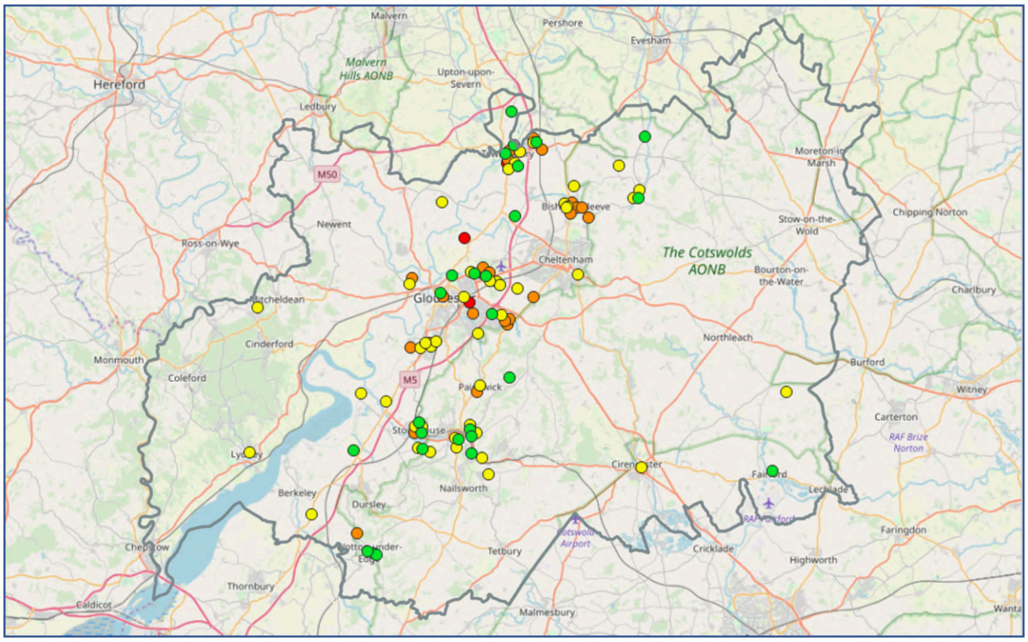

Figure 40: Final location of Gloucestershire Centroids for flood affected LSOA displaying OSVI rank

6.3.2 AFFECTED HOUSEHOLDS & PERSONS

All buildings within the study zones were mapped using *Ordnance Survey OS Open Map Local* data (see Figure 41). Buildings are separated into commercial and residential and all residential buildings were used to represent potential homes. Originally, the OpenStreetMap 'buildings' layer (highlighted green in Figure 41 (a)) was to be used but was found to be missing lots of buildings when overlaid on to satellite imagery. This was especially noted in rural areas. Ordnance Survey OS Open Map Local data represented a more accurate representation of location and number of buildings (highlighted purple in Figure 41 (b)). Buildings layer sections were joined and clipped by different flood zones, resulting in buildings within the flood zone (highlighted red in Figure 41 (c)) and those outside the flood zone (purple). LSOA/OSVI attributes were joined to buildings data by location and buildings were 'snapped' (algorithmically linked) to the closest ITN road segment (Figure 41 (e)). Final 'snapped' buildings data including flood status and LSOA data represented as buildings-per-road segment for population and needs analysis (Figure 41 (g)). 'Unsnapped' buildings data showing those in flood zone (highlighted red in Figure 41) and not in flood zone (purple).

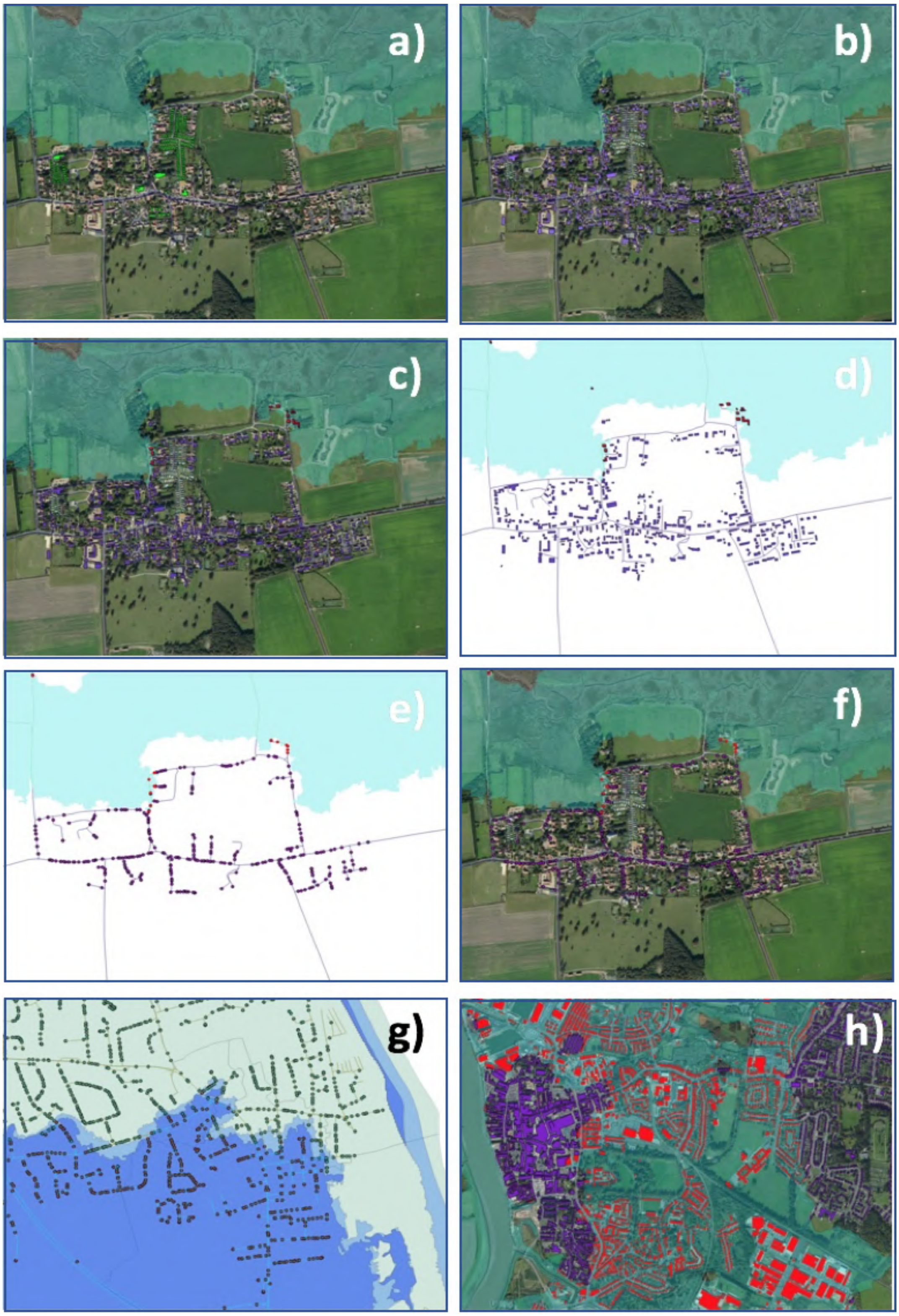

Figure 41: Outline of process used to calculate the number of potentially affected persons for each road segment

6.3.3 RESOURCE REQUIREMENTS

During a domestic flood response, the BRC offers support in a range of ways including:

- emergency response support, such as rescue operations and evacuation management, if asked to do so by the Category 1 responder.
- the provision of physical and psychological support in rest centres.
- transport support for those affected, including transportation to and from hospitals and rest centres.
- the provision of medical support supplies, such as wheelchairs.
- the provision of bottled water, food parcels, family aid packages, blankets, sandbags.
- the provision of cleaning supplies to assist in post-flood clean-up.

Using the likely affected households and population data produced above, the quantity of resources likely required to respond to each scenario was calculated.

The BRC is unlikely to be the sole responder to a national flood and would not be expected to assist every affected household or person. Information collected on the BRC's Gloucestershire response efforts indicated that at least 5,000 people were assisted by the BRC in some way (see section 6.3.2). This number likely includes all those the BRC provided assistance to, supplied resources to, assisted at a rest centre, and/or provided guidance to in some way. Thus, this number likely does not represent the sum of people assisted as it likely includes replication as well as includes services not being considered here. Nevertheless, it is the only viable number that was found and so is used as a benchmark for both the Gloucestershire and Norfolk scenarios and used during model validation (see section 7.4.6).

Demographics analysis for both case study areas suggests that the average household occupancy is 2.7. This was rounded up for analysis. Table 16 outlines the likely household and population that will require assistance for each case study area.

	Total Households likely affected	Total population likely affected	Households to be assisted	Individuals to be assisted
Gloucestershire	10,126	30,378	1,696	5,088
Norfolk	40,134	120,402	1,967	5,901

Table 16: Total number of likely affected households and people and the numbers to be assisted in each case study area

Given the scenarios developed in section 8.1, and using past BRC experience and government recommendations, Table 17 outlines the total quantity of each resource being considered that is required to be distributed for both case study areas and the total loads required based upon respective transport capacity outlined in section 7.3.2.

	Sandbags	Water	Blankets	Hygiene Kits	Cleaning Kits
Gloucestershire	10,176 (169)	122,112 litres (339)	5,088 (17)	15,264 (169)	5,088 (56)
Norfolk	11,802 (197)	141,624 litres (393)	5,901 (20)	17,703 (197)	5,901 (66)

Table 17: Total quantity of resources required and delivery loads (in brackets) in each case study area

Following initial interviews and focus group sessions, it was decided that modelling recent BRC flood responses would be an ideal way to test the validity of a resultant model. However, obtaining the information required to recreate accurately past BRC emergencies and model response strategies was a difficult task. After conversations with staff and volunteers, it was discovered that the information required was not routinely collected. No "master" spreadsheet existed that recorded all the resources distributed, staff and volunteer hours spent responding to the event, or the number of people assisted. To obtain even the basic information required for timing of response efforts and the kinds of resources distributed, it was necessary to talk to response managers directly (after a series of formal/informal introductions and project discussions with Division and/or Team managers) who often had information stored in a notebook, in an email chain, or summarised in a news brief. After a series of introductions and discussions, information was uncovered for BRC response efforts to a series of floods that impacted Gloucestershire, and much of the United Kingdom, in 2007.

Context: 2007 UK Floods*

- Summer 2007 was one of the wettest summers on record in the UK - two months' worth of rain fell in just 14 hours in Gloucestershire.
- 80% of properties were affected and were overwhelmed by flash flooding.
- 350,000+ people were without drinking water.
- 135,000 homes (over half the homes in Gloucestershire) were without drinking water for up to 17 days.
- 48,000 homes were without electricity for two days.
- 10,000 motorists were stranded on county roads, including the M5 where many people remained overnight.
- 5,000 homes and businesses were flooded.
- 500 businesses were affected.
- 500 commuters were stranded at Gloucester train station.
- Flood water reached 7 feet in some vulnerable areas.
- The estimated cost to repair the county's roads was £25 million.
- Overall estimated cost to the county was £50 million.

* All information taken from Gloucestershire County Council Press Release published 21.07.2017. Available here: https://bit.ly/2BW06BR

Although the available information was limited, it was the best available and sufficient to build a model of the BRC response strategy[25]. The following are a selection of excerpts from BRC and IFRC briefs, internal reports, and emails that provide information on the response efforts:

> "In Gloucestershire, the British Red Cross…continued its work distributing hundreds of thousands of litres of water, as well as hygiene packs and food packs to residents…with more than 3,750 helped in the area so far [in the first three days]"

[25] Data was uncovered late in the research period and as such much of the model development and testing used a "generic" flood case study using the flood zones created by the Environment Agency for Norfolk, not an actual past flood event, and using simple response strategies developed based upon wider literature, not actual strategies undertaken in response to a real-world emergency. This was due to a lack of data availability at the time.

"They brought me enough water for five days, a big bagful of food and lots of household cleaning stuff"

"The Red Cross…helped over 5,000 vulnerable people in Gloucestershire and delivered more than 140,000 litres of bottled water"

"It's absolutely brilliant when the Red Cross just turned up on my doorstep with all this water"

"four vehicles were loaded with 2,300 litres of water and 2 boxes of WAG BAGS [mobile toilet bags]"

"35,000 litres of water and several hundred five-day food packs plus a large quantity of hygiene packs [were delivered in the first four days]"[26]

All information relating to resource distribution, be it type or totals distributed, the number of staff, working hours and miles travelled, was summarised and consolidated into a single timetable outlining key events and response efforts undertaken:

Thursday 19 July - Friday 20 July

- Gloucestershire Fire and Rescue Service called out to 1,800 incidents over 48-hours (compared to the usual 8,000 annual incidents).
- BRC contacted by Gold Command.

Saturday 21 July

- BRC provides thousands of litres of water, as well as hygiene packs and food packs, to at least 550 people.
- At least 25,000 litres of water distributed in total.

Sunday 22 July

- River Avon breaks its banks.
- Tewkesbury completely cut off by flood waters. No road access and three feet of water recorded.
- BRC reports having provided water, hygiene and food packs to at least 3,750 people.

[26] All quotes taken from: BRC (2007) UK: Vulnerable struggle to cope in Gloucestershire after floods available at: https://reliefweb.int/report/united-kingdom-great-britain-and-northern-ireland/uk-vulnerable-struggle-cope-gloucestershire

- At least 35,000 litres of water distributed in total.

Monday 23 July

- 50,000 homes across Gloucestershire without electricity after a Castle Meads electricity substation switched off.
- 10,000 motorists stranded on the M5 motorway overnight.
- At least 46,000 litres of water distributed in total.

Tuesday 24 July

- 420,000 people without drinking water across Gloucester, Cheltenham, and Tewkesbury.
- 900 drinking water bowsers brought in and Army personnel tasked with distributing three million bottles of water a day.
- BRC provides ambulance support to Gloucestershire Ambulance Service.
- BRC provides 80 duvets and 16 sleeping bags to Tewkesbury at the request of the local authority.

Thursday 26 July

- 2,300 litres of water and 2 boxes of WAG BAGS distributed by four 4x4s with trailers.
- Four extra 4x4 vehicles provided to the BRC Quedgley distribution centre.

Monday 30 July

- 11,000 litres of water and several hundred food packs distributed to individual households
- BRC reports 5,000 people in Gloucestershire assisted in some way and more than 140,000 litres of bottled water delivered in total.

Tuesday 31 July

- At least 16,000 litres of water distributed.

Wednesday 1 August

- 13,000 litres of water and various food packs delivered.

Thursday 2 August

- 15,000 litres of water and 150 food packs and 96 hygiene packs delivered.

Tuesday 7 August

- At least 16 vehicles used to distribute resources throughout Gloucestershire – 8 BRC vehicles plus Wessex 4x4 Response and Gloucestershire 4x4 Response services provided at least eight more 4x4s (see Figure 42).
- At least 8,000 miles travelled by all vehicles involved over 12 days.
- In excess of 300,000 litres (300 tonnes) of water distributed in total over 12 days.
- Several hundred five-day food parcels and a similar number of hygiene packs delivered in total.
- Water supplies returned and tap water declared safe to drink.

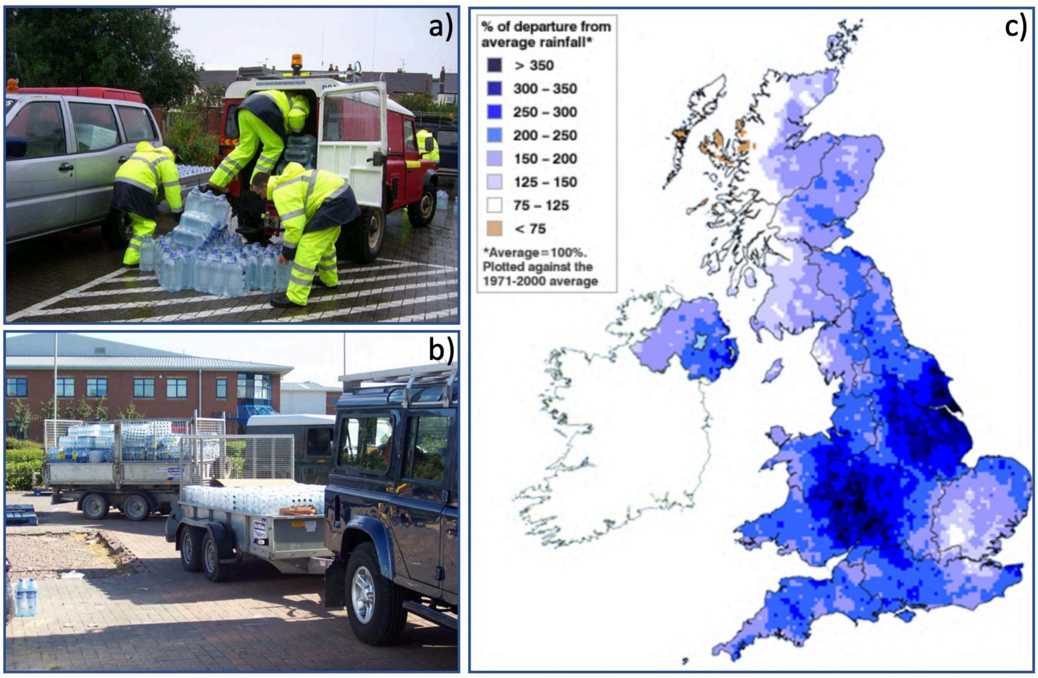

Figure 42: (a) volunteers loading water bottles into 4x4s (source: 4x4 Response Network, 2007); (b) 4x4s with trailers transporting up to 2,300 litres of water at a time (source: 4x4 Response Network, 2007); (c) rainfall map for UK over June-July 2007 (source: Met Office, 2007)

A list of likely key variables and model parameters was created that required input from the BRC to ensure the end model was as realistic and representative as possible. BRC staff provided the following information directly or provided reports that supplied the information:

- The location of BRC offices within each study area was provided. This included one office in Gloucestershire and two in Norfolk.
- BRC staff who responded to the Gloucestershire floods in 2007 provided the location and details of temporary locations that were used as shelters or distribution points. This information was provided directly during conversations or indirectly via reports.
- Where available, BRC staff and after-action reports provided information on the number of vehicles, staff, stock quantities, and warehousing capacity in relation to the Gloucestershire floods response of 2007 (see Table 18). Where available, information was provided that explained what resources were distributed (water, blankets, food *etc*), when resources were distributed, and the differences in storing, handling and distributing them (time to pack, storage capacity, number per household, refresh rate *etc*). Where this information was directly available in a report, staff provided it based upon working knowledge.
- As the Norfolk case study was based upon a theoretical flood emergency, the BRC *Emergency Response and Management* Team and the local team at the Norfolk offices provided information on the number of vehicles, staff and stock quantities that they currently have and would be able to utilise during the theoretical emergency described.
- Scheduling and event time information was provided by BRC staff where available in reports or from working knowledge of the Gloucestershire or other response efforts. This information focused on when actions were undertaken (*e.g*. when certain resources were distributed), the timings for stock replenishment (*e.g*. estimates of when new sandbags would be ready or blankets delivered) and the overall runtime of the response efforts (see section 3.1 for more information).

- QGIS was used to identify the nearest road segments to each BRC location provided to use during routing. These points were stored as a separate *BRC Locations* shapefile for each study area.
- The BRC *Emergency Response and Management* Team provided information on shift patterns, responsibilities and restrictions set on BRC staff and volunteers during flood responses. This information was taken directly from BRC guidance documents that are provided to ensure the safety and wellbeing of staff and volunteer

Given the BRC's overall strategy interests and likely future work, the availability of data from past BRC response efforts, and the strengths of the chosen modelling method, it was decided to focus on modelling the distribution of resources before, during and after the flood event, namely sandbags, bottled water and cleaning supplies as a starting point. These actions are undertaken by the BRC during most domestic flood events and are governed by specific timeframes (sandbags distributed before a flood, water bottles during, cleaning supplies after). Following the consolidation of the above information, and information available on the number of resources that are likely available (BRC warehouse data on bottled water and county council data on sandbags, for example), as well as the quantity that is likely needed based on population numbers and past event analysis, BRC staff helped to build a list of likely resources available at regional BRC distribution points (see Table 18).

Over the time that this thesis has been in development, efforts have been put in place at the BRC to record routinely and systematically response data. Response managers are asked to track a predetermined list of resources and personnel data across the entire response lifetime and record event-specific notes. It is hoped that this recording process will improve event awareness and planning and will be utilised within future model development/testing.

Resource	Max. availability	Max vehicle load	Details
Staff	14		Fully trained. Can drive 4x4 Land Rovers and Transit-style vans. Can work 12-hour shifts for a maximum of 40 hours per week. Can enter flood waters.
Volunteers	8		Not all are trained. Cannot drive 4x4 Land Rovers or Transit-style vans. Can work 8-hour shifts for a maximum of 40 hours. Cannot enter flood waters.
Cars	6	4	Can be driven by volunteers. Able to navigate through flood waters (<12 inches).
4x4 Land Rovers	2	4 + 1 staff driver	Requires staff driver. Able to navigate through flood waters (<24 inches).
Transit-style van	2	5 + 1 staff driver	Requires staff driver. Able to navigate through flood waters (<12 inches).
Sandbags	1,500	60	Average of 6 per household. Average weight of 15kgs. Refreshed up to every 48 hours. Long load and distribute time.
Water Bottles	10,000	30-50 (360-600 litres)	Come in packs of x24 500ml bottles. 1 pack per household per day. Refreshed every 24 hours.
Blankets	5,000	500+	Average of 3 per household. Come in packs of 10. Very light. Refreshed up to every 72 hours, if required.
Hygiene Kits	5,000	500	1 per household. Contains 3 WAG Bags (toilet bags), liquid sanitizer, wipes *etc*. Refreshed up to every 72 hours, if required.
Family Packs	500	30-50	1 per household. Contains a range of tinned and jarred foods, long shelf-life drinks, blankets, books, and nappies if required. Refreshed up to every 72 hours, if required.
Cleaning Kits	1,000	30-50	1 per household. Contains bucket, mop/broom, sponges, gloves, anti-mould spray, rubbish bags. Refreshed up to every 72 hours, if required.

Table 18: Likely resources available at a BRC distribution point - quantities and details provided by BRC staff and based upon records or working knowledge from past response efforts

6.4 SCENARIO & STRATEGY DEVELOPMENT

It was decided to examine two flood scenarios: one based upon a theoretical event in Norfolk that the regional BRC team were planning for, and one based upon the actual events that occurred in Gloucestershire in 2007. Each case study is discussed in more detail in section 3.1 and timelines of each scenario as well as the parameters used during modelling are presented in Table 21, Table 23, Table 26 and Table 28 in the results chapter.

The type of resources distributed during each scenario is determined by flood event progression and follows the response efforts undertaken during the Gloucestershire floods. Initial distribution will focus on sandbags to likely flood affected areas before the flood; followed by the distribution of bottled water, blankets and hygiene kits *during* the flood event; and cleaning supplies *after* the flood. This is the typical response strategy for the BRC when responding to a UK flood. Details regarding the quantity of each resource that is required under each scenario are presented in the respective results sections.

Following scenario discussions and case study selection, a focus group with the BRC *Emergency Response and Management* Team led to the development of emergency response strategies that could be tested using the model and that integrate the OSVI. Table 19 details these strategies:

Distribution Strategy	Details
Most vulnerable	Flooded LSOA with the highest OSVI scores are delivered to first. Resources are distributed to flood affected LSOA in order of their OSVI vulnerability rating 1) high 2) moderate-high 3) low-moderate 4) low – highest first. This strategy was chosen to test the usefulness of the OSVI as a tool for determining, locating, and prioritising resource distribution.
Priority residents	Flooded LSOA with the highest priority resident rating (PRIOS) are delivered to first – see Table 10 for more information on PRIOS categorisation. This strategy was chosen as the BRC is regularly tasked with coordinating the care of 'priority' individuals during emergencies. Focus is often on the elderly, those with limited actions, and children.
Highest impact	Flooded LSOA with the highest flood index score (FIS) are delivered to first – see Table 10 for more information on FIS categorisation. This strategy was chosen as it is often the proximity to the hazard that determines the impact and the BRC is regularly tasked with assisting those worst affected.
Random	A random selection of affected LSOA are delivered to first Resources (water, blankets, sandbags *etc*.) are distributed to all flood affected LSOA Centroids (or the closest non-flooded location) with the order of delivery chosen at random. This strategy was chosen to examine how the above strategies compare to simply distributing resources at random to those affected.

Table 19: Distribution strategies

Figure 43 provides an overview of the testing process for each of the chosen scenarios. As can be seen, all four distribution strategies are tested for each case study. In addition, the impact of multiple distribution points is tested in the Norfolk scenario. Norfolk has two BRC facilities that are fully equipped to respond to a flood emergency and so it was decided to examine how multiple independent facilities affect overall model performance. In addition, 'control' tests are run to examine the impact of flooding on distribution: all roads are navigable under the control scenario tests, whereas accessibility changes throughout both the Gloucestershire and Norfolk scenarios as the flood develops.

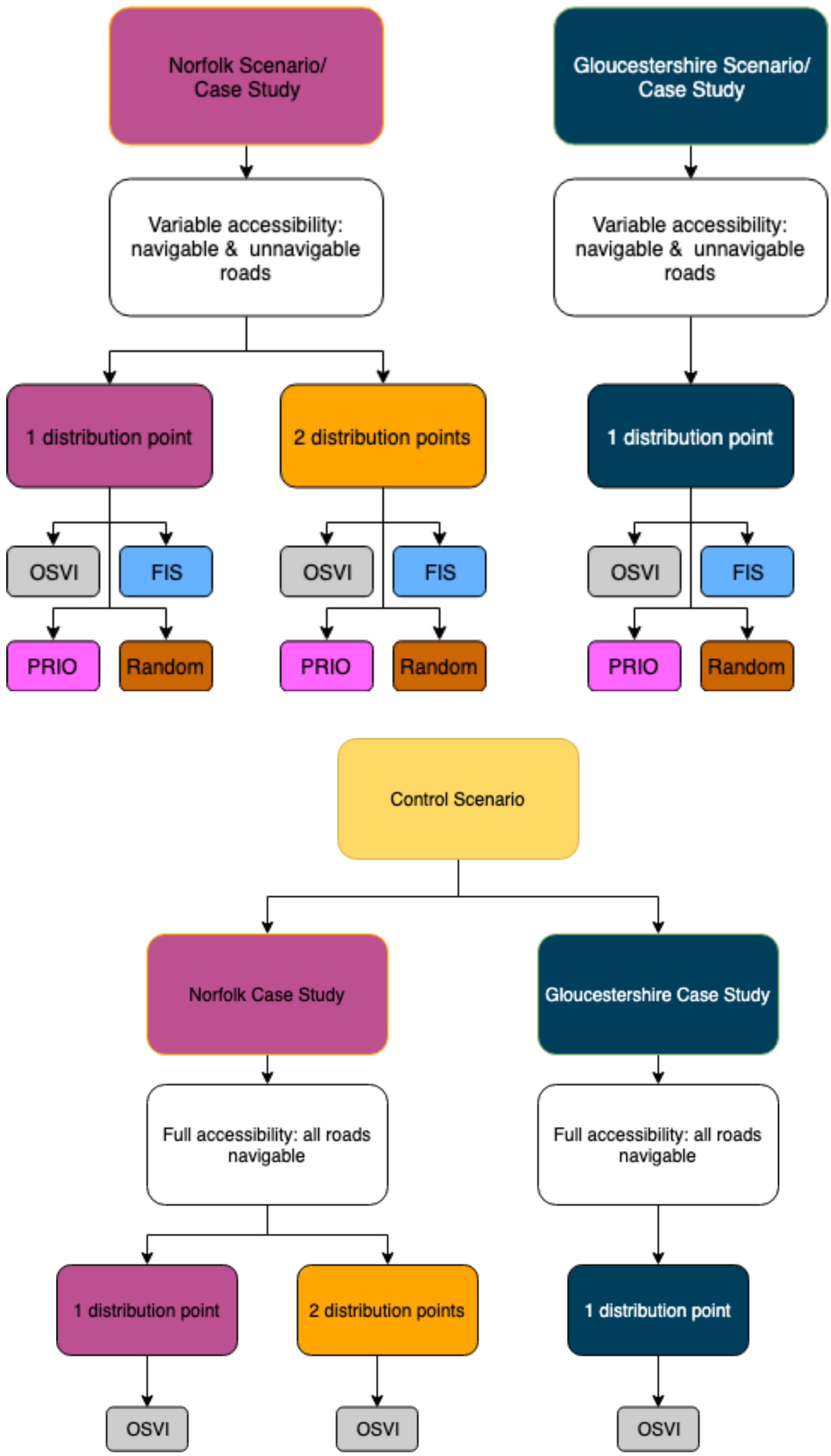

Figure 43: Overview of scenarios and strategies tested - the control scenario (bottom diagram) is used to determine the impact of flooding (during this scenario it is assumed that no flooding has occurred – results can then be compared to the two flood scenarios)

A number of assumptions were made for scenarios that relate to when, how and where the BRC can work. These are based on the BRC's working practices and real-world limitations on their work and ensure the validity and applicability of model outputs. For example, it is presumed that:

- **the BRC has received a request for assistance from Gold Command**. As outlined in footnote 10, this action is required before the BRC can begin response efforts.
- **the BRC has been assigned to distribute sandbags, water bottles, blankets, hygiene kits and cleaning kits and all resources are housed at regional BRC facilities**. This is in keeping with BRC practice for domestic response efforts whereby resources are purchased, maintained and stockpiled across the country at all times. Local councils often provide sandbags for residents before major floods, but no information could be sourced for either case study area as to where sandbags would be stored, where they would be distributed from, or how many would be made available.
- **resources available are finite**. It is rare that the BRC, or any other such organisation, would have an infinite supply of staff or supplies. Although stock can be replenished by suppliers given sufficient time and funding and mutual assistance operations are often put in place whereby neighbouring regional BRC offices can supply resources, BRC Emergency Response staff wanted to test scenarios where these options were not available.
- **the BRC can distribute resources as they see fit and have not been assigned a specific list of individuals, houses or areas to focus on by Gold Command**. It is often the case that Gold Command will distribute responsibilities and designate areas to organisations and teams to ensure resources are spread appropriately. However, the BRC wanted to test a number of distribution strategies that required a level of autonomy.
- **the BRC will work in 12-hour shifts.** Although emergencies often require 24-hour support, it is rare for the BRC to perform distribution work 24-hours a day due to recipients resting on evenings and potential dangers of working during the night in flooded areas. Staff and volunteers work

12-hour shifts (with regular breaks). Each modelled day will consist of, and be limited to, 12 hours of distribution time (packing, delivering, distributing, returning), representing a 7am to 7pm workday.

A number of specific model development aims were agreed, in addition to the wider project aims and restrictions set out in Chapter 6. to ensure the suitability and use of the model by the BRC. The full list of model and wider project requirements are as follows:

- The model must **utilise the OSVI and present a range of prioritisation strategies**.
- The model must be **flexible enough to examine a range of flood scenarios and strategies** within the UK.
- The model must **allow staff to dictate or directly input key model parameters** (particularly vehicle numbers and resources).
- The model must be **able to run on BRC computers**.
- The project must **align with the BRC's 2010–2015 corporate strategy**: *Saving Lives, Changing Lives*[27] (and later the 2015-2019 corporate strategy: *Refusing to ignore people in crisis*[28]).
- All work, including all products, reports, briefings and external materials, must **abide by the BRC's Fundamental Principles**[29]**.** This ensures such materials can be widely disseminated within and by the BRC.
- The project must **focus on methods and understanding that are currently beyond the abilities of the BRC** and must guide the organisation's internal development.
- The project must **lead to outcomes and/or outputs that can be utilised by BRC staff and volunteers to assist their work**.
- All **secondary data used must be from the public domain and free to use.** This corresponds with the desires of the BRC to limit its use of proprietary data in an effort to reduce costs and support the wider use and dissemination of their data and findings. Where possible, open

[27] Available here: https://goo.gl/rOs1Mb
[28] Available here: https://goo.gl/o1M38B

[29] See Appendix 11.2 for more information on the BRCs Fundamental Principles.

source software should be utilised. Failing this, only proprietary software that the BRC has access to should be utilised in an effort to reduce expenditure and maximise the use of the resultant techniques and software by BRC personnel.

- The use of **any data provided by the BRC must conform with the BRC's Information Governance Guidelines**[30].

[30] For more information, see British Red Cross: Information Governance Policy Available here: https://bit.ly/2T2IvDr

7 METHODOLOGY: MODEL DEVELOPMENT

Introduction	Literature Review	Stakeholder Engagement	Methodology OSVI	Results OSVI	Stakeholder Engagement	**Methodology Model**	Results Model	Discussion	Conclusion
Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5	Ch. 6	**Ch. 7**	Ch. 8	Ch. 9	Ch. 10

"To make agent-based modelling useful we must proceed systematically, avoiding arbitrary assumptions, carefully grounding and testing each piece of the model against reality and introducing additional complexity only when it is needed."

~ Farmer & Foley, (2009: 686)

This section is concerned with the later stages of the participatory modelling approach (outlined in Figure 44) and details the array of technical methods used to create the model. The model development process is broken down into its core components: conceptualisation, including the development of the high-level model overview; the development of the model from outline and raw data inputs to final working code and reporting structure; verification, calibration, and validation processes; and final model evaluation procedure.

7.1 MODEL OVERVIEW

To outline the modelling process, including model inputs, interactions and feedbacks, calculations and outputs, and provide stakeholders and users with a better understanding of its interactions and processes, a high-level model overview was developed (see Figure 45). Developed in conjunction with BRC staff, the modelling process, including inputs, model parameters, and outputs is outlined.

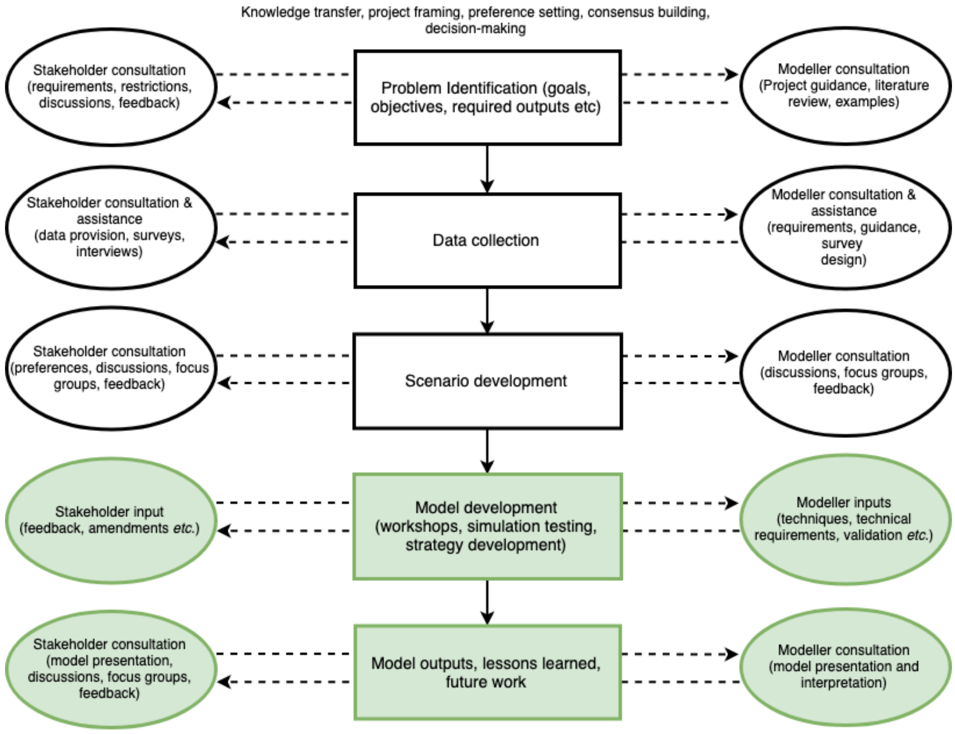

Figure 44: Participatory modelling approach – the green highlighted sections will be discussed in this chapter, with the non-highlighted sections discussed previously in Chapter 5: *Methodology: Stakeholder Engagement*

The general model was conceived as a set of discrete modules within the wider model system. This approach was used as it was hoped that future development of the model would allow for modules to be adapted, or "swapped", depending on the situation being examined. For example, the model framework presented below includes four main modules consisting of:

1. event/location and scenario parameters;
2. household demographics and population parameters;
3. Agent attributes and decision-making dynamics; and
4. scenario and strategy parameters.

The individual parameters within these four modules can be changed, adapted or deactivated entirely depending on the situation being examined.

As input, the model takes event and location parameters, including boundary and road network data, demographic data and hazard data. This is combined with parameter data that is provided by the user. These data are divided in to three categories: scenario, agents, and response strategy parameters. Scenario parameters include inputs to define the hazard event that is the reason for the emergency response, such as event timing and its impacts on networks, and initial synthesis of the local population. Agent parameters and response strategy parameters represent the key inputs that are designed to be controlled by the user and to be tested by the model to examine organisational and strategy changes that can lead to improved response procedures. Agent parameters include total number of agents, their type, speed and home (start) and goal points. Response strategy parameters include the number and associated skills of agents (staff or volunteers), resource type and location, and resource distribution strategy. These parameters were chosen by BRC staff as representing those that can be controlled for and are most likely to impact overall response outcomes. The final input is vulnerability and is represented by two parameters: the OSVI and a calculation of the affected population, their number and location.

The model engine represents the model environment as a whole, including the combined inputs, the modelled experiments (the processes, parameters and strategies defined by the user), and the modelled interactions and feedbacks. In its simplest, the model engine is what the user interacts with.

Finally, as output, the model produces scenario and strategy reports that are collated from a set number of model runs. These reports include a record of all resources distributed and where to and a record of journey times and distances. This information can then be used to determine the effectiveness and efficiency of modelled strategies given a set model scenario.

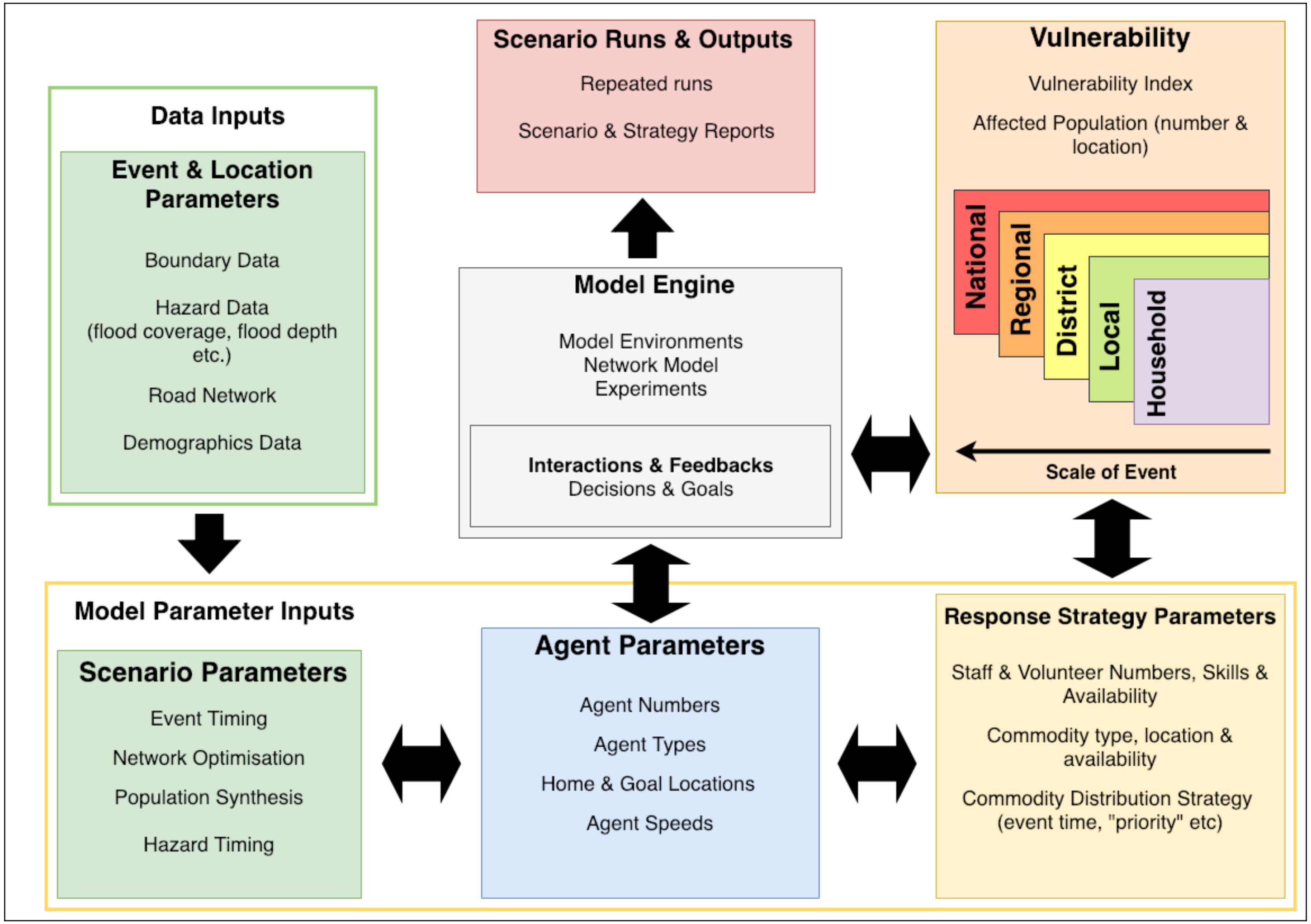

Figure 45: Model Framework

7.2 MODEL DEVELOPMENT: ITERATION PROCESS

Figure 46 and Table 20 outline the model development process, from the simple abstract command line model to the final model and highlights the key features and processes of each variant. Model development was a highly iterative approach, with each model variant representing a significant change based on BRC feedback, or significant improvement or addition of code over its predecessor. Model development was performed using the Eclipse integrated development environment (IDE), Java 8, the MASON simulation library, and GeoMASON extension

7.2.1 BASIC RELIEF DISTRIBUTION MODEL

Based upon findings from discussions, focus groups and past event debrief reports, key aspects of BRC flood response work (what is done, when, why and how) was factored into a generic distribution model (see Appendix 10.7). This was constructed in cooperation with BRC staff, who provided feedback and guidance during group discussions, and was built using the information provided during the data collection and scenario development stages (see Chapter 5).

Resource availability was determined: what resources are available immediately, what is the maximum number of each resource that can be stored or transferred at a time, what is the average refresh rate or are resources finite. Task timeframes, such as time taken to load and unload vehicles, refuel *etc* were determined. This information was provided by BRC staff with direct knowledge and experience of the tasks and is detailed in section 6.3.3 and Table 18.

Basic movement parameters (speed, range, carrying capacity *etc*) were decided upon. It was decided that initially 30 mph would be the set speed, vehicle range would be unlimited, and, to keep the model as simple as possible at this early stage, agents were provided goal locations at random from the entire list of LSOAs in each case study area. These decisions were made to keep model development quick and simple in the early stages.

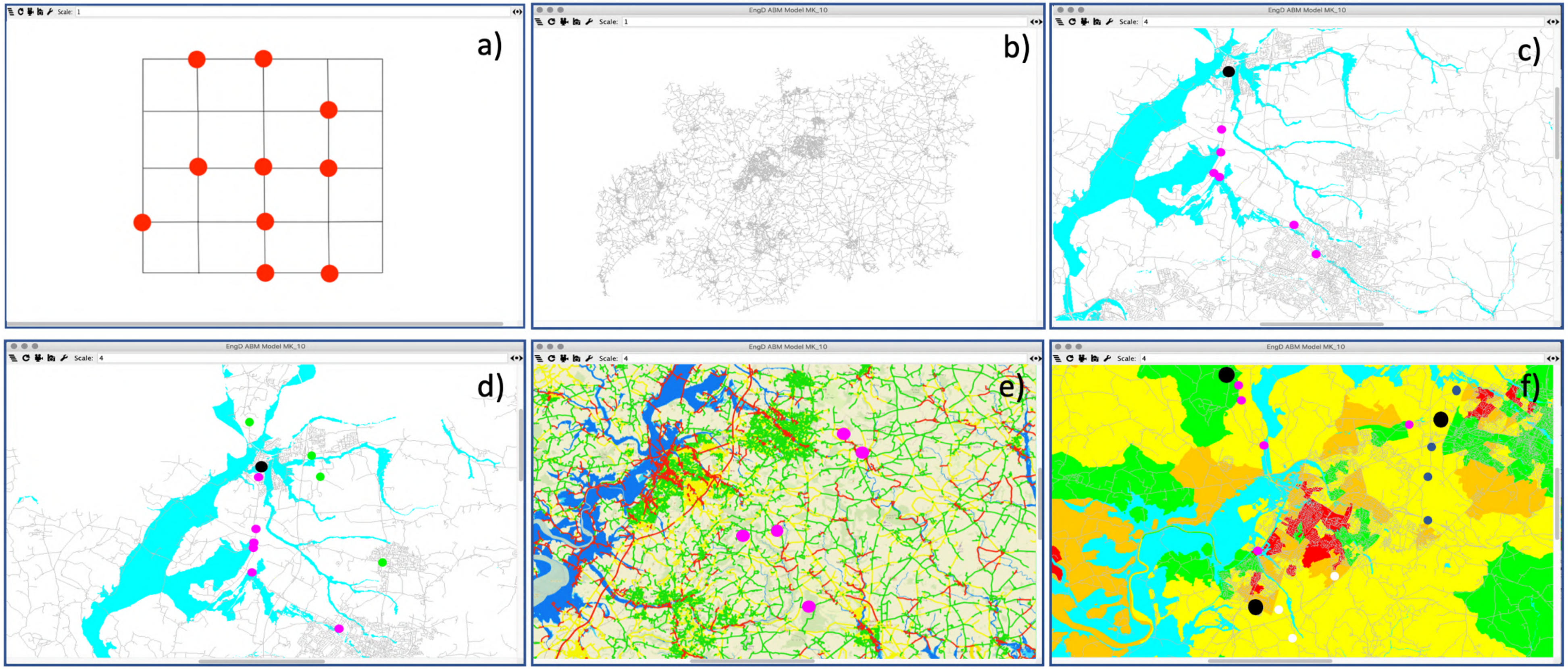

Figure 46: Iterative model development (a) `MK_1`: basic grid-based model, agents move at random from node to node (b) `MK_2`: real-world road network added (c) `MK_5`: flood zones added and distribution points; (d) `MK_6`: multiple agents classes added (e) `MK_9`: road network updated to include impact of flooding on each segment, testing (f) `MK_10`: multiple 'depots' added (black dots), multiple agents classes and multiple independent goals set.

Model Variant	Key Features & Processes
`MK_0`	• Simplistic, generic traversable network – abstract representation of lines and nodes. • Agents – 10 basic, static Agents that are placed on the network. No attributes, no skills, no movement. • Time – simplistic representation of time – each ‘step’ in the model represents 1 second. • Model runs indefinitely.
`MK_1`	• Agent movement added (Agents assigned random start point and move independently across the Network. When Agents reach a junction, they decide to go left or right at random). • Model outputs decisions (‘left’ or ‘right’) to the Command Line. • Model runs indefinitely. Square model boundary – boundary that marks the extent of the model ‘world’.
`MK_2`	• Real-world road network imported and converted to navigable network: all nodes and segments tested for connectivity, segments unattached are removed. • Agents still assigned random start point and choose next direction at random. • Model runs indefinitely.
`MK_3`	• Graphical User Interface (GUI) added: user can play/pause/stop the model. • Norfolk road Network used. • Start and goal locations hardcoded. • All Agents have the same set speed. • Route is determined by A* algorithm.

	• Agents move from start location to goal location and wait for all other Agents to arrive before returning. • Model outputs 'Agent has reached goal' to the Command Line when each Agent completes a journey. • Model runs indefinitely.
MK_4	• Agents assigned start points at random: road network stored as array, each Agent is assigned an exclusive starting point. • Agents still assigned random goal locations from hardcoded Array. • Goal locations stored as Array and assigned at random during Agents creation. • Agents act independently and no longer wait for all other Agents to reach their goals before returning. • Model runs indefinitely.
MK_5	• Additional shapefiles imported: county boundary, administrative boundaries, flood zones. • Model end point created: when all Agents return 'home' after reaching their goal location, model ends. • All agents assigned same starting point instead of random start points. • Agents assigned random goal location from Array every time they return to the start point. • Model tested successfully with 100,000 Agents. • Model runs indefinitely.
MK_6	• Multiple agent classes added: agents assigned random attribute values for speed, car type, manifest size. • All agents assigned same starting point instead of random start points. • Vehicle agents assigned random goal location from full road network array every time they return to the start point. • Model runs until all goal locations have been visited.

	• Model tested successfully with 100,000 Vehicle agents. Run time in excess of 180 minutes. • Model reporting added: model exports .TXT file reporting time taken (number of steps and run time) at end of run.
MK_7	• Live charts added displaying 'traffic' statistics during model runs: maximum speed, average speed, and minimum speed of Vehicle agents. • Inspector added so User can select an agent and see attributes as well as their current network location. • Model initialisation and step time considerably lengthened by additional data loading. Full model run-time average of 42 minutes with 100 Agents; 68 minutes with 1,000 Agents; in excess of 180 minutes with 100,000 Agents. • Additional Vehicle agent attributes added: sex (male or female), transport mode ('car' or '4x4') which in turn determines maximum speed, shift status (on or off shift) *etc*. • Model runs until all goal locations have been visited.
MK_8	• LSOA Centroids shapefile added to GUI. OSVI visualisation added. Model reads OSVI CSV during initialisation and creates polygons to match the LSOA boundary. OSVI polygons are coloured depending upon the OSVI ranking: low vulnerability; low to moderate vulnerability; moderate to high vulnerability; high vulnerability • CSV of Centroids 'snapped' to nearest road segment read in during model initialisation, stored as Array. Agents assigned goals at random from Centroids Array – multiple Agents can be assigned same goal location. • Goal locations chosen at random from LSOA Centroids. • Model runs until all goal locations have been visited.
MK_9	• Distribution Point agents added: controls aid resources, distribution priority, and assigns goal Centroids and manifests to Vehicle agents. • Delivery priorities and strategies added: o Goals can be chosen from LSOA Centroids based upon their OSVI rating, number of Priority Residents (PRIOS) or most flood affected areas (FIS) – highest rated areas first

	o or from LSOA Centroids based upon their proximity to the HQ (*e.g.* closest first or furthest first) o or goals can be chosen from LSOA Centroids based upon a combination of the above *e.g.* closest highest OSVI rated area first o or goals can be chosen from LSOA Centroids at random. • Distribution Point has set number of bays. Vehicle agents at Distribution Point must be <= number of bays. Vehicle agents wait at Distribution Point for a free bay when another Vehicle agent leaves the Distribution Point; first come, first served. • Distribution Point agents assigned maximum load capacity. o This represents the maximum number of items the Distribution Point can physically store. This was based upon informal discussions with BRC staff at Gloucestershire and Norfolk facilities and is an estimate. • Vehicle Agents assigned 'loading time' and 'delivery time' based upon the resource being distributed. Vehicle agents wait at Distribution Point and goal location for set times. • Resource refresh scheduler added. o A refresh rate for the resource being distributed can be set by the user. For example, during the Gloucestershire floods, the BRC received approximately 50,000 bottles of water every 24 hours from a variety of sources, including commercial and private donations. The BRC physically do not have the space to store all the resources needed so it is necessary to refresh stocks periodically as they are distributed. • Failed delivery probability added: chance that a delivery fails when a Vehicle Agent reaches its goal. o Represents rare events where a delivery is not made due to priorities changing, an emergency occurring, or an area unable to accept the delivery. It was felt by the modeller and BRC staff that the feature would improve model stochasticity. Sensitivity tests and discussions with BRC staff (see section 7.4.3) determined that a 1% rate was suitable and could factor in other unknown actions that regularly occur during an emergency situation. • Road Network updated to include impact of flooding on each segment: Green/1: road segment has multiple connections and is not directly impacted by the FZ; Yellow/2: road segment has restricted or limited connectivity;

	Orange/3: road segment is unreachable, or segment is only reachable from roads entirely cut off by FZ; Red/4: road segment is entirely within FZ and has no unflooded connectivity • Vehicle routing can be restricted to specific road segment classifications • Vehicle history added: Vehicle ID, time step when leaving Distribution Point, time step when arriving at goal, total distance travelled • Delivery history added: LSOA name and ID, total number of deliveries • Model runs until all goal locations have been visited
MK_10	• Vehicle agent activity attribute added: 'at HQ', 'Out on Delivery, 'Distributing', 'Returning to HQ'. • Multiple Distribution Points added: each Distribution Point has set number of bays and Vehicles. Resources and goals shared amongst Distribution Points *e.g.* goal chosen from LSOA Centroids based upon their OSVI rating (highest rated first) but then assigned to a Vehicle whose Distribution Point is closest to that goal. • Live chart displays number of Vehicles within each activity, number of miles travelled, and resources distributed. • Maximum manifest value added. Represents the maximum number of each resource type each vehicle can transport. Value is dependent on the type of resource being distributed and the type of vehicle. • Breakdown probability added: chance that a Vehicle agent will breakdown either at the Distribution Point or while out delivering. Vehicle agent pauses for 2 hours and returns to the Distribution Point. o Represents breakdowns and traffic accidents. Such events are rare as the BRC maintains and replaces all vehicles regularly, but it was felt by the modeller and BRC staff that the feature would improve model stochasticity. Sensitivity tests and discussions with BRC staff (see section 7.4.3) determined that a 1% rate was suitable and could factor in other unknown actions that regularly occur during an emergency situation. • Model runs until all affected Centroids have received aid (determined by number of affected households read in at start) or set number of days has elapsed – chosen by user. • Model reporting finalised:

	o Resource record: *load ID, Distribution Point ID, time step of departure, LSOA delivered to, time step load delivered, driver ID* o Round record: *Vehicle ID, duration (number of time steps), distance travelled, time step load delivered* o LSOAs visited: *LSOA name and ID, total number of deliveries*

Table 20: Model development process: model variants and key processes

7.3 FINAL MODEL STRUCTURE

As detailed in Table 20, and in cooperation with BRC staff and volunteers, the distribution model was redesigned multiple times across multiple iterations. Key changes include:

- Incorporate different relief strategies, model scenarios, routing algorithms and display and reporting methods.
- Use of different case study areas.
- Increase scope of agent attributes and agent status modes.
- Creation of distribution strategies through the creation of different decision algorithms.
- Development of live charts that display key model statistics during runs and creation of output reports.
- Incorporate the OSVI into the model display.

The original and generic distribution model process that was used for model iterations `MK_0` to `MK_5` and the redesigned model process from iterations `MK_6` to `MK_8` are presented in Appendix11.7. The final model process used for iterations `MK_9` and `MK_10` is detailed in Figure 47.

Following the work of Hall & Virrantaus (2016), who found that the workings of ABMs can be visualized through three flexible and easily understandable diagrammatic visualization approaches, three model visualisations are presented below:

1. an overview diagram of the final model structure, detailing inputs, parameters, and sub processes which underlie the simulation (Figure 47).
2. a model process diagram, including key actions, interactions and relationships (Figure 48).
3. a data model outline detailing key inputs, parameters and values, and detailing user inputs (Figure 49).

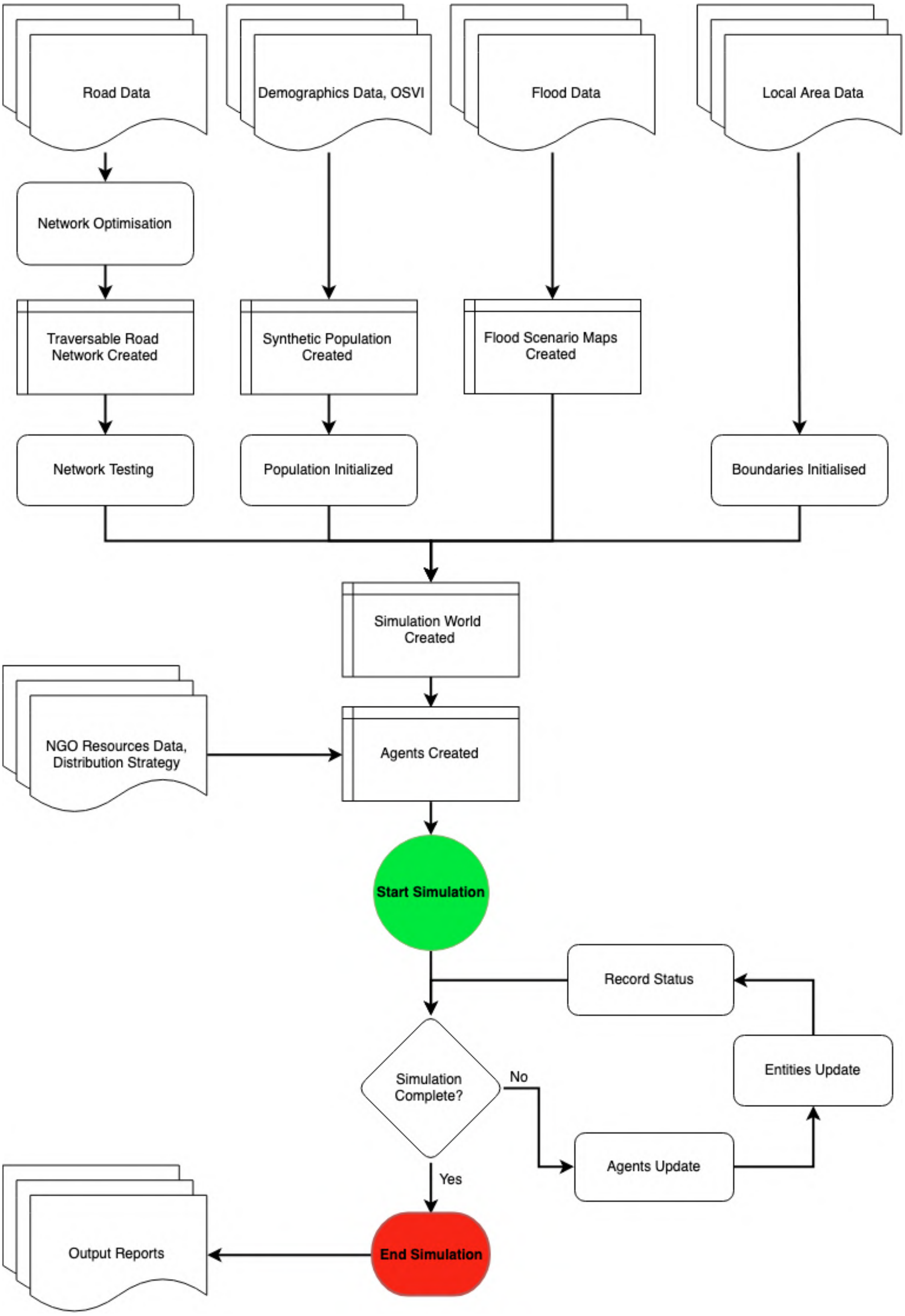

Figure 47: Overview of final model structure, detailing how data is used within sub processes which underlie the simulation. Information on the final model folder structure can be found in Appendix 0

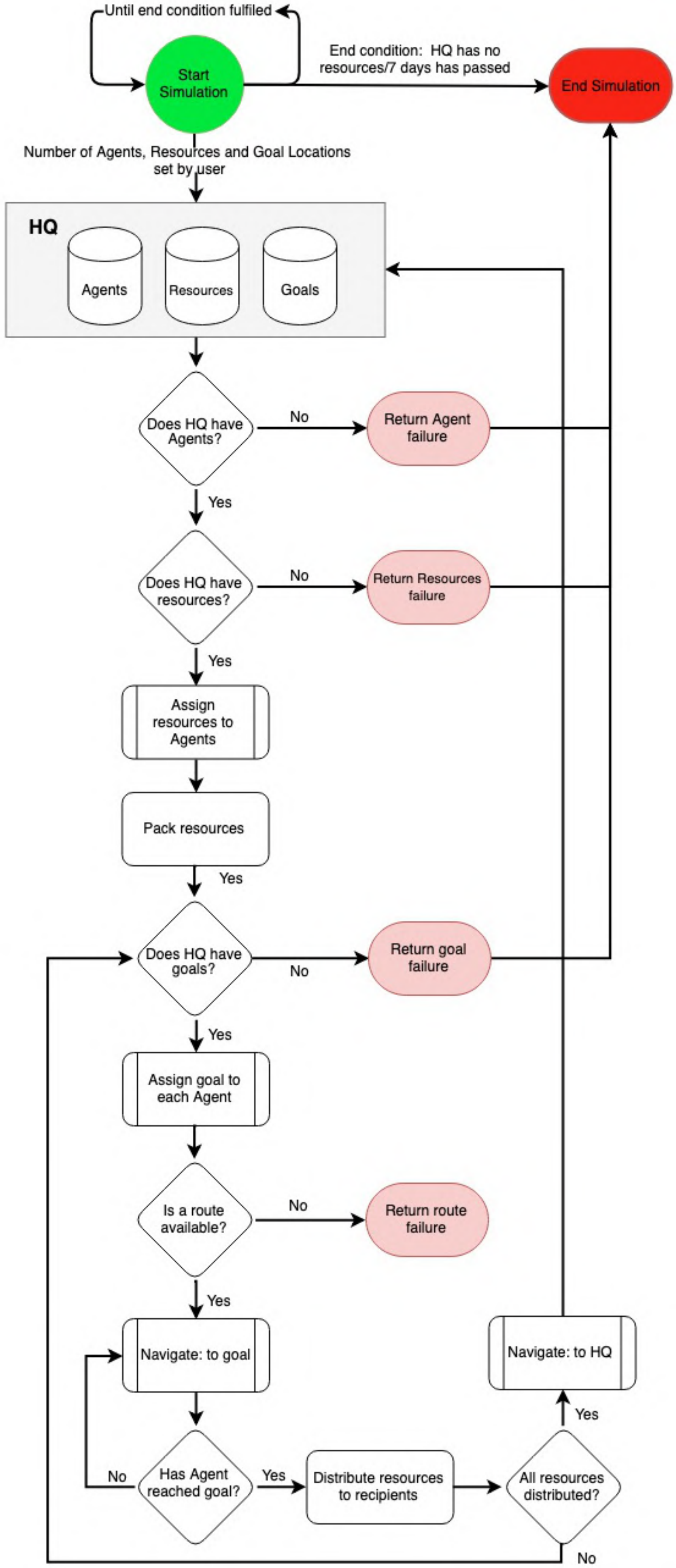

Figure 48: Final model process outline (see section 7.3.1 for an outline of model time and scheduling)

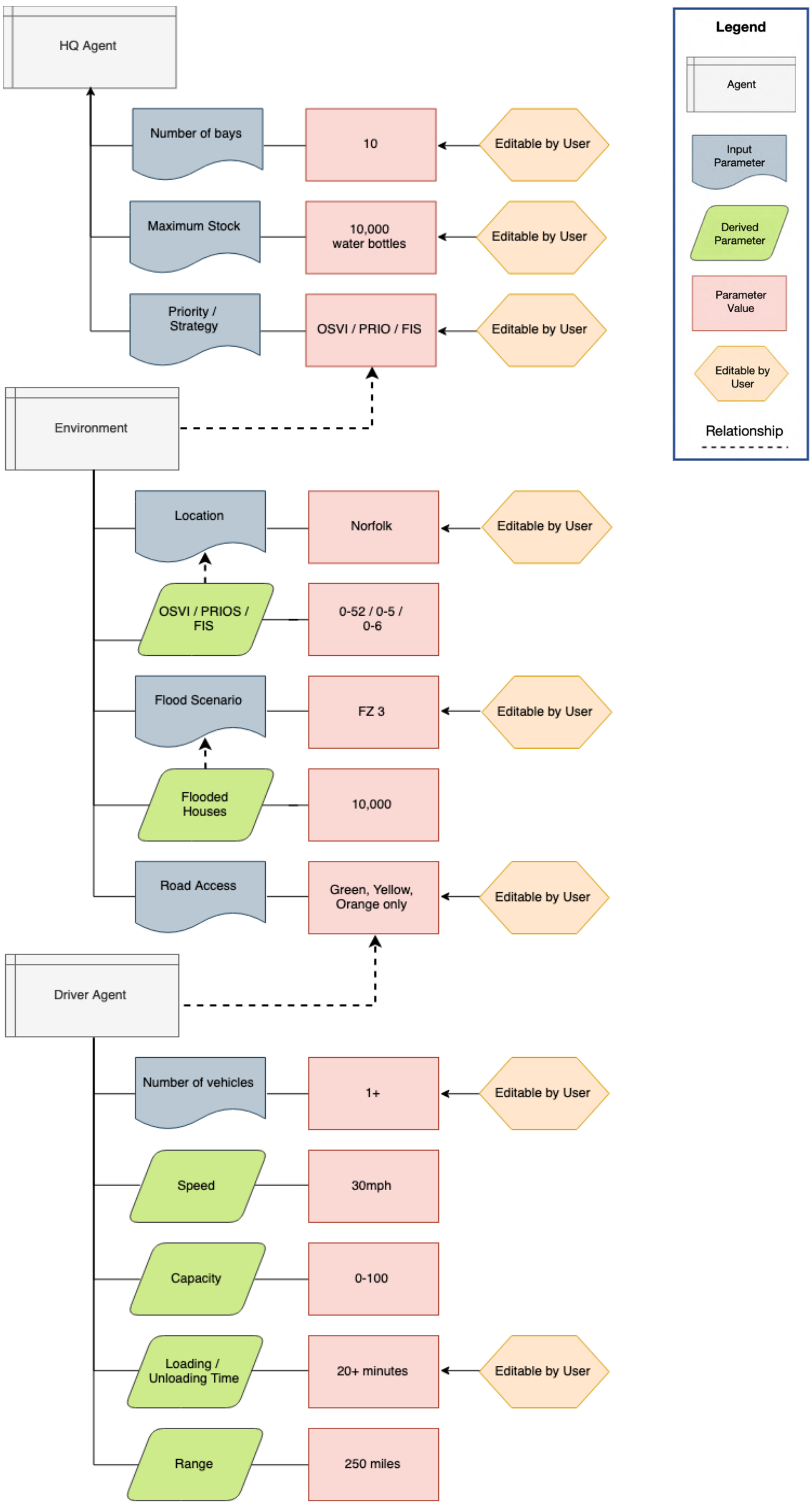

Figure 49: Data Model outline detailing key parameters and values

Attribute	Details
Agents	
`vehicleID`	Randomly generated ID for each vehicle agent
`homeBase`	Hardcoded road segment of agents' home base (distribution point)
`targetDestination`	Road segment of LSOA Centroid for current delivery
`currentIndex`	Current road segment
`approxManifestSize`	Maximum number of parcels each agent can carry
`status`	Current status of agent: 'at *HQ*', *'Delivering'*, *'Distributing'*, *'Returning to HQ'*
`speedVehicle`	Hardcoded maximum speed of vehicle (km/h)
`roundDriveDistance`	Current distance travelled by agents for current round (km)
Distribution Point	
`loadingTime`	Time taken to load vehicle at Dist. Point in increments of 5 minutes
`deliveryTime`	Time taken to unload vehicle at destination and deliver goods in increments of 5 minutes
`numMaxAgents`	Maximum number of vehicles per model run
`numBays`	Number of loading bays at the Dist. Point / the number of vehicles that can be loaded simultaneously
`inBays`	Number of loading bays currently in use
`waiting`	Number of vehicles currently waiting for a free loading bay
`rounds`	Total number of rounds completed by all Vehicles
`loads`	Total number of loads delivered by all Vehicles
Resources	
`parcelID`	Randomly generated ID for each parcel
`parcelStatus`	Current status of parcel: *undelivered, failed delivery attempt, out for delivery, delivered*
`deliveryTime`	Time parcel was delivered to destination

Table 21: Key model attributes/parameters and description (details for `homeBase, speedVehicle, loaingTime, deliveryTime, numMaxAgents` and `numBays` was provided by BRC staff where available – see Table 18 and section 6.3.3)

A number of complexity-oriented design concepts are central to the model and are specified in Table 22.

Concept	Description / Example
Emergence	The model relates the imposed emergence of flooding to the emergence in relief distribution as well as the geographic disparity across LSOAs.
Adaption	Agents have various state changes and routing decisions and consider environmental changes (flooded roads *etc.*) during simulations to re-plan routes.
Fitness	Goals are updated dynamically throughout the model runs and these "objectives" are considered a measurement of fitness as various routes are measured and compared.
Sensing	Agents consider a number of environmental state variables, observing or "sensing" changes in the environment, such as flooded roads or other agents, and adapt/interact.
Interaction	Responder agents regularly interact with each other through traffic dynamics and with the Distribution Point agents when receiving goals.
Stochasticity	Stochasticity plays a role in Agent routing, as well as Agent generation and attributes. In addition, random variables are used for parameters, including speed. The simulation runs presented here use a static flood 'environment' which provides consistency across runs and that the dependent variable being tested is the Agent behaviour. Future work would add levels of stochasticity to the flood as well (*e.g.* probability any given road segment is flooded) to simulate more accurately the changeable nature of floods.

Table 22: Key model design elements and concepts (adapted from Cohen & Axelrod, (2000) and Grimm & Railsback (2005))

7.3.1 SCHEDULING & TIME

Time is a key element of the model. Each emergency scenario and response strategy have a distinct temporal element, be it the length of time a flood hazard is present, travel time of responders or the time of day. Time in the model is modelled in discrete time 'steps' or 'ticks' with each one lasting for a specified duration depending on the process (agent movement, hazard refresh *etc*). It was decided that each 'step' would represent five minutes and that all events, activations and actions would be scheduled at this resolution with elements of the model updating at different times: for example, agents update every five minutes (one 'step') regardless of their action, 'loading' and 'distributing' tasks take 20 minutes (four 'steps') and 30 minutes (six 'steps') respectively, while the

Distribution Point and its resources as well as the flood hazard update every 24 hours (288 'steps'). These timings can be changed, but this scheduling was suggested by BRC Emergency Response staff as an accurate representation of the timing of information flows and commodity updates that the BRC work within an emergency situation. Scheduling must be taken into account during model development as an increase in updates can add a significant burden on computing resources when simulating complex agent interactions over a broad extent of space, such as an entire English county.

Significant discussion focused on the ordering of agent invocation: random asynchronous execution of responder Agent on each model tick, or event-driven where responder Agents only act when invoked. It was decided that all responder Agents would be invoked at the beginning of the simulation as the model assumes that the BRC's help has been requested and that they have been assigned the specific tasks being modelled and would therefore start distribution as soon as possible.

Total simulation runtime was discussed extensively with BRC staff and volunteers during conversations and workshops throughout the modelling process (see section 6.3 above). Emergency situations, especially floods, are often drawn out processes with adverse effects impacting individuals and communities for months and years. However, the BRC's operating capacity, its capabilities, and available resources require that an exit strategy be planned when responding to emergencies. Although the priority is to provide those affected with the help they need, the overall goal is to help them regain their independence. It was decided that the temporal focus of the model should be the short-term (days). An examination of past domestic BRC flood response after-action reports and conversations with responders found that much of the BRC's domestic emergency distribution work is done within seven days of the event, with focus turning towards recovery work. Thus, it was decided that, instead of allowing the model to run until an equilibrium within a certain metric is reached, the simulation would continue until either seven days have passed or until all resources have been distributed.

As stated above, BRC staff and volunteers regularly work 12-hour shifts (with regular breaks). Each modelled day will consist of, and be limited to, 12 hours (144 'steps') of activities (loading, delivering, distributing, returning), representing a 7am to 7pm workday.

7.3.2 AGENTS

Within ABM, Agents perceive their environment and, on the basis of this and according to a set of condition-action rules set forth by the modeller (examples presented below for this model), act within it to accomplish their objectives (again, set forth by the modeller). Hall and Virrantaus (2016) argue that the workings of an ABM can only be understood through the behaviour of Agents and put forth five types of Agents relationships that are required to understand sufficiently how the elements of an ABM interact: categorisation, space, time, behaviour, and causality. This concept is used here to describe the Agents and outline the behaviour of the model.

AGENT CATEGORIZATION

The main agents within the model are NGO responder agents, such as BRC staff and volunteers. Agents are endowed with a knowledge of where those affected are located, where hazard zones are located and a set of rules governing their actions (*e.g. if Agent runs out of resources, head back to base; if Agent encounters flood waters, find alternate route*).

Responder Agents are categorised into 'base Agents' and 'vehicles'. Base Agents represent those Agents that remain at the Distribution Point during model runs. In the real-world, these Agents would be supervising work and preparing for the next vehicles to arrive at the Distribution Point. Base Agents are not visualised since they remain within the Distribution Point and are represented within the code as the difference between the number of drivers and the number of bays at the Distribution Point. Drivers are the Agents that traverse the road network and travel from the Distribution Point to the goal location. Drivers are actually an abstract representation of two BRC staff/volunteers and a vehicle.

The type of vehicle can be determined by altering model parameters, including speed limitations, range, the number of resources that can be transferred per journey, and the ability to traverse flooded roads. For example, the default vehicle represented is a Volvo XC70, a car common to most BRC regional offices that has the highest speed but cannot traverse flooded roads. Alternatives include the Land Rover Defender, which has a larger carrying capacity and can traverse flooded roads but has a slower maximum speed and is restricted to certain staff (those with 4x4 training), and the 'Transit-style' light commercial vehicles that have much higher carrying capacities (and therefore longer packing and unpacking times), but slower average speeds and cannot traverse flooded roads.[31]

As well as the responder Agents, the distribution points have been 'agentised'. The distribution points control the responder Agents from a strategic standpoint: choosing where to distribute relief, and what relief to distribute depending on the strategy being used, as well as the current flood status, availability of resources and the information provided to it from the OSVI.

NUMBER OF AGENTS

The number of responder Agents is dependent upon the scenario and strategy being modelled and is determined at model setup. For the scenarios and strategies examined, the number of responder Agents was decided through discussions with BRC staff and the examination of past personnel deployments and is described in the respective results sections.

Similarly, the number of distribution point agents is dependent upon the scenario being tested. In the Gloucestershire case study, only one BRC location was utilised during the response efforts of 2007. However, in the Norfolk case study, two BRC offices are available and are prepared to respond to flood emergencies.

[31] The XC70 has a carrying capacity of 575kg, the Land Rover Defender 110 has a maximum carrying capacity of 1,525kg but is smaller than the standard transit-style van that can carry 1,000kg. This needs to be factored in when determining what vehicles to use to transport, say, sandbags or the larger but lighter cleaning kits.

AGENT LOCATION

As with the number of Agents, the location of responder Agents is determined based upon the scenario and strategy being modelled (see also section 6.4). Discussions with BRC staff and an examination of BRC facilities allowed for current BRC facilities and related emergency facilities to be located, as well as likely locations for temporary headquarters or distribution points.

The location of the agents is recorded at all times, allowing for each route to be mapped and examined, and the metrics (start and goal locations, total movement time, distance travelled, average speed *etc*.) of each agent's "round" to be examined.

AGENT BEHAVIOUR & DECISION MAKING

Agents can exert active independent influence within a simulation due to their autonomy and heterogeneity: proactive (goal orientated); reactive (perception of surroundings, prior knowledge based on experiences); observation (ability to take actions accordingly). Vehicle agents are tasked with distributing relief as per the strategy being tested but will be able to respond proactively and reactively to developments within the model that they observe (changes in access, changes in the location/need of those affected *etc*.).

Vehicle agents start the simulation at the BRC Distribution Point in the case study area (or, if multiple BRC offices are present, Agents can be distributed by the user or distributed at random by the model). Each Distribution Point has a maximum number of 'loading bays'. These bays represent the maximum number of vehicles that can be parked and loaded simultaneously – a figure that is determined by the User based on the number of staff/volunteers available at that location. Depending on the number of BRC Agents generated and the number of vehicles, Vehicle agents are held outside of the Distribution Point as they wait for a 'loading bay' to become available. Once a vehicle enters a loading bay, the vehicle is loaded with the resources that are to be distributed. The time taken to fully load each vehicle is set by the user. This time can be changed by the User depending on the vehicle being used (estate cars, Land Rovers, light commercial

‘Transit’ vans *etc*), the number of staff available (fewer staff result in longer pack times), or by the kind of resource being packed (faster to pack 10x packs of 10 blankets than 6x 18kg sandbags). Similarly, the time taken to distribute the resources at their goal location can be determined by users. BRC staff noted that distribution time is usually longer than packing time as conversations are often had with those receiving the resources or other actions occur, such as meetings with first responders or other relief efforts. Again, distribution time can be changed depending on the vehicle being used, the number of staff available, the resource being distributed *etc*.

Vehicle agents are assigned goal locations (`targetDestination`) by the Distribution Point depending upon the distribution strategy being used. For example, if the ‘most vulnerable’ strategy is being utilised, the Distribution Point determines the LSOA with the highest OSVI rating and assigns it to the first vehicle that is ready to leave the Distribution Point. This continues until the appropriate number of resources have been dispatched. Then the next ‘most vulnerable’ LSOA is chosen and the process continues.

AGENT MOVEMENT

Once Vehicle agents have been assigned goal locations (`targetDestination`) they determine a route. Agents utilise an A* routing algorithm coded in MASON. The A* algorithm is a “best-first”, or informed search, algorithm, that aims to find a path from a specific starting node to a given goal node with the smallest ‘cost’ – with ‘cost’ defined as, for example, the least distance travelled or the shortest overall travel time. The A* pathfinding algorithm is generally seen as an extension of the Dijkstra shortest-path algorithm as it takes into account the cost/distance *already* travelled and achieves better performance and accuracy through its use of search heuristics (see Figure 50 for a pseudocode description of the A* process). Soltani et al. (2002) and Van Wezel (2005) evaluated the performance of both the Dijkstra's algorithm and the A* algorithm and found that Disjkstra’s algorithm can be computationally costly due to redundant searches from a starting point to *all* other nodes, whereas the A* algorithm usually calculates a *single* path towards the target with minimal distance by default and thus is far less complex and computationally costly. Van Wezel (2005) concludes that the A* search algorithm is the best choice for most static environments – such as the one being utilised in the model presented.

```
Initialise open list of nodes, which contains only the
starting node
Initialise closed list of nodes, which is empty
Set starting node as current node – f set to 0

While (open list is *not* empty)
      If
            neighbour node is in open list
            and calculated g value is lower
                  update neighbour node with lower g value
      Else if
            neighbour node is not in open list
            neighbour node is not in closed list
                  add neighbour node to open list
                        set g value
      Update f
Iterate through open list
      node with the lowest f value
      or if f values are the same node with lower h value
      Set path from final target node to starting node
```

Figure 50: Example pseudocode for A* algorithm

Agents move at a predetermined speed. This speed is chosen at random from a range between 30 and 40 mph for each agent. This process adds a level of stochasticity to agent movement. Alternative methods could be used, such as using the maximum allowed speed, or a range up to the maximum, for each road segment, but the computational requirements needed to do this during model runs significantly slowed down each run. BRC staff recommended a speed range of between 30 and 40 mph as they felt it suitably represented the likely average speed travelled in a flood emergency situation across a road network with speeds ranging from 20 to 70mph based upon their experience responding to such emergencies. Maximum speed is not likely to represent realistic movement on a road network during an emergency event, where traffic and travel times are highly changeable. To simulate traffic, the speed at which a Vehicle agent travels is reduced when more than one agent is on the same road segment. Future work would aim to integrate real-world traffic data.

During different scenarios and strategies, the extent of the road network that is traversable is altered (see Table 24, Table 26 and Table 28 for a full list of scenario parameters). For example, during one scenario examined, Vehicles agents were restricted to non-flooded roads, *i.e.* roads with a flood cost of 1 or 2. Roads that were deemed flooded (4) or unreachable (3) were discounted during routing. Future work would aim to integrate flood depth data to determine passable and impassable roads for different vehicle types.

In addition, agents can only operate within the study area. This is an unrealistic restriction on the model but not limiting road accessibility would mean that the entire road network would be considered during routing and this would increase significantly the time and computing power needed for each model run.

AGENT REPORTING

The Distribution Point keeps track of all agents throughout the entire model run. Their locations and routes are recorded, as well as the resources that have been packed and into which vehicle, the resources that have been distributed and to which LSOA, and resources that have been returned. The Distribution Point uses this information to determine how many resources are still required by each affected LSOA and to distribute them appropriately.

When Vehicle agents return to the Distribution Point after delivering resources, the process starts again until all resources available at the Distribution Point are distributed, all affected areas have been serviced, or seven days has passed (see section 7.2 for the rationale behind these decisions).

AGENT AUTONOMY, HETEROGENEITY & STOCHASTICITY

Throughout the ABM literature, one essential agent attribute is noted: autonomy (Woolridge, 2009). Within the model presented, Vehicle agents are autonomous units; centrally tasked by the strategy under examination, but not governed by it. Agents are both proactive (once initialised and presented with an overall goal, such as ‘deliver aid’, they will follow their available decision-making process to complete the task) and reactive (changing task or route in response to changes in the environment). Agents are able to process and exchange information with other Agents (of each type: Vehicle, Distribution Point, LSOA Centroid) in order to make independent decisions as to where to move to next, and under certain strategies, what relief to distribute. Each Vehicle agent has its own properties, such as speed, area knowledge, skills; allowing for more aggregate phenomena to develop. These properties are based upon the general demographics of the responders, as provided by the BRC and determined by user choices during model setup.

Stochasticity (randomness) is introduced in a number of ways. For example, the proximity of Vehicle agents to other Vehicle agents determines their maximum speed. This is a simplistic representation of traffic whereby vehicle speed decreases when more than one Driver is on the same road segment. In addition, breakdown and failed delivery probabilities are factored in to better represent the erratic and unpredictable nature of emergencies.

7.3.3 FINAL MODEL DISPLAY & REPORTING

When launched, the final model opens in two main windows: the main simulation map window; and a model outline and setup window where the model is described, and the user can alter the model's parameters (see Figure 51).

The model reports on key statistics in two ways: live model reporting as the model runs, and end-of-run reporting when all statistics are exported, and key parameters summarised. Live model reporting consists of:

- A live bar chart displaying the number of Agents within each activity ('at HQ', 'Delivering', 'Distributing', 'Returning to HQ'), and line charts displaying the total number of miles travelled and total number of resources distributed (see Figure 52).

End-of-run reporting takes the form of multiple comma-delimited text files that include:

- Resource record: load ID, Distribution Point ID, time step of departure, LSOA delivered to, time step load delivered, driver ID.
- Round record: Driver ID, duration (number of time steps), distance travelled, time step load delivered.
- LSOAs visited: LSOA name and ID, total number of deliveries.

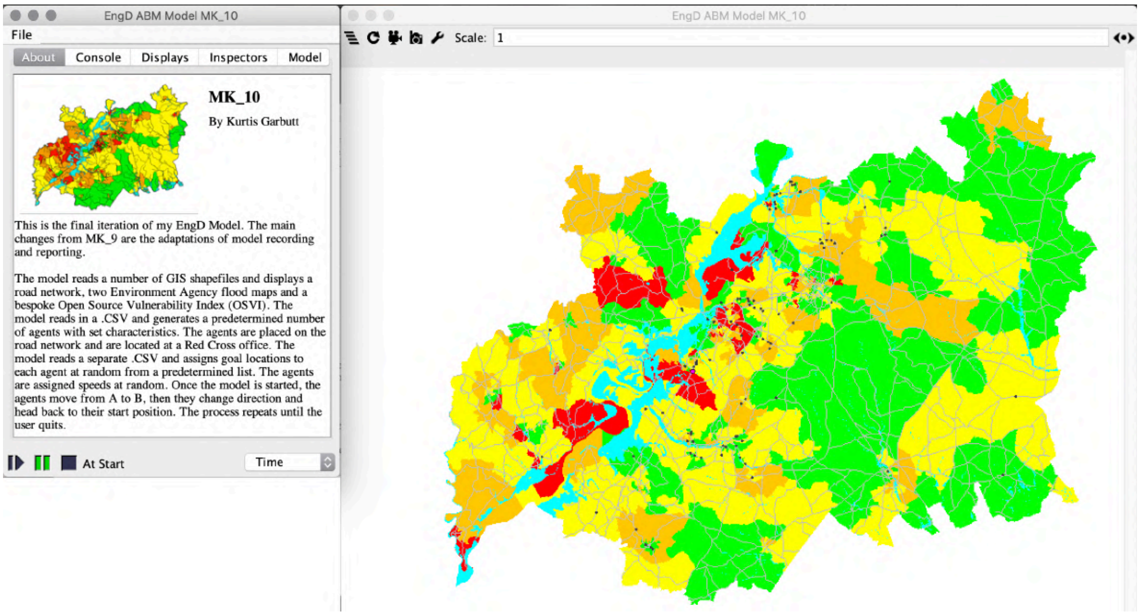

Figure 51: Final model GUI

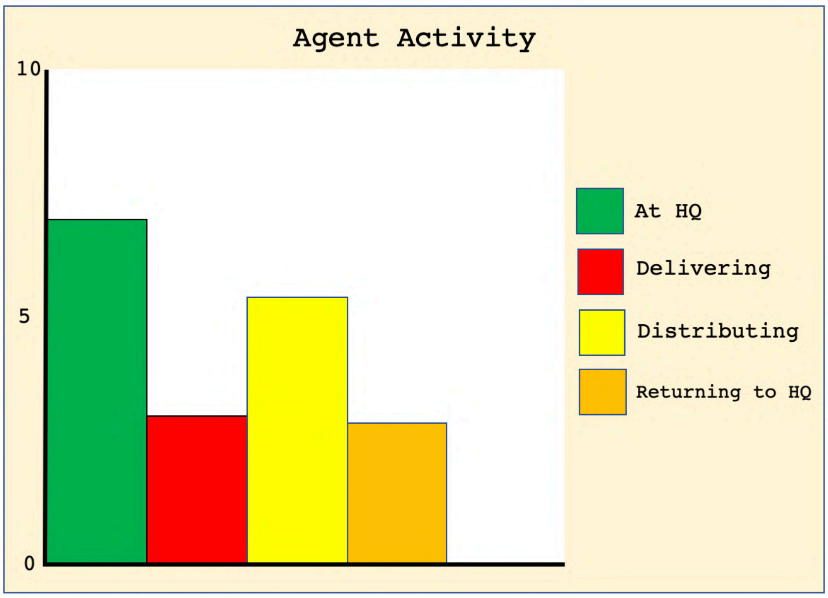

Figure 52: Example of live model reporting chart

```
Loading simulation...

///////////////////////
INPUTTING DATA
///////////////////////

Reading in OSVI shapefile from: data/GL_OSVI_2019.shp...done
Reading in All Centroids from: data/GL_Centroids_2019.shp...done
Reading in 1x Depot from: data/BRC_HQ_GL.shp...done
Reading in Full, Non-Flooded Road Network from: data/GL_Roads.shp...done
Reading in OSVI from data/GL_OSVI_2019.shp...done
Reading in County Boundary from :data/Gloucestershire_Boundary_Line.shp...done
Reading in Flood Zone 2 from: data/Gloucestershire FZ 2.shp...done
Reading in Flood Zone 3 from: data/Gloucestershire_FZ_3.shp...done

Cleaning the road network...testing...
Setting up Distribution Centre(s)...2P2F
Generating parcels...
Prioritising unassigned LSOA...
         Gloucester 008D (LSOA ID: 33) has a OSVIF rating of 37 and it has 37 households that may need assistance.
                  Current list of high priority unassigned wards: [33]
         Gloucester 006D (LSOA ID: 164) has a OSVIF rating of 37 and it has 115 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164]
         Gloucester 001C (LSOA ID: 219) has a OSVIF rating of 37 and it has 89 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219]
         Gloucester 010A (LSOA ID: 239) has a OSVIF rating of 37 and it has 194 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239]
         Gloucester 007G (LSOA ID: 345) has a OSVIF rating of 37 and it has 178 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239, 345]
         Gloucester 010E (LSOA ID: 158) has a OSVIF rating of 35 and it has 84 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239, 345, 158]
         Gloucester 002E (LSOA ID: 223) has a OSVIF rating of 35 and it has 178 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239, 345, 158, 223]
         Gloucester 002C (LSOA ID: 233) has a OSVIF rating of 35 and it has 17 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239, 345, 158, 223, 233]
         Forest of Dean 010B (LSOA ID: 243) has a OSVIF rating of 35 and it has 108 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239, 345, 158, 223, 233, 243]
         Forest of Dean 001E (LSOA ID: 246) has a OSVIF rating of 35 and it has 110 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239, 345, 158, 223, 233, 243, 246]
         Gloucester 007A (LSOA ID: 247) has a OSVIF rating of 35 and it has 149 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239, 345, 158, 223, 233, 243, 246, 247]
         Gloucester 010C (LSOA ID: 360) has a OSVIF rating of 35 and it has 113 households that may need assistance.
                  Current list of high priority unassigned wards: [33, 164, 219, 239, 345, 158, 223, 233, 243, 246, 247, 360]
Sorting parcels by chosen strategy for Distribution Centre: 2P2F
Running simulation...
         Driver 6GNM has BROKEN DOWN!
         Driver 1CEN has BROKEN DOWN!
         Driver XEED has NOT been able to deliver parcel to: POINT (381183.4246222474 212709.48584634456)
         Driver DUGE has BROKEN DOWN!

Simulation ended.

/////////////////////////
OUTPUTTING DATA
/////////////////////////
```

Figure 53: Terminal output during model run

7.4 EVALUATION, CALIBRATION, VERIFICATION & VALIDATION

To ensure that a model accurately represents the phenomenon being simulated and is fit for its intended use it must be evaluated (tested for consistency and reproducibility), verified (model code ‘debugged’), calibrated (model parameters fine-tuned using real world data), and finally validated (model outputs compared to real observations). To model a social phenomenon it is necessary to ‘translate’ it through abstraction (Sobiech, 2008) and so a model will never, and should never, duplicate the phenomenon exactly. Agents in an ABM are meant to represent heterogeneous and autonomous entities that can make independent decisions based upon assigned attributes and behaviour rules (Sobiech, 2008) – just like the real-world systems under analysis - and as such there is a level of stochasticity present that will prevent modelled outputs matching those observed in the real world. Different runs of the same model will likely create variation in the outputs due to changes in the initial setup of the model, the parameters used, and the stochastic behaviours within the model (Castle & Crooks, 2006). It is therefore necessary to examine the consistency and reproducibility of the model through the statistical distribution of modelled outputs. Although difficult, especially when examining emergent outcomes, systematic model evaluation where runs with identical setup conditions and parameter values are performed can provide an understanding of the level of stochasticity and likely distribution of results within the model.

As can be seen in Figure 54, the testing and feasibility process follows a logical model design and testing strategy. The process begins with *experimental design* which involves the creation of simple model designs likely carried out during workshop sessions that can be interrogated by potential users and refined. *Model setup* follows, with the initial creation of the model and the inclusion of all available datasets. *Initial evaluation* involves the examination of initial results and the model’s running process: do results match those that are expected? Is the model running correctly? *Feasibility testing* involves checking the model is fit for purpose under likely scenarios and organisation use case. For example, can the model be used to model likely scenarios (can the model run scenarios that are of an appropriate scale and detail) and can the model be utilised as intended (can the model be utilised on BRC equipment in the field or provide timely usable information).

Following *feasibility testing* and the feedback generated from initial model runs, an *experimentation* stage begins whereby multiple model parameters are tested, including the determination of an appropriate number of model runs, hypothesis testing, strategy and scenario testing, and appropriate visualization and reporting to non-technical audiences. The *experimentation* stage is a lengthy process and must be undertaken with rigorous reporting and feedback to ensure the model design progresses. The *results* produced during the experimentation stage are recorded and examined: are the results as expected? Are there clear limitations or bottlenecks within the model process? Finally, an overall *evaluation* process is undertaken. Depending upon the outcome of the *evaluation* stage, the process of *experimentation* begins again with changes to the model made where necessary.

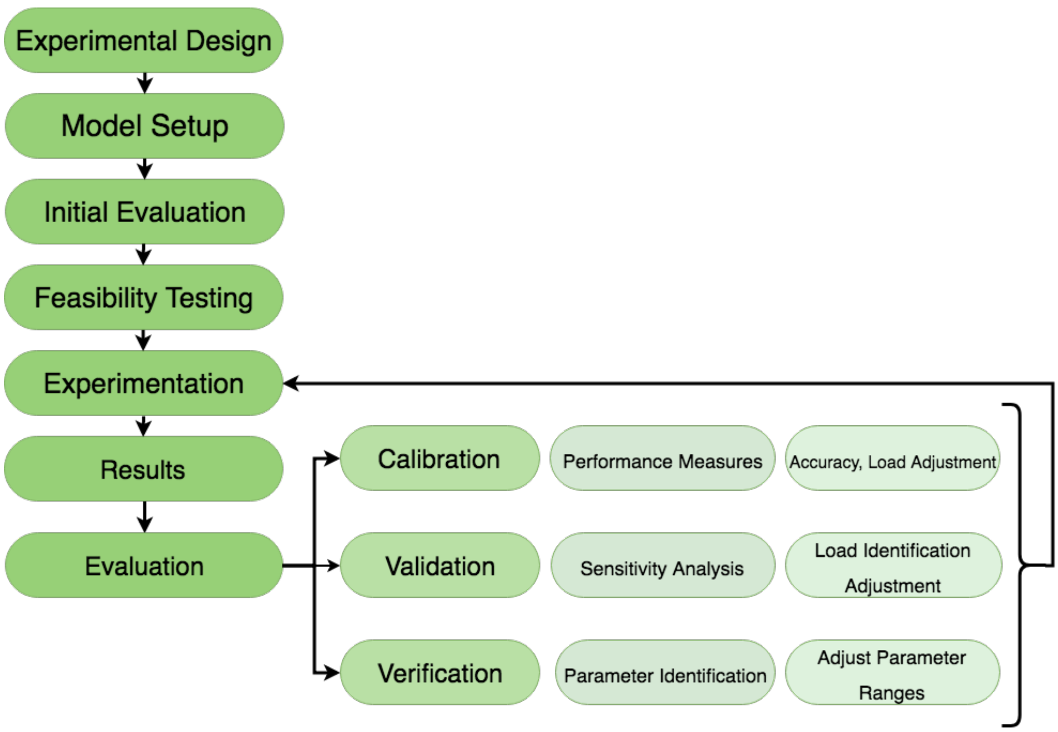

Figure 54: Testing and feasibility process

7.4.1 EVALUATION

A series of *informal* workshops were also held to discuss and explain particular aspects of modelling. The first workshop focused on introducing the theory of modelling emergencies, offering examples and future uses of models within an NGO setting as well as an early example of the model. The workshop also served as a platform for the exchange of views and the sharing of domain experience and knowledge. The workshop was used to validate the findings from stakeholder interviews, including the main goals of the model and the expectations for the final model and its place within emergency response procedures. The second workshop presented a more refined model, version `MK_7` (see section 7.2 for an outline of model iteration) and asked for user feedback. These sessions allowed stakeholders and potential users to engage directly with the model during its development. This participatory method allowed for the model to be developed and refined quickly based upon feedback in the sessions. Users could "play" with the model and report back on problems and provide suggestions for improvement. It also allowed for the model strategies and scenarios to be tested and refined where necessary. The approach taken mirrors that of exploratory data analysis where data and approaches are summarised using visual methods so that patterns can be found and recommendations and conclusions built (see Seltman, (2014) and Dubbelboer, (2015)).

During an informal workshop session, members of the BRC *Emergency Response and Management* team guided the creation of a set of performance indicators that would be used to measure effectively the modelled outputs and outcomes. This information was provided based upon their institutional knowledge of what is prioritised during domestic flood responses and aligns with the overall goals and objectives of the BRC[32]. Three main performance priorities were identified: 1) number of recipients assisted, 2) amount of resources distributed, and 3) overall costs of the operation. Further discussions led to the following performance indicators, adapted from the work of Beamon (1999) and

[32] See: general BRC guidance document here: https://www.redcross.org.uk/about-us/how-we-are-run/corporate-strategy

later Davidson (2006) and Beamon and Balcik (2008), being chosen to examine the cost of each strategy modelled:

- **Recipients assisted**: number of recipients provided with resources (total and by OSVI vulnerability level and priority rating per strategy).
- **Resource costs**: resources distributed (total and by type), mileage (total by strategy).
- **Response time**: operation response time (total and by action per strategy).

The above indicators were considered to best represent the BRC's goals of providing adequate and timely response efforts to those affected (whoever and wherever they are) and were compatible with metrics that could be recorded and tested at all stages of model development.

7.4.2 CALIBRATION

Calibration is the fine tuning of the model, whereby the model parameters are determined using real world data (Ngo & See, 2012). Calibration occurs in stages throughout model development and is usually an iterative approach that repeats until modelled outcomes match real-world data (within a reasonable tolerance) (Castle & Crooks, 2006). In many ways, model calibration can be undertaken during the verification process and builds upon the findings of the verification process outlined below.

The model presented was continuously calibrated throughout development. The participatory modelling approach used meant that individuals with knowledge of the systems being modelled could report on unlikely behaviours or outputs, and guide development and 'tweaking' of micro-level processes throughout the entire development of the model. However, as noted by (Castle & Crooks, 2006), it was important that the model not be overly calibrated and remain general enough to be used for a range of scenarios, strategies and locations. Thus, it was decided to present key elements of the model (namely Agents routing and interaction) to stakeholders using a range of locations, networks and scenarios.

7.4.3 SENSITIVITY ANALYSIS

One-factor-at-a-time (OFAT) sensitivity analysis was undertaken through the process of parameter sweeps: each of the parameters was varied in turn in order to give a sense of the impact of the variable on the overall behaviour of the system and the model's dynamics underlying the recorded outcomes (Ligmann-Zielinska *et al*., 2014) and to examine the robustness of the model outcomes with respect to changes of the parameter values (Leamer, 1983; 2010; Axtell, 1999). See section 2.3.2 in the Literature Review for more information on sensitivity analysis techniques commonly used with ABMs.

A parameter sweep provides a rough sense of how the model parameters affect the model outputs and provides the opportunity to identify and fix any obvious 'bugs' in the model and fine tune the parameter value ranges. A parameter sweep is a standard, but coarse, form of sensitivity analysis (Malleson, 2014) and, ideally, the outputs of these sweeps would be compared against a standard: either real-world data on the phenomenon being examined or data from a comparable and well-validated model. As previously discussed, (see section 2.3.2 and Chapter 6), real-world data is limited, and no comparable model exists. To compensate for these limitations, and following the work of Boero and Squazzoni (2005), Moss and Edmonds (2005) and David, Fachada and Rosa (2017), staff and volunteers at the BRC were asked to examine the values used and the outputs of the parameter sweeps and compare them to the available real-world data and their past experiences during a workshop and guide evaluation, calibration, verification and validation of the model (see section 7.4).

Given the large number of results produced during parameter sweeps - five parameters, each with integers between 1 and 10, would require a total of 100,000 model runs -, only the main results of dependent variables are presented: minimum, mean and maximum changes in the cumulative number of households provided with resources within the Control scenario (all roads accessible) with all other parameters set to default values but variations in `speedVehicle`, `loadingTime`, `deliveryTime`, `probFailedDelivery` and `probBreakdown`. Details of the parameter sweep are given in Table 23.

Parameter	Details	Sweep Values			
`speedVehicle`	Hardcoded maximum speed of vehicle (mph)	30	50		70
`loadingTime`	Time taken to load vehicle at Distribution Point (minutes)	20	40		80
`deliveryTime`	Time taken to unload vehicle at destination and deliver goods (minutes)	30	60		120
`probFailedDelivery`	Failed Delivery Probability	1%	10%	50%	90%
`probBreakdown`	Breakdown Probability	1%	10%	50%	90%

Table 23: Parameter Sweep Details

The `speedVehicle` parameter influences the maximum possible speed Agents can achieve when the road network permits. Intuitively this should allow Agents to reach their destinations much faster and deliver more resources. However, there is little variation amongst the three sweep values presented in Figure 55. This limited variation is likely due to the rural nature of the case study locations, with maximum speed on most road segments restricted to 30mph, and the traffic conditions modelled. Under all the 70mph simulations all impacted LSOA received deliveries within the seven-day timespan. This was not the case for the 30 and 50mph simulations, or the final simulations presented in the Results chapter where speed is restricted. As discussed in section 7.3.2, BRC staff recommended a speed range of between 30 and 40mph as they felt it suitably represented the likely average speed travelled in a flood emergency situation across a road network with speeds ranging from 20 to 70mph based upon their experience responding to such emergencies.

As shown in Figure 56 and Figure 57, there is a notable difference in the cumulative number of households provided with resources overall between the three sweep values examined (20, 40 and 80 minutes) for `loadingTime` and `deliveryTime` respectively. Varying this parameter produces the most dramatic influence on the model outputs. Disagreement was noted between BRC staff and volunteers as to what was a realistic time for loading and delivery, with a considerable range noted between delivery times in particular. As previously discussed (see section 7.3.2), delivery time is usually longer than loading time as conversations are often had with those receiving the resources or first responders.

The `probFailedDelivery` (Figure 58) and `probBreakdown` (Figure 59) parameters represent, respectively, the likelihood of an Agent failing to deliver their load and the likelihood of the Agent's vehicle breaking down. As with `loadingTime` and `deliveryTime`, varying the failure and breakdown parameters has a predictable impact on the cumulative number of households provided with resources: decreasing the parameter increases the rate of successful deliveries. BRC staff and volunteers noted that, based on past experience, only the 1% failure rate was realistic, with the 10, 50 and 90% failure probabilities far outside those experienced or expected (described in more detail in Table 20). The sensitivity tests show that the parameters tested function as designed.

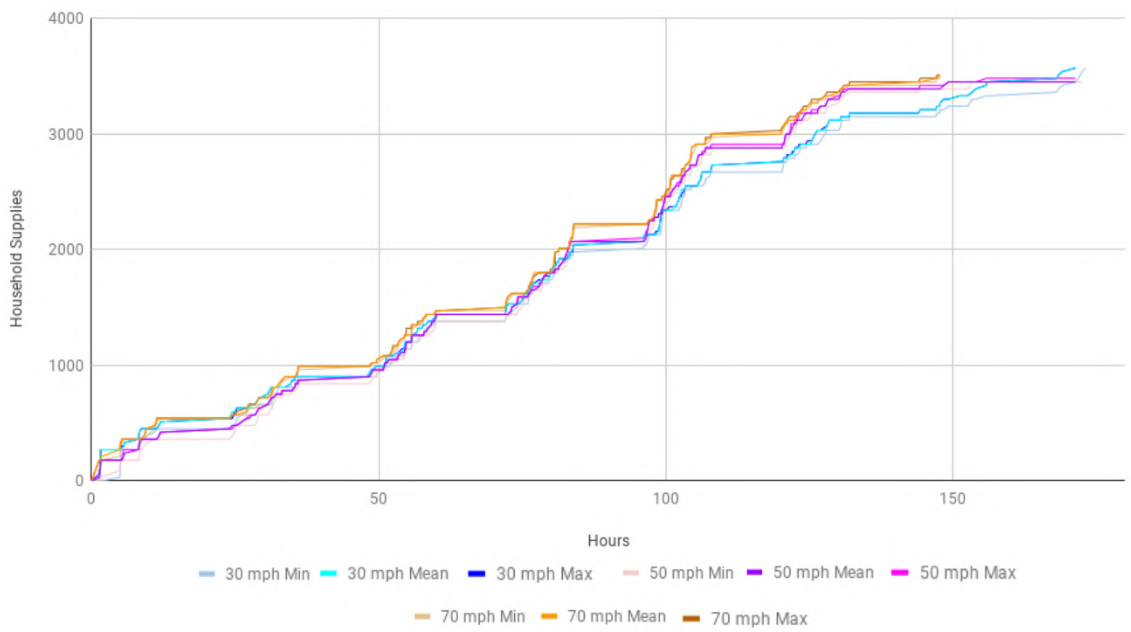

Figure 55: Cumulative number of households provided with resources within the Control scenario (all roads accessible) with default parameter settings but variations in the `speedVehicle` parameter

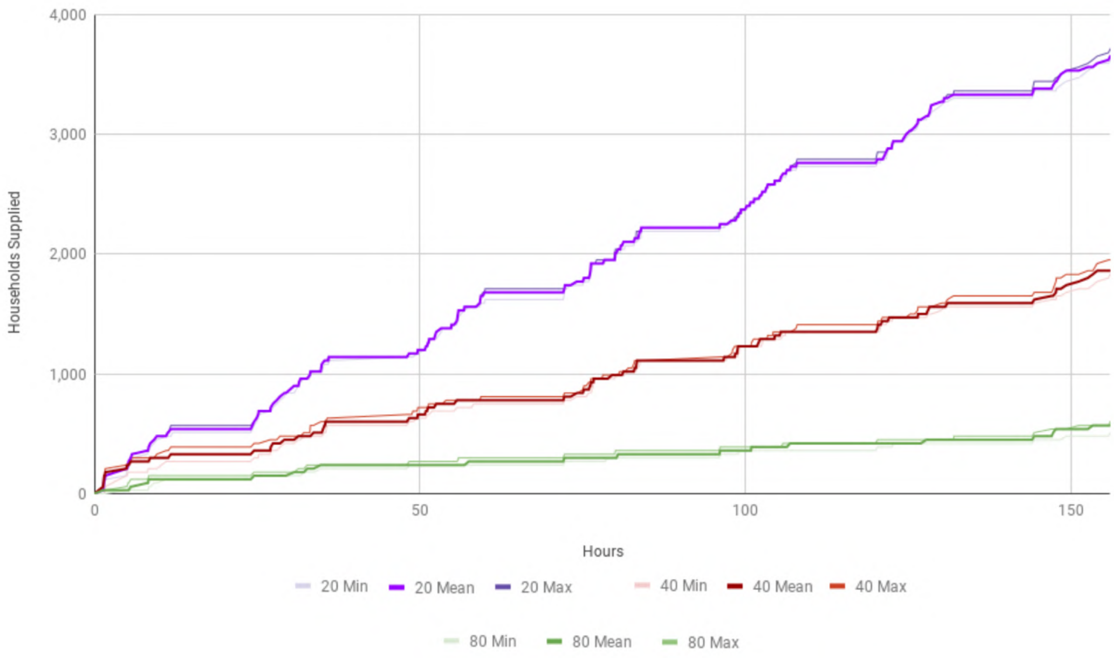

Figure 56: Cumulative number of households provided with resources within the Control scenario (all roads accessible) with default parameter settings but variations in the `loadingTime` parameter

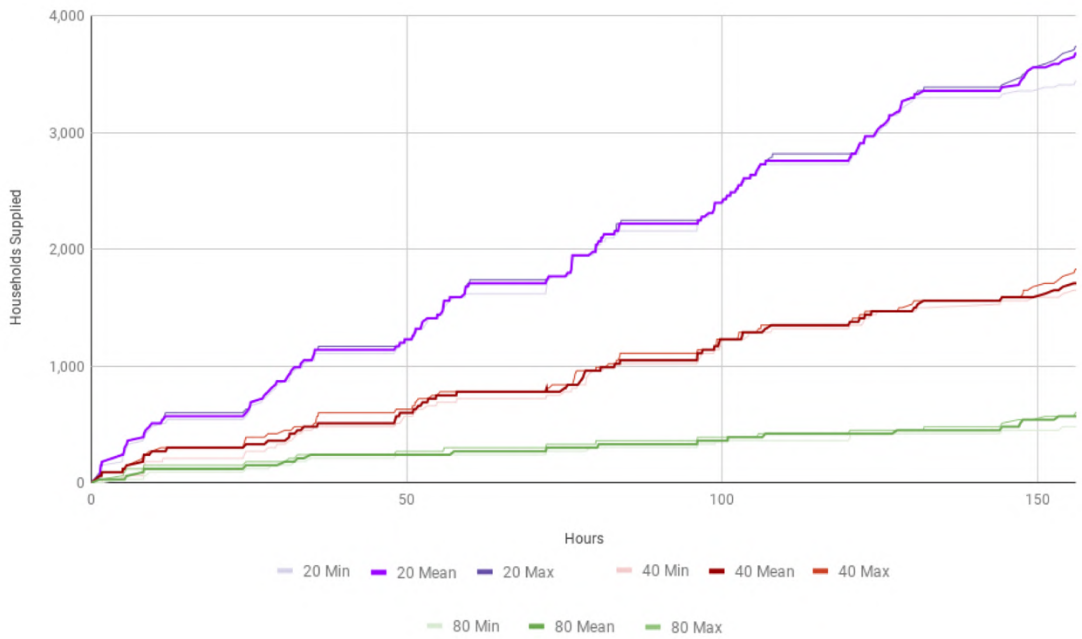

Figure 57: Cumulative number of households provided with resources within the Control scenario (all roads accessible) with default parameter settings but variations in the `deliveryTime` parameter

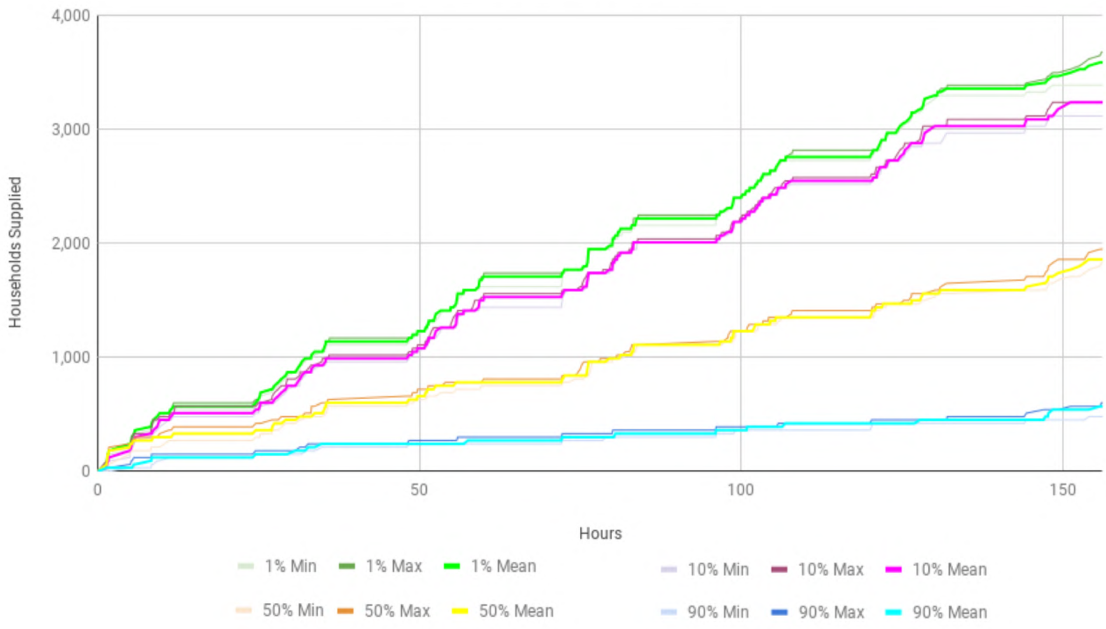

Figure 58: Cumulative number of households provided with resources within the Control scenario (all roads accessible) with default parameter settings but variations in the `probFailedDelivery` parameter

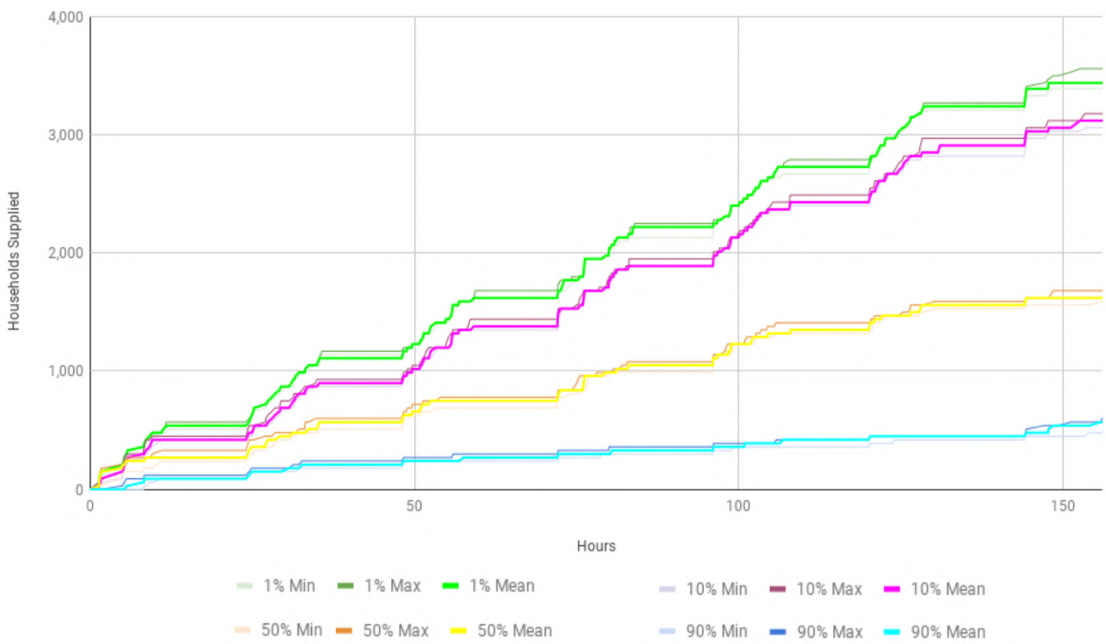

Figure 59: Cumulative number of households provided with resources within the Control scenario (all roads accessible) with default parameter settings but variations in the `probBreakdown` parameter

7.4.4 SAMPLE SIZE

It is common convention to run ABMs a number of times to account for stochasticity within the model. A measure of central tendency of those runs is taken as a representative outcome and variation across runs is used to estimate consistency (Groff, Johnson & Thornton, 2018). Angus and Hassani-Mahmooei (2015) and Groff *et al*'s (2018) surveys of ABM literature revealed that sample sizes are often low and conveniently selected: sample sizes of 100 are common or, if the model is relatively simple, are exorbitantly high, likely in an effort to increase the sensitivity of statistical tests. 44% of publications analysed reported using between 11 and 100 runs, with a further 27% not reporting the information. Similarly, 49% did not report conducting even a partial parameter sweep (Groff, Johnson & Thornton, 2018). The determination of the minimum number of required runs partly relies on the analytical objective of the project and the time available (large and complex ABMs are likely to require long run times, str*etc*hing into days or weeks depending on a multitude of factors (Lee *et al.*, 2015)). Conversely, the sample sizes of more expedient models are often so high that the sensitivity of statistical tests expose contextually inconsequential differences (Lee *et al.*, 2015).

Determining the minimum number of model runs in advance of analysis is difficult, often subjective, and can be constrained by available resources, especially in terms of processing power/time (Groff, Johnson & Thornton, 2018). Knowing the sample size at which outcome mean and variance can be used for accurate reporting of descriptive statistics is near impossible. As such, no specific sample size was decided a priori, instead the minimum number of model runs was decided based upon the shape of the model's output distributions after each five model runs. Once a relative stability was noted amongst the tests for each parameter, testing moved on to the next parameter. It was found that 30-50 model runs could be comfortably achieved within the available time, with relative stability within output distributions and variability remaining within a presumed confidence interval around the mean - assumed to be a Gaussian distribution – as per the approach presented by Law *et al*. (1991).

7.4.5 VERIFICATION

Verification, or informally, debugging is the testing of the logic of the model structure; ensuring that the model satisfies the specification as it is intended to (Gilbert, 2008). Put simply, verification ensures that the model is free from errors. The four-step verification process presented by Van Dam *et al*. (2012) was used:

1. Theoretical predictions.
2. Breaking points.
3. Variability testing.
4. Timeline practicality.

To verify the model, explicit predictions were made regarding what Agents would do when provided with well-defined inputs and the overall behaviour of the model was examined to see if it was consistent with the predicted logical behaviour. This process was repeated for four main model processes and allowed for examination of the model's behaviour at the Agent-level, but also the system-level where emergent behaviour is likely to be visible:

1. Single-Agent behaviour testing.
2. Single-Agent tracking.
3. Multi-Agent behaviour and interaction testing.
4. Multi-Agent tracking.

The model was examined under 'normal' inputs (based upon the real-world Gloucestershire information outlined in section 6.3) and then extreme value inputs were provided to test the edges of 'normal' behaviour within the model. Varying model parameters during 'parameter sweeps' allowed for the 'breaking point' of Agents' behaviour to be determined as well as system-level points where the model will fail.

Variability between model runs was examined. A single run of an ABM is not an adequate test as the stochasticity within such models can result in considerable variability within model outputs (Ritter *et al.*, 2011; Byrne, 2013; Bukaçi *et al.*, 2016). However, the model is computationally heavy and restrictions on resources meant that it was not possible to run the model as many times as suggested by Mas *et al*., (2012) (1,000 repetitions). The model was tested using the Control Scenario settings (described in section 8.1.1) for a range of repetitions allowing for variability between model runs to be seen allowing for an appropriate number of model repetitions to be determined that provides a good sample of results. Deviation between the medians and ranges of 30 to 50 repetition runs was found to be considerably smaller than those for the lower repetition choices (5, 10, 15) and so a target of 30-50 repetitions, as suggested by Dubbelboer (2015), was deemed appropriate and attainable.

Finally, the timeline of the model was examined by performing model runs and examining behaviour and outputs under representative parameter settings. Do unexpected results or behaviours manifest after a given time? Can an obvious and logical end point be determined (for example, is a steady model state reached, or do resources run out)? In addition, BRC staff and volunteers were asked to examine model runs to identify any unusual behaviour that could not be explained by the model logic and to offer guidance as to the logical end points of various scenarios (for example, based on past experience, BRC sandbag distribution lasts three days and water bottle distribution lasts on average seven days, or BRC emergency assistance is only required for two days whilst local council/government resources are mobilised). These tests were executed multiple times and showed that the model is an accurate translation of its conceptualisation.

7.4.6 VALIDATION

A model that has been verified and calibrated is not guaranteed to be valid. Validation is the process of determining if a model is an accurate representation of the phenomenon being simulated and that it is suitable for its intended use (see Figure 60). A model can be verified, because it runs as it is supposed to, but may be a poor representation of the world under examination or may not be suitable for its users and so is not valid (Gilbert, 2008).

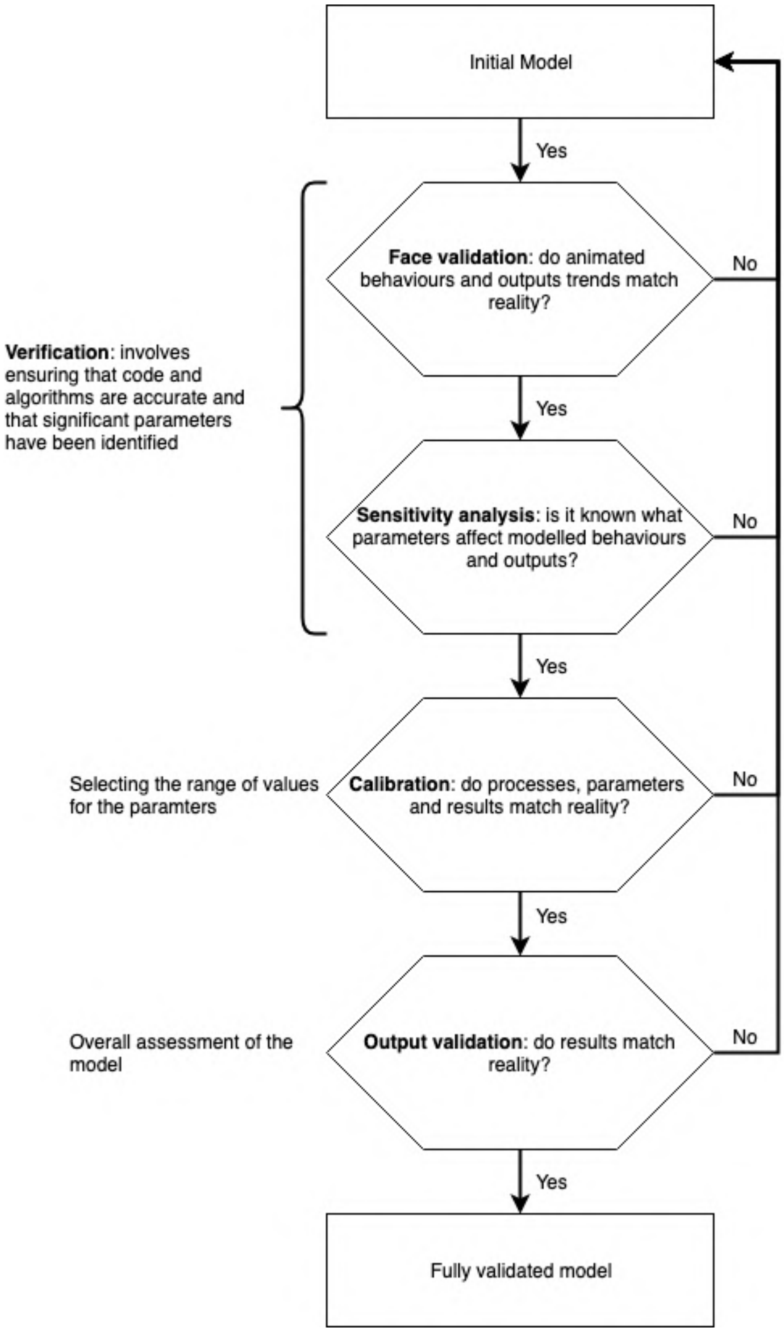

Figure 60: General validation process of an ABM (adapted from Ngo & See (2012)

The validity of a model is usually determined by comparing the model output to real observations. However, the model presented is built upon a limited number of real-world observations (primarily, anecdotal estimates of supplies distributed (see section 6.3)) and simulates highly variable situations (flood waters, population movements and vehicle routing). It was not possible to evaluate the model comprehensively using, for example, Bayarri *et al.*'s (2007) full evaluation processes (see Appendix 11.8) or compare the model's data-generating processes and outputs to real-world equivalents (outside of the Gloucestershire scenario) as would usually be recommended (Windrum *et al.*, 2007; Fagiolo *et al*., 2006; Fagiolo *et al*., 2007). Instead, evaluation of the model focused on 'internal' validation and calibration of model parameters, or what Berk (2008: 291) calls "internal quantitative credibility" – that is to say: does the model output correspond well to observations that are a part of the data used to develop and calibrate the model? This was an iterative process undertaken throughout the entire participatory model development process, with steps loosely based on Bayarri *et al*'s. (2007) six-step framework for validation (each 'step' used will be highlighted below - see Appendix 11.8 for more information).

The model was programmed to recreate an actual flood crisis the BRC responded to – the 2007 Gloucestershire floods. By reviewing the available information regarding real-world actions taken during the Gloucestershire response efforts and comparing these with the outputs of the model runs, it was possible to gain insight into the effectiveness of the model at simulating resource distribution efforts. Although comparison was hindered by the limited availability of information (as discussed in section 6.2), model validation was strengthened through the continuous input and interaction with the BRC. This predominantly stakeholder-focused iterative model validation technique, or a combination of quantitative and qualitative validation methods when data is scarce, has been found to be successful by other researchers (see: Hammond, 2015; Dubbelboer, 2016; Ligtenberg *et al.*, 2010; Joffre *et al*., 2015; Stewart-Koster *et al.*, 2017; Refsgaard *et al.*, 2005; Dobbie, 2016; Moss, 2008).

Throughout the entire model development process, the BRC guided the specification of model inputs (step 1) and evaluation criteria (step 2), provided data and assisted in testing iterations of the model (step 3), assessed model outputs (step 5), aided the understanding of extreme outcomes or spurious model actions and provided feedback to improve aspects of the model (step 6). Model evaluation was carried out with several BRC personnel over two informal sessions. During session one, feedback was given on key elements of the model (model setup and run time, visualisation *etc*.). Focus was on verifying that the logic of the model itself and the processes involved, calibrating the model to ensure it worked appropriately, and validating the model by comparing the model outputs against case study data and the institutional learning that BRC responders had accumulated from real-world experience in the field. Where necessary, changes were made to the model based upon feedback. For example, BRC staff recommended extending the loading and unloading times (originally set at 30 minutes each to 50 minutes and 100 minutes respectively) to account for time spent ‘chatting’ with those affected and being updated on the emergency (see section 9.2.2). In addition, vehicle speed was originally based upon the maximum speed allowed on each road segment (based on road classification: ‘residential’ = 30mph, ‘single carriageways’ = 60mph, and ‘dual carriageways/motorways’ = 70mph), but this was reduced following BRC staff feedback. Staff with experience of responding to flood emergencies in the UK felt it was unlikely that fully loaded BRC vehicles navigating in the conditions expected during each scenario would consistently travel at the maximum speed allowed (see section 7.3.2 for more information). Session two involved a different group of BRC personnel who had not helped with conceptualising and designing the model. The updated model was examined as in session one and staff offered feedback and suggested changes based upon their needs and experience. It was hoped that the combination of the participatory modelling method used, the two BRC evaluation sessions, and the meshing of Bayarri *et al.*'s (2007) and Berk’s (2008) validation methods would improve the overall suitability, applicability, and usefulness of the model and compensate for the limited inputs and inability to compare the model’s outputs to real-world equivalents outside of the scenario being modelled.

The model mechanics, logic and outputs were deemed to represent a “satisfactory range of accuracy consistent with the intended application of the model” (Schlesinger *et al*. 1979). No similar models were found to be available and so comparison of model results with those of others could not be done. In addition, retrodictive (the use of historical datasets to test model predictions) and predictive (the comparison of model predictions to outcomes of real world events/field experiments) validation techniques (Hawe *et al.*, 2015) were difficult to perform. The Gloucestershire case study was chosen as it was the only BRC flood response that suitable resource distribution data could be found, yet the data was too limited for full model retrodictive validation, and predictive analysis is limited by a lack of comparative floods in Norfolk.

However, the participatory modelling approach utilised throughout this project allowed for potential end users and relatively independent third parties to examine the modelling processes and outputs, providing a degree of accreditation and credibility to the data used, the actions coded, and the model produced. The overall patterns of behaviour shown by the model are in line with the findings of the wider literature (examined in section 2.2), as well as expert opinions and the real-world response data provided by the BRC. Throughout the entire modelling process field experts provided knowledge, guidance, and feedback that determined the model parameters and development. These third party validation processes are recommended by Sargent (2009) and are consistent with the process used by other modellers in the field of flood modelling (Dubbelboer *et al*., 2016) and emergency response modelling (Jain & McLean, 2003). It is noted that limitations of using 'face validation' (Sargent, 2009) do exist: even expert knowledge is likely biased, and those who provided guidance on the design of the model are likely to see more positive outputs due to their vested interest, but the two BRC evaluation sessions outlined above aimed to negate that. The validation of the model presented in this study is incomplete. As more data becomes available (see page 218) it will be possible to improve the model and the overall evaluation processes used.

8 RESULTS: MODEL

Introduction	Literature Review	Stakeholder Engagement	Methodology OSVI	Results OSVI	Stakeholder Engagement	Methodology Model	**Results Model**	Discussion	Conclusion
Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5	Ch. 6	Ch. 7	**Ch. 8**	Ch. 9	Ch. 10

"Essentially, all models are wrong, but some are useful."

~ Box & Draper, 1987: 424

8.1 SIMULATION OUTCOMES

As outlined in section 6.4 and detailed in Figure 61, although only two case study areas are being considered, the Norfolk case study was split into two scenarios: one with one distribution point, and one with two. When the Control Scenario (outlined in more detail in section 8.1.1 next) is included, a total of six scenarios variations are being examined, with each scenario simulated using each of the four distribution strategies (discussed in section 6.4) and a range of 30 to 50 repetitions for each (as outlined in section 7.4.5) resulted in excess of 450 sets of simulation output files (see Figure 43 for an overview of the scenario and strategy testing process). This chapter presents the aggregated results of all the model simulations. Data are presented separately for the control scenario and both of the case study areas and will be broken down by strategy. Then the changes in simulated response performance for each of the three performance indicators (*recipients assisted, resource costs,* and *response time*) are presented.

8.1.1 CONTROL SCENARIO

In order to determine the impact of the floods on the distribution of resources, the model was run with the flood module disabled. Both Norfolk and Gloucestershire areas were used for the control scenario (see Figure 61).

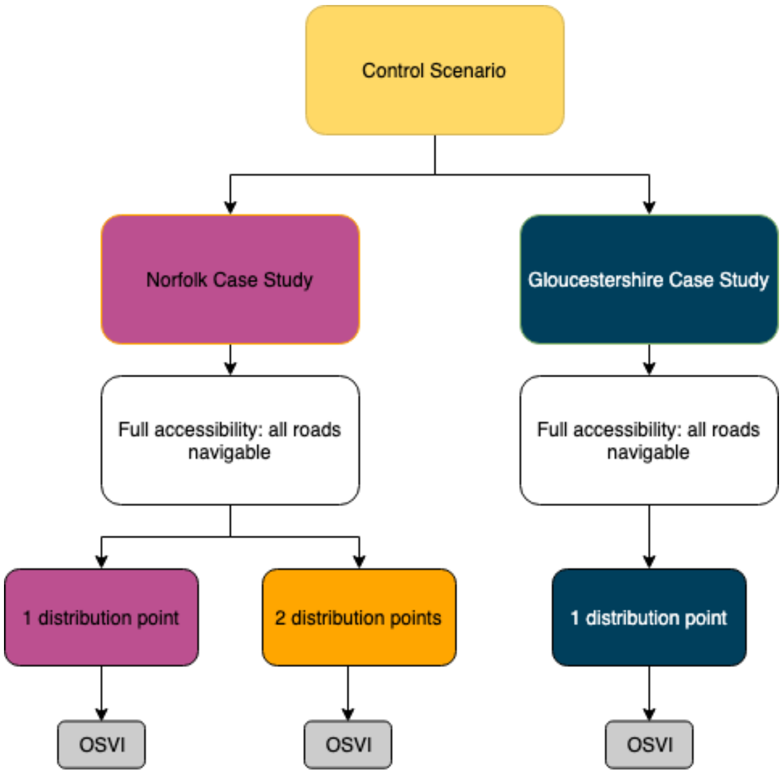

Figure 61: Outline of the Control scenario model test process

Each strategy was modelled with no road closures and the following default parameters:

- Number of Vehicles: 5-8 (10-16 for the Norfolk 2 Control scenario).
- Number of Bays: 10 (20 for the Norfolk 2 Control scenario)
- Loading Time: 50 minutes (10 'steps').
- Delivery Time: 100 minutes (20 'steps').
- Breakdown Probability: 1%.
- Failed Delivery Probability: 1%.
- Simulation run: 7 12-hour shifts (7 x 144 'steps').

Table 24 outlines the timeline of the control scenario and lists the flood status and road access, the number of vehicle Agents available per day, and the resources being distributed. The strategy used was OSVI. All roads were navigable.

As can be seen in

Table 25, as well as Figure 62, Figure 64 and Figure 65, the Gloucestershire scenario recorded the highest number of resources distributed for each resource category as well as the highest number of deliveries and unique LSOA visits. However, the Norfolk Control Scenario with two distribution points (Norfolk 2 Control) recorded the highest number of households reached and recipients assisted. Examination of the individual delivery records and underlying LSOA data suggest this is due to the highest OSVI areas prioritised in Norfolk having a higher household/population density.

The Norfolk Control Scenario with one distribution point (Norfolk 1 Control) recorded the lowest number of complete deliveries and unique LSOAs visited. When the total miles driven is examined, it is clear that the low delivery rate is due to the time taken to drive to the affected LSOA that are located far from the Norwich-based distribution point 1, with most LSOA with a high vulnerability rating affected by flooding located in Kings Lynn and Great Yarmouth (see Figure 63). The Gloucestershire Control scenario and the Norfolk 1 distribution point Control scenario both recorded the highest number of distributed resources when compared to the OSVI, PRIOS and FIS Strategies for both areas under flooded conditions (described in more detail in sections 8.1.2 and 8.1.3). In comparison, the Norfolk Control Scenario with two distribution points (Norfolk 2 Control) recorded a slightly lower complete delivery rate and distributed fewer sandbags, water, blankets and cleaning kits than the OSVI, PRIOS and FIS strategies for the same area under flooded conditions (described in more detail in sections 8.1.2 and 8.1.3). This was contrary to expectations. It was predicted that *all* Control Scenarios would prove to be the most productive in terms of successful deliveries and resources distributed due to unencumbered access to the full road network and that the Norfolk 2 Control scenario would be the most productive of all due to the extra vehicles (from a second location). However, this was not the case due to two reasons. First, examination of the LSOAs prioritised under the different strategies revealed that the fully navigable road network was not a significant benefit within the Norfolk 2 Control scenario due to the location of the second distribution point in Great Yarmouth being sufficiently close to LSOA with high vulnerability ratings under all strategies (see Figure 63) and routes to those LSOA not affected by flooding. Second, although resources and goals can be shared amongst multiple distribution points and the distribution of resources can be determined by proximity and based upon strategy rating, inadequacies in task allocation prioritisation were noted. For example, the Norwich distribution point was found to be delivering to LSOA that are closer to the Great Yarmouth distribution point but are also closer to the Norwich distribution point than some of the LSOA in Kings Lynn (see Figure 63). This led to lower than expected distribution rates. It is believed this is due to the order in which resource loads are generated and then allocated within the model code, but more work is needed to examine this issue further. The issues of area-based strategy selection and task allocation amongst multiple distribution points are discussed in greater detail in the Discussion Chapter.

<table>
<tr><th>Day</th><th>Flood status</th><th>Road access</th><th>Vehicles</th><th>Resources</th></tr>
<tr><td>Day 1</td><td>Flood Alert Issued

“Flooding is possible”
2 days in advance of flooding</td><td>All roads accessible</td><td>5</td><td>6x sandbags per flooded household</td></tr>
<tr><td>Day 2</td><td>Flood Warning

“Flooding expected. Immediate action required.”
30 mins to 1 day in advance of flooding</td><td>All roads accessible</td><td>6</td><td>1x 24-pack of water bottles + 3x blankets per flooded household</td></tr>
<tr><td>Day 3</td><td rowspan="2">Severe Flood Warning

“Danger to life”
Peak water levels</td><td>All roads accessible</td><td>8</td><td rowspan="3">1x 24-pack of water bottles + 3x hygiene kits per flooded household</td></tr>
<tr><td>Day 4</td><td>All roads accessible</td><td>8</td></tr>
<tr><td>Day 5</td><td rowspan="2">Flood waters stable or receding</td><td>All roads accessible</td><td>8</td></tr>
<tr><td>Day 6</td><td>All roads accessible</td><td>8</td><td>1x 24-pack of water bottles + 1x cleaning kit per flooded household</td></tr>
<tr><td>Day 7</td><td>Flood waters fully receded</td><td>All roads accessible</td><td>6</td><td>1x 24-pack of water bottles per flooded household</td></tr>
</table>

Table 24: Outline of the timeline for the Control scenario simulations.

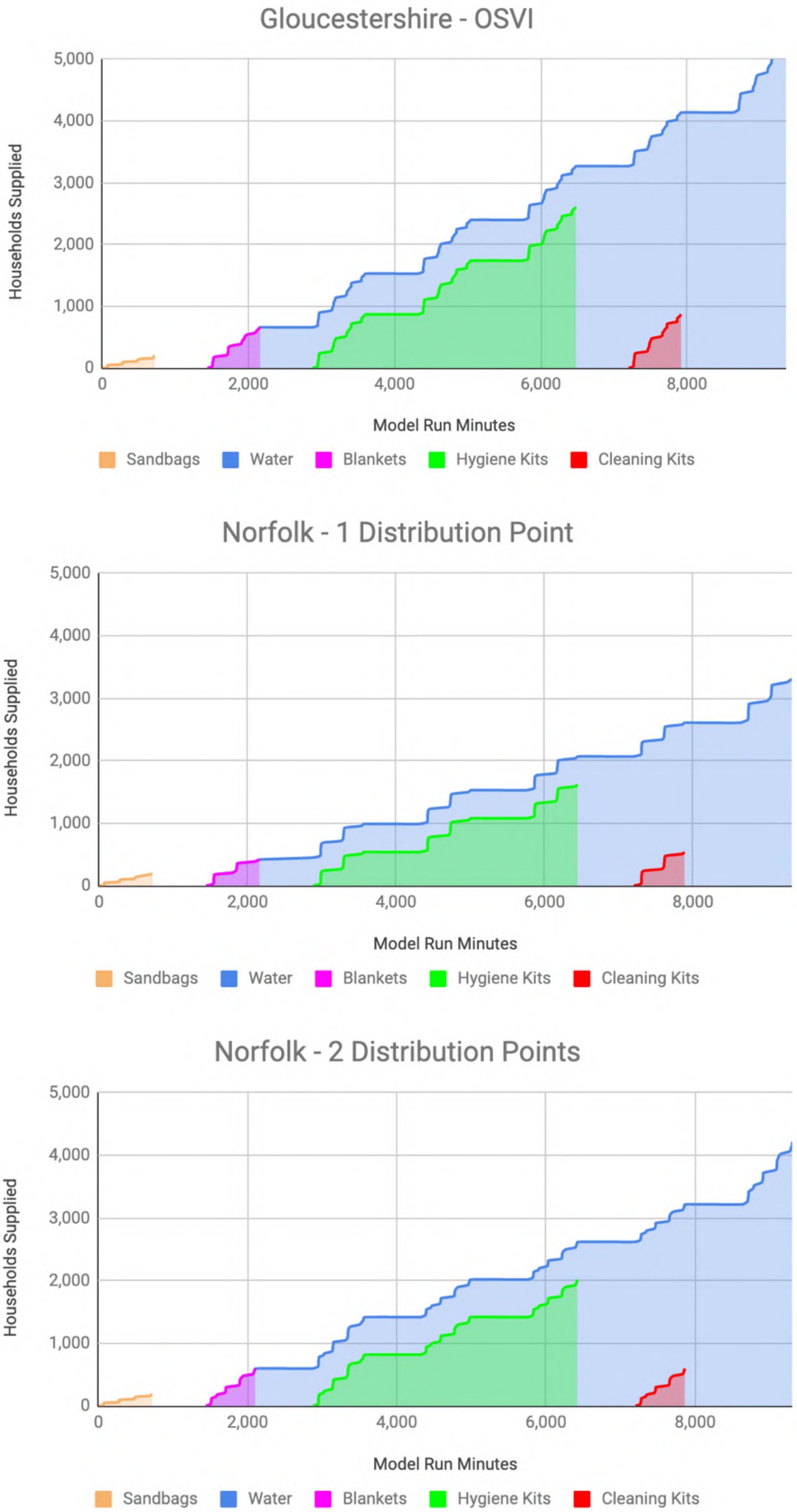

Figure 62: Cumulative number of households provided with resources by resource type over 7-day model run for each Strategy within the Control scenario (all roads accessible)

	Gloucestershire 1 dist. point	Norfolk 1 dist. point	Norfolk 2 dist. points
Complete deliveries	**195**	153	162
Unique LSOAs visited	**25**	13	24
Households reached	1,568	1,224	**1,860**
Recipients assisted	4,704	3,672	**5,580**
Sandbags delivered	**1,200**	900	1,080
Water delivered	**68,520 litres**	55,440 litres	56,640 litres
Blankets delivered	**2,160**	1,800	1,620
Hygiene kits delivered	**8,640**	6,480	7,560
Cleaning kits delivered	**960**	720	600
Total miles driven	1,517	**3,213**	1,807

Table 25: Key outputs for each Control scenario (note: the strategy used was OSVI)

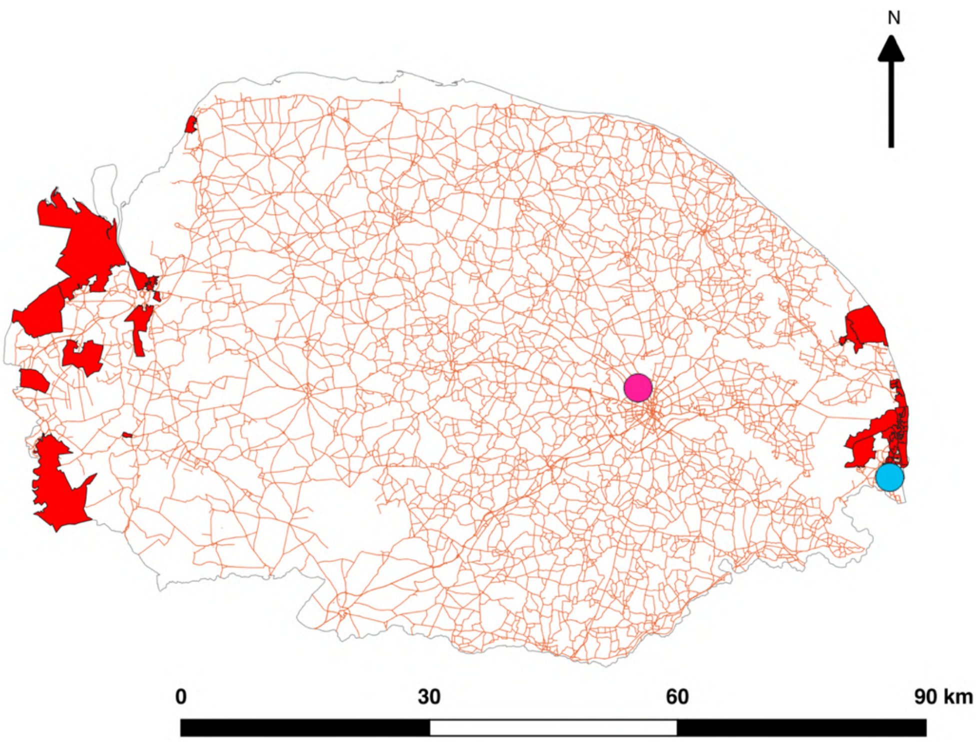

Figure 63: LOSA rated 'high' in the Local OSVI affected by floods (red) and BRC Norwich Distribution Point 1 (pink) and Gt Yarmouth Distribution Point 2 (blue)

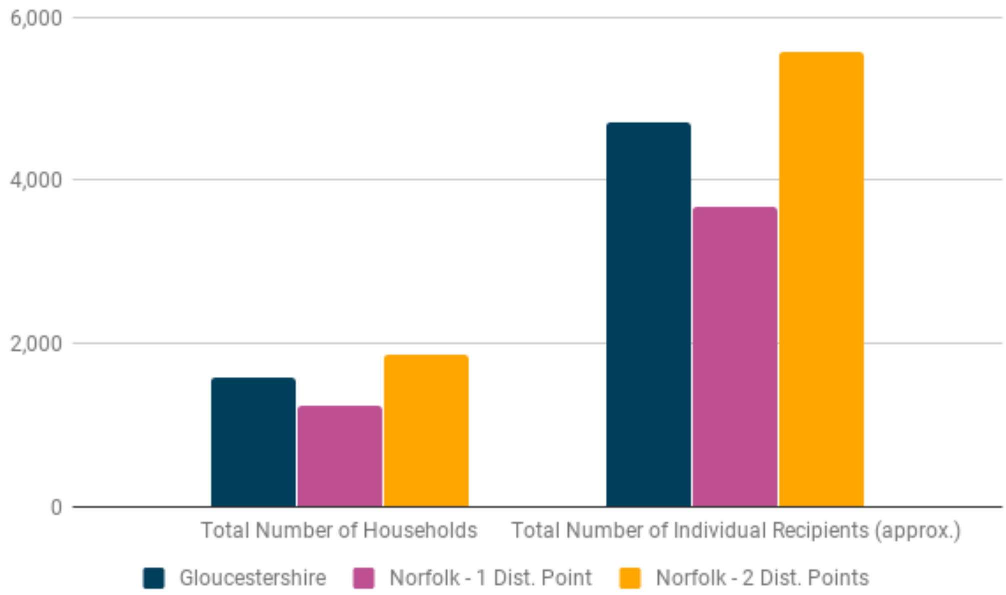

Figure 64: Total number of households and individuals (approx.) who received assistance under the three Control Scenarios

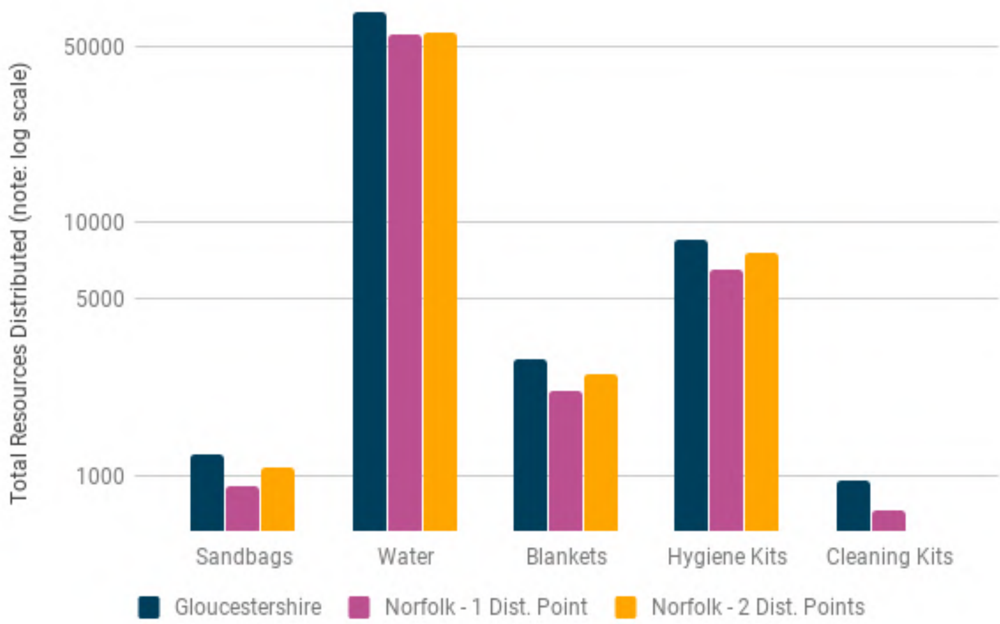

Figure 65: Total resources distributed by type under the three Control Scenarios

8.1.2 GLOUCESTERSHIRE SCENARIO

The Gloucestershire scenario is based upon the BRC's response efforts to the floods in Gloucestershire in 2007. The flood status and road access are based upon reports of the real-world situation during the 2007 floods. The parameters of the model were determined by the details in the information outlined in section 3.1.2 and further conversations with BRC responders and match those of the Control scenario:

- Number of Vehicles: 5-8
- Number of Bays: 10
- Loading Time: 50 minutes (10 'steps')
- Delivery Time: 100 minutes (20 'steps')
- Breakdown Probability: 1%
- Failed Delivery Probability: 1%
- Simulation run: 7 12-hour shifts (7 x 144 'steps')

Figure 66 and Table 26 outline the Gloucestershire scenario and the timeline of the flood status and road access, the number of vehicle Agents available per day, and the resources being distributed.

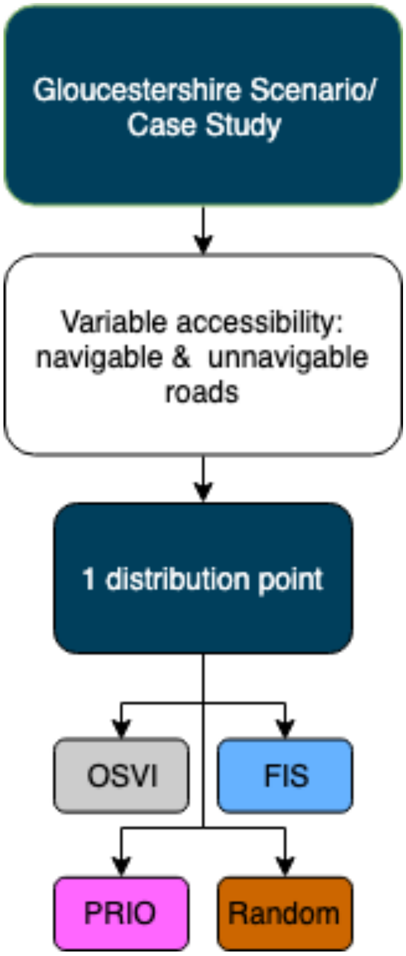

Figure 66: Outline of the Gloucestershire scenario model test process

As can be seen in Figure 67 and Table 27, the OSVI strategy recorded the best overall performance, delivering the most loads (183) and distributing the most resources across each category, and delivering to the highest number of unique LSOA across the seven day simulation (28). However, the FIS strategy recorded the highest number of recipients assisted (4,812). This is likely due to the higher population of high-ranking FIS LSOA. The FIS strategy recorded the fewest miles travelled (1,341 miles) and fewest cumulative work hours (304). The PRIOS strategy recorded a notably higher mileage, almost twice that of the OSVI and FIS strategies. The Random strategy recorded the fewest complete deliveries (148) and the fewest unique LSOA deliveries (20). No strategy delivered the required number of resources across each category.

Day	Flood status	Road access	Drivers	Resources
Day 1	Flood Alert Issued *"Flooding is possible"* 2 days in advance of flooding	All roads accessible	5	6x sandbags per flooded household
Day 2	Flood Warning *"Flooding expected. Immediate action required."* 30 mins to 1 day in advance of flooding	Red/Level 4 road segments entirely within FZ and with no unflooded connectivity are restricted.	6	1x 24-pack of water bottles + 3x blankets per flooded household
Day 3	Severe Flood Warning *"Danger to life"* Peak water levels	Orange/Level 3: road segments unreachable, or only reachable from roads entirely cut off by FZ, are restricted as well as Red/Level 4 road segments entirely within FZ and with no unflooded connectivity are restricted.	8	1x 24-pack of water bottles + 3x hygiene kits per flooded household
Day 4			8	
Day 5	Flood waters stable or receding	Red/Level 4 road segments entirely within FZ and with no unflooded connectivity are restricted.	8	
Day 6		All roads accessible	8	1x 24-pack of water bottles + 1x cleaning kit per flooded household
Day 7	Flood waters fully receded	All roads accessible	6	1x 24-pack of water bottles per flooded household

Table 26: Outline of the timeline for the Gloucestershire scenario simulations

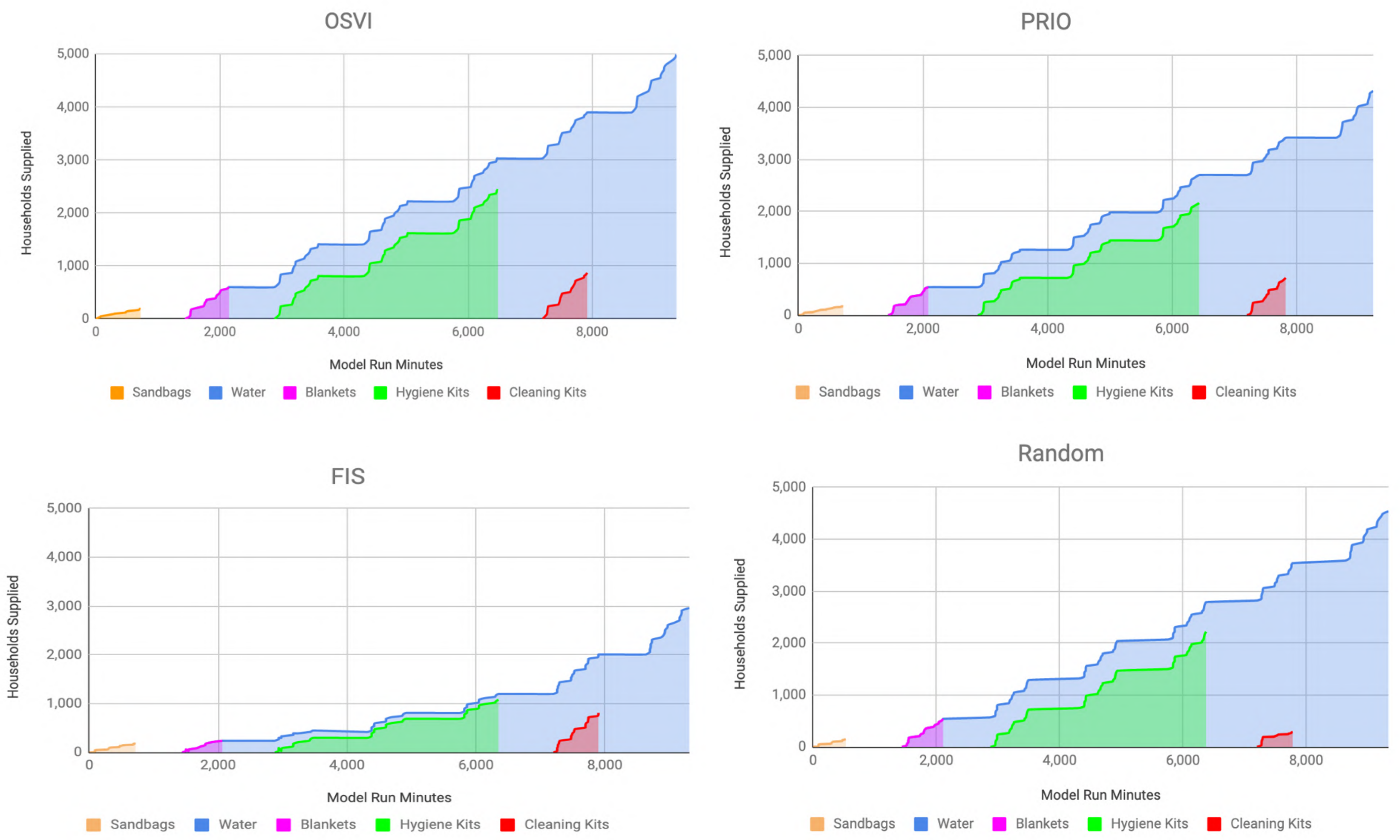

Figure 67: Cumulative number of households provided with resources by resource type over 7-day model run for each strategy within the Gloucestershire scenario

	OSVI	PRIOS	FIS	Random
Complete deliveries	**183**	169	146	148
Unique LSOAs visited	**28**	24	27	20
Households reached	1,568	1,488	**1,604**	1,328
Recipients assisted	4,704	4,464	**4,812**	3,984
Sandbags delivered	**1,200**	1,020	1,200	900
Water delivered (litres)	**64,200**	60,240	50,880	52,440
Blankets delivered	**1,890**	1,710	1,350	1,620
Hygiene kits delivered	**7,830**	7,290	5,130	6,480
Cleaning kits delivered	**960**	870	930	720
Total miles driven	1,602	**2,162**	1,341	2,065
Cumulative work hours	399	**411**	304	400

Table 27: Key Gloucestershire scenario outputs for each strategy

8.1.3 NORFOLK SCENARIO

The Norfolk scenario is based upon the projected impact of a major flood in Norfolk and the expected BRC response efforts. Flood status and road access as well as default parameters are the same as those for the Gloucestershire scenario apart from the addition of a second distribution point. As discussed in section 3.1.1, the BRC has two fully staffed facilities in Norfolk able to respond to a flood emergency. Ergo, the number of Vehicles and Bays is the same for each distribution point, but the total is twice that of Gloucestershire.

- Number of Vehicles: 10-16 (5-8 per location).
- Number of Bays: 20 (10 per location).
- Loading Time: 50 minutes (10 'steps').
- Delivery Time: 100 minutes (20 'steps').
- Breakdown Probability: 1%.
- Failed Delivery Probability: 1%.
- Simulation run: 7 x 12-hour shifts (7 x 144 'steps').

Figure 68 outlines the Norfolk test process and Table 27 outlines the timeline and lists the flood status and road access, the number of vehicles available per day, and the resources being distributed.

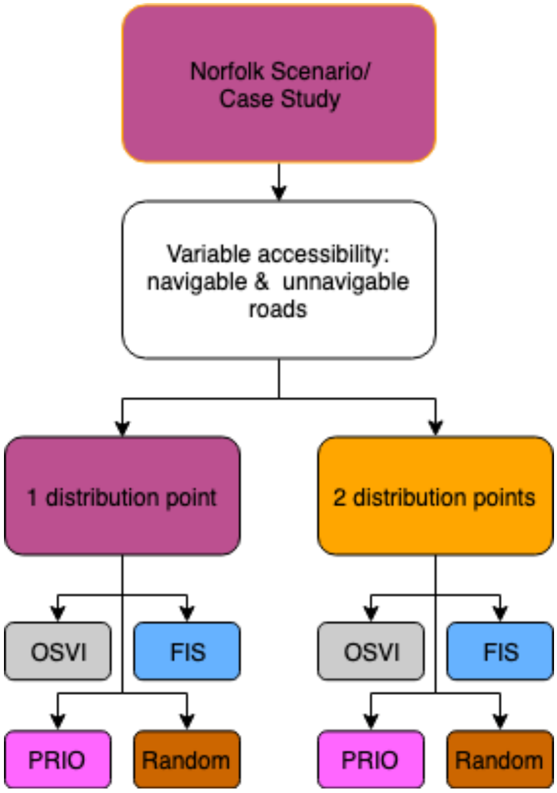

Figure 68: Outline of the Norfolk scenario model test process

As shown in Table 29, and when comparing Figure 70 and Figure 71, the number of deliveries made to unique LSOAs is much reduced in the 1 distribution point scenario, with most strategies recording half the number of deliveries as the 2 distribution point scenario. This is likely due to the location of the distribution point being located centrally in the county in a low OSVI/FIS/PRIOS area and the majority of high OSVI/FIS/PRIOS areas in Norfolk being located at the outer edge of the country, namely Kings Lynn and Great Yarmouth. This is reflected in the above average mileage recorded by each strategy, with the OSVI, PRIOS and FIS strategies recording twice as many total miles driven as under the Norfolk 2 scenario. The most successful strategy, in terms of the number of resources distributed, is FIS, with, for example, a total of 51,120 litres of water compared to 41,040 litres under OSVI. In addition, out of the OSVI, PRIOS and FIS strategies, FIS reached the most households and assisted the most people. However, the Random strategy recorded the most reached households and recipients assisted despite recording the lowest number of unique LSOAs visited. This is due to the 11 randomly chosen LSOA having above average household/population densities than those in the other strategies. Under the

Norfolk 2 scenario, the PRIOS strategy recorded more complete deliveries (173), reached more unique LSOA (25), and delivered the most resources of each type, including 60,720 litres of water. This is likely due to the location of the second distribution point in Great Yarmouth, which is the most vulnerable LA in Norfolk with approximately 70% of LSOA in both indices rated *high*, providing quicker access to affected LSOA. As under the Norfolk 1 scenario, the Random strategy reached more households and assisted the most people (see Figure 69).

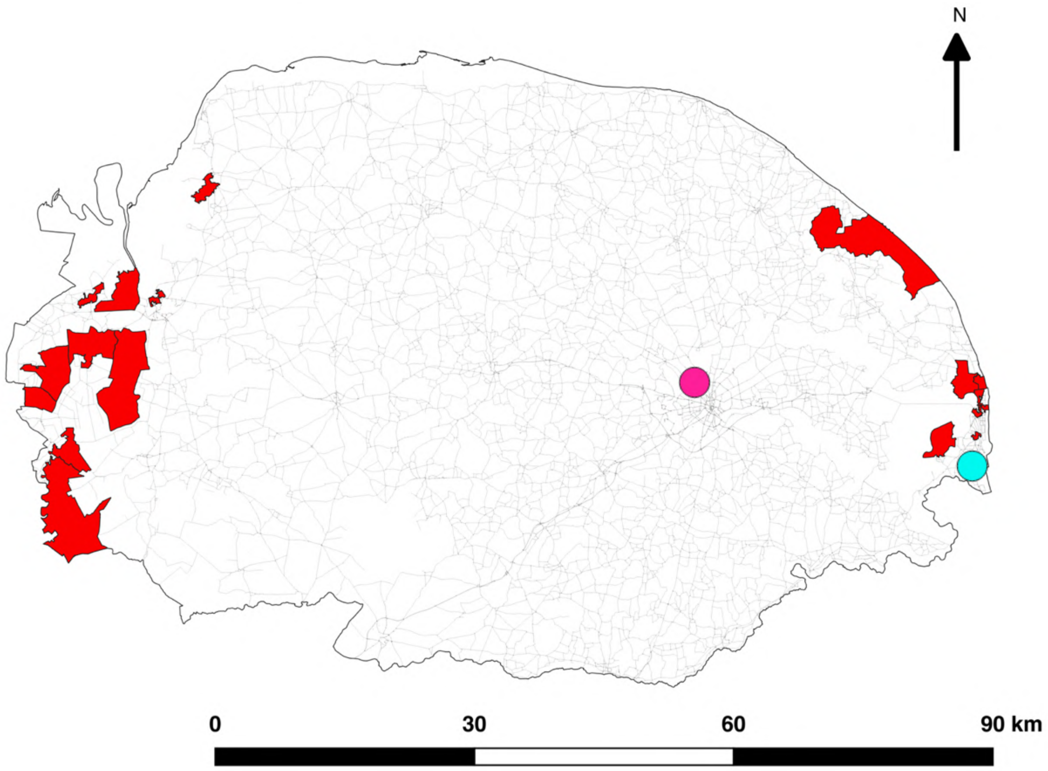

Figure 69: LOSA with a 'high' PRIOS rating affected by floods (red) and BRC Norwich Distribution Point 1 (pink) and Gt Yarmouth Distribution Point 2 (blue)

Day	Flood status	Road access	Drivers	Resources
Day 1	Flood Alert Issued *"Flooding is possible"* 2 days in advance of flooding	All roads accessible	5	6x sandbags per flooded household
Day 2	Flood Warning *"Flooding expected. Immediate action required."* 30 mins to 1 day in advance of flooding	Red/Level 4 road segments entirely within FZ and with no unflooded connectivity are restricted.	6	1x 24-pack of water bottles + 3x blankets per flooded household
Day 3	Severe Flood Warning *"Danger to life"* Peak water levels	Orange/Level 3: road segments unreachable, or only reachable from roads entirely cut off by FZ, are restricted as well as Red/Level 4 road segments entirely within FZ and with no unflooded connectivity are restricted.	8	1x 24-pack of water bottles + 3x hygiene kits per flooded household
Day 4			8	
Day 5	Flood waters stable or receding	Red/Level 4 road segments entirely within FZ and with no unflooded connectivity are restricted.	8	
Day 6		All roads accessible	8	1x 24-pack of water bottles + 1x cleaning kit per flooded household
Day 7	Flood waters fully receded	All roads accessible	6	1x 24-pack of water bottles per flooded household

Table 28: Outline of the timeline for the Norfolk scenario simulations

	OSVI 1 dist.point | 2 dist. points	PRIOS 1 dist.point | 2 dist. points	FIS 1 dist.point | 2 dist. points	Random 1 dist.point | 2 dist. points
Complete deliveries	117 | 164	113 | **173**	**145** | 169	116 | 143
Unique LSOAs visited	12 | 24	12 | **25**	**13** | 24	11 | 24
Households reached	1,304 | 1,476	1,224 | 1,856	1,684 | 1,952	**1,788** | **1,972**
Recipients assisted	3,902 | 4,428	3,672 | 5,568	5,052 | 5,856	**5,364** | **5,916**
Sandbags delivered	900 | 1,140	900 | 1,140	900 | 1,140	600 | 1,080
Water delivered (litres)	41,040 | 57,000	46,800 | **60,720**	**51,120** | 59,280	41,760 | 50,040
Blankets delivered	1,080 | 1,800	1,260 | **1,980**	**1,530** | 1,890	1,080 | 1,260
Hygiene kits delivered	4,320 | 7,020	5,670 | **7,290**	**6,390** | 7,020	5,670 | 5,670
Cleaning kits delivered	720 | 810	690 | 870	720 | 870	480 | 810
Total miles driven	3,348 | 1,621	3,772 | 1,666	**4,281** | 1,726	3,870 | **2,611**
Cumulative work hours	380 | 370	429 | 376	**457** | 370	443 | **401**

Table 29: Key Norfolk scenario outputs for each strategy. Note: the results for the scenario with 1 distribution point are on the left, and the results from the for the scenario with 2 distribution points are on the right.

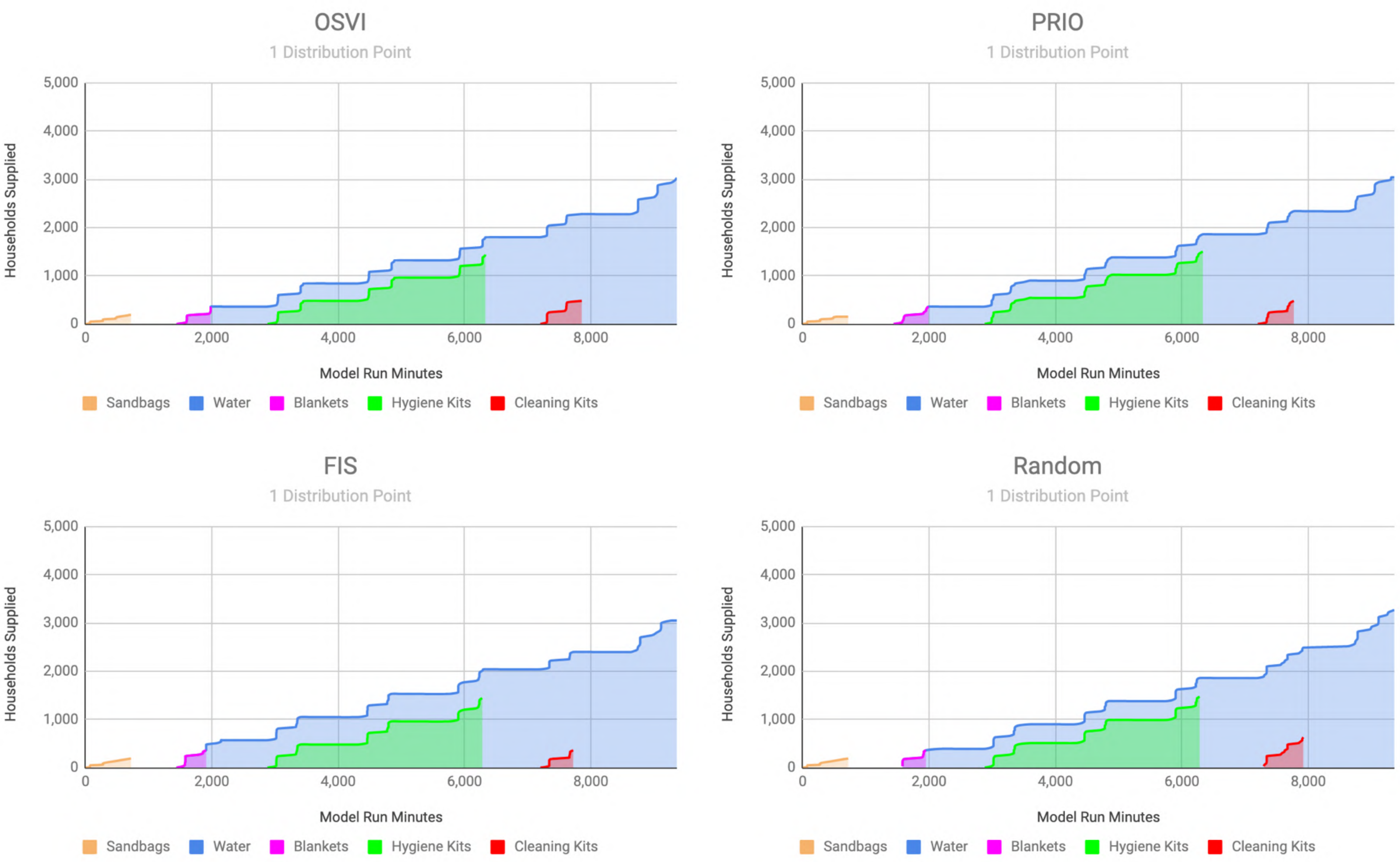

Figure 70: Cumulative number of households supplied with resources by each strategy over 7-day model run within the Norfolk scenario (1 distribution point).

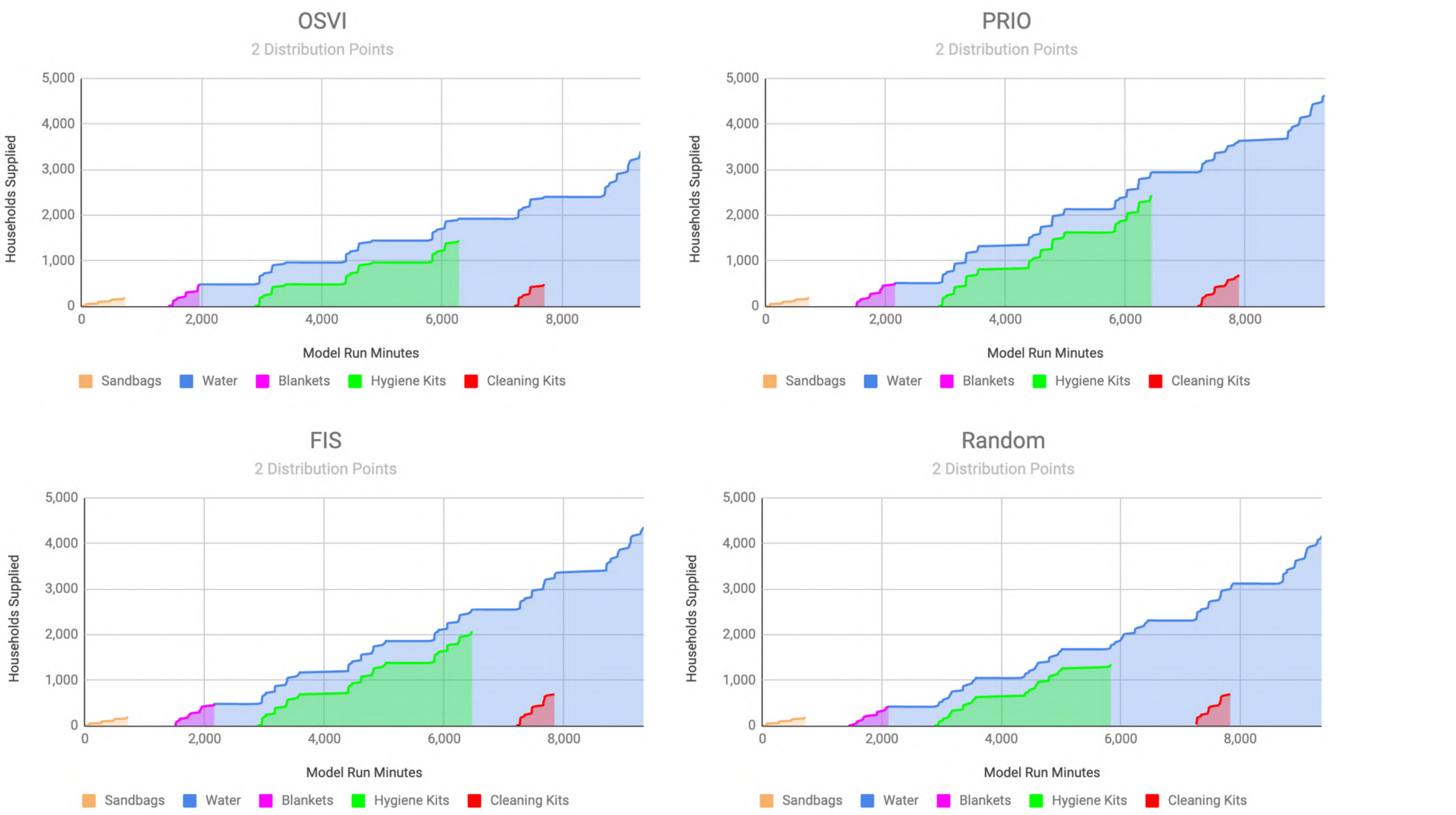

Figure 71: Cumulative number of households supplied with resources by each strategy over 7-day model run within the Norfolk scenario (2 distribution points)

8.2 CHANGES IN RESPONSE PERFORMANCE

As discussed in section 7.4, three performance indicators were chosen to examine the cost of each strategy modelled: *recipients assisted, resource costs*, and *response time*. These can be further broken down to gain a greater understanding of how different strategies affect, for example, the number of unique affected areas assisted, the impact of limited access on performance (the control scenario has full road access), and staff hours and miles travelled – the latter of which can be used by the BRC to examine the performance of each strategy in terms costs (staff and fuel cost, for example).

8.2.1 RECIPIENTS ASSISTED

The number of people assisted is one of the indicators the BRC, and many other NGOs, use to demonstrate the work they do (see section 7.4.1). Examining the number of recipients assisted provides an estimate of the number of those affected that could be assisted over the lifetime of the event depending on the strategy used.

As can be seen in Figure 72 and Figure 73 and Table 30, the number of households and recipients assisted *in some way* ranges from 62-100% of those likely affected. The Norfolk 2 scenario in particular appears highly successful with a range of 75-100% for both households and recipients assisted. The Norfolk 1 distribution point scenario performance is weaker – likely due to the central location of the Norwich distribution point discussed previously -, with 60+% of all likely affected households and people are reached. However, these figures are highly misleading as they do not represent households or individuals receiving the full array of resources required or the full quantity of resources required and undoubtedly include households and individuals receiving, for example, multiple days of water, but others receiving just one day's supply. As detailed in section 6.3.3, the BRC is not expected to provide all affected individuals with assistance. In fact, during the 2007 Gloucestershire floods more than 350,000 people were without drinking water for several days but as the information outlined in section 6.3.3 shows, the BRC did not provide all of those affected with bottled water, nor were they expected to. In situations like the Gloucestershire floods, a number of agencies assist those affected – for example, the British Army and a number of NGOs also distributed bottled water in Gloucestershire – and tasks and geographical areas are assigned to responders by Gold Command (see footnote 10 on page 41 for more information). As can be seen in Table 30, and across Figure 74 Figure 75, no strategy successfully delivered all the required resources and assisted all the likely affected individuals in the case study areas. The Gloucestershire Control Scenario was the most successful, delivering 44% of required loads.

The Random distribution strategy in Gloucestershire only delivered 27% of required loads. The disparity amongst households/individuals assisted *in some way* and the percentage of those affected in some way is made clear when examining the percentage of affected LSOA that *actually* received resources. For example, the Random strategy for the Norfolk 2 scenario reached the most affected LSOA, 58%. The same strategy for the Norfolk 1 scenario only reached 18% - likely due to a combination of the inefficient random goal selection process and the location of the Norwich distribution point being far from most flood affected LSOA (as previously discussed in section 8.1.1 and shown in Figure 63). The most prominent disparity between the total number of likely affected and those assisted is on day one of each strategy under each scenario. Distribution on day one focuses on sandbag distribution and represents the smallest resource to load ration, with only 10 houses assisted with each carload. In comparison, day seven records the smallest disparity between likely affected and those assisted. This is due to distribution focusing solely on water and the resource-to-load ratio being highest, with 50 houses (approximately 150 individuals) assisted with each delivery.

As noted in section 8.1.1, the Control scenarios tested were relatively successful, recording the highest number of recipients assisted for 17 of the 21 days displayed in Figure 74. This is likely due in part to the increased routing options available under the Control scenarios (all roads are navigable) and demonstrates the negative impact that flooding can have on distribution in terms of successful deliveries.

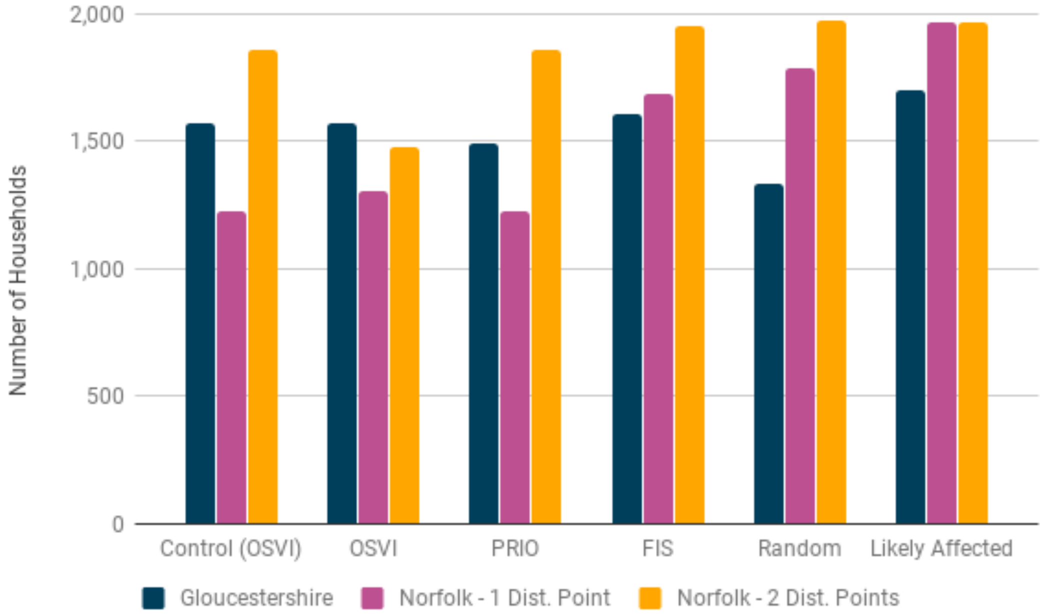

Figure 72: Comparison of the total number of households that received assistance in some way for all five strategies under each scenario. Includes the number of likely affected households for each scenario.

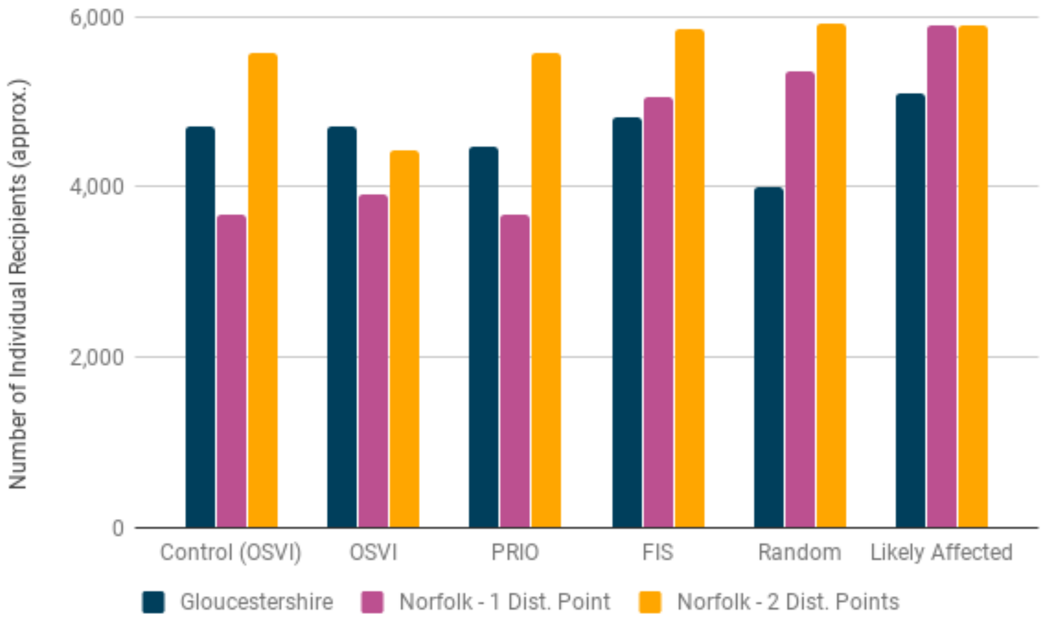

Figure 73: Comparison of total number of recipients assisted in some way for all five strategies under each scenario. Includes the number of likely affected individuals for each scenario.

		Households assisted in some way	Recipients assisted in some way	Percent of affected households assisted in some way	Percent of affected recipients assisted in some way	Percent of affected LSOAs visited	Percent of required deliveries made
Gloucestershire	**Control (OSVI)**	1,568	4,704	92%	92%	26%	**44%**
	OSVI	1,568	4,704	92%	92%	**29%**	41%
	PRIOS	1,488	4,464	88%	91%	25%	38%
	FIS	**1,604**	**4,812**	**95%**	**95%**	28%	29%
	Random	1,328	3,984	78%	78%	21%	27%
Norfolk 1 Dist. Point	**Control (OSVI)**	1,224	3,672	62%	62%	**22%**	**29%**
	OSVI	1,304	3,912	66%	66%	20%	22%
	PRIOS	1,224	3,672	62%	62%	20%	26%
	FIS	1,684	5,052	86%	86%	**22%**	23%
	Random	**1,788**	**5,364**	**91%**	**91%**	18%	23%
Norfolk 2 Dist. Points	**Control (OSVI)**	1,860	5,580	95%	95%	40%	31%
	OSVI	1,476	4,428	75%	75%	40%	32%
	PRIOS	1,856	5,568	94%	94%	42%	**34%**
	FIS	1,952	5,856	99%	99%	40%	33%
	Random	**1,972**	**5,916**	**100%**	**100%**	**58%**	27%

Table 30: Breakdown of households and recipients assisted in some way by strategy for each scenario

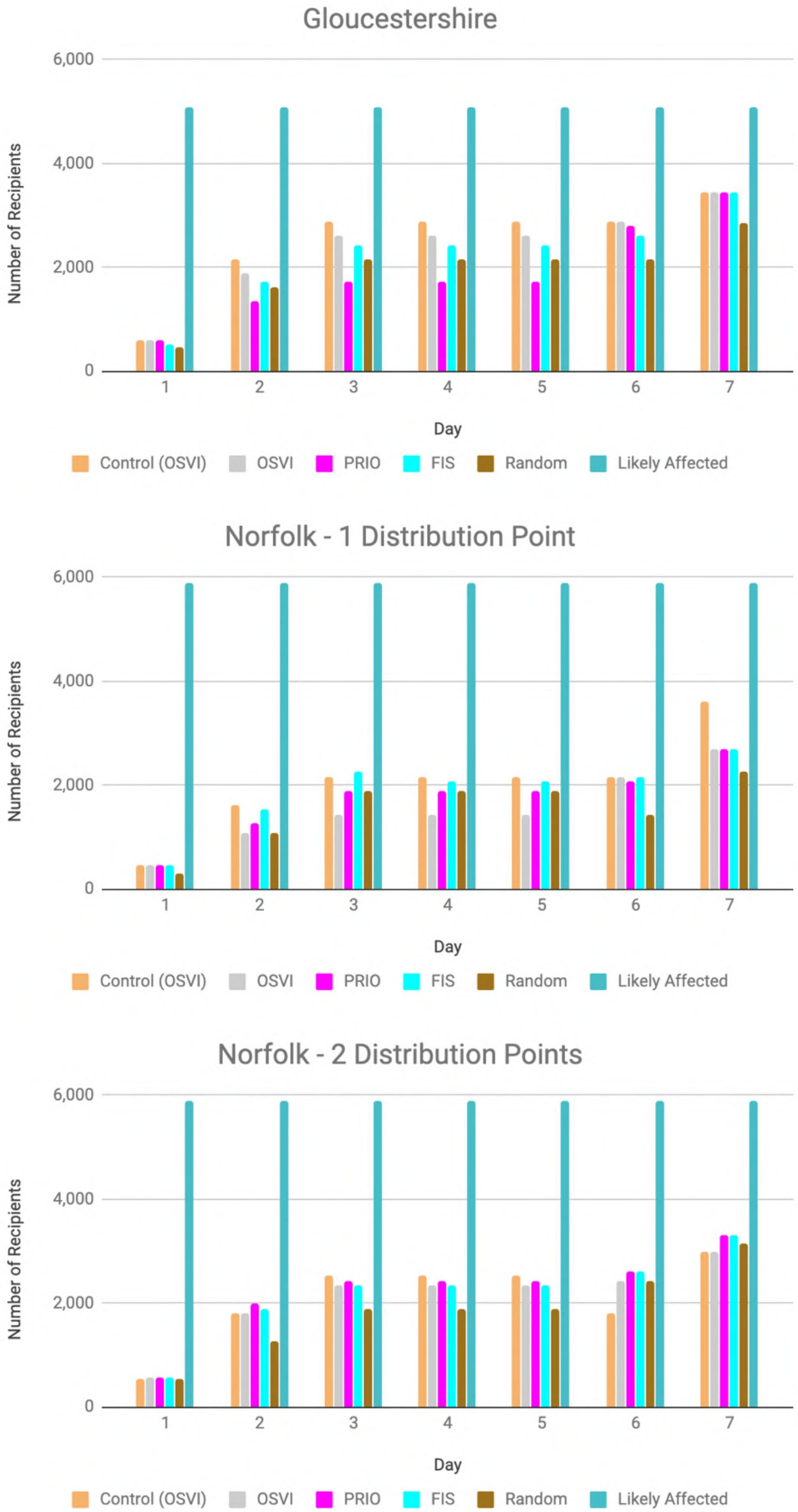

Figure 74: Total number of recipients per day by strategy over 7-day model run

8.2.2 RESOURCE COSTS & RESPONSE TIME

Examining the total number of resources distributed, as well as miles driven, and staff hours, allows the BRC to examine the effects of changes to resource allocation on response outcomes as well as the actual costs of resources needed (staff, fuel and storage expenses, as well as item costs) – valuable capacity, capability and finance planning details for an NGO.

As can be seen in Figure 75 (note: log scale), and as discussed in sections 8.1.1, 8.1.2 and 8.1.3, no area received all the required resources in the available time. Given that the delivery of resources is highly time dependent and delivery time windows are limited (sandbags before the flood, water and hygiene kits during, and cleaning kits after), it is necessary to consider increasing the load capacity of vehicles, increasing the number of vehicles and/or increasing the hours that staff can work (and be compensated for). All of these options will impact response expenses and response time.

As Figure 76 and Figure 77 show, and as would be expected, there is a clear positive relationship ($r = 0.6$) between total miles driven and total drive time. However, there is variation within this relationship by strategy and area. For example, in the Norfolk 1 scenario there is spike in miles driven for the FIS strategy on day three. As previously discussed in section 8.1.3, the central location of the distribution point and the location of high FIS areas towards the county boundary means that most FIS journeys are longer than the average. Examination of the model exports found that this spike relates to an area in Great Yarmouth that has particularly limited accessibility. Similarly, in the Norfolk 2 scenario, the Random strategy records spikes in total miles driven on days 2-5 that relate to several areas in Kings Lynn and West Norfolk that can only be accessed via a circuitous route when roads are flooded. These variations suggest that the choice of strategy *and* the location of the distribution point should be considered in unison as both impact the number of miles driven/drive time and therefore the number of resources distributed and success of the strategy.

As shown in Table 31, the relationship between staff work hours and the number of individuals assisted in some way is not as clear as the miles driven-drive time relationship. Only under the Random strategy in the Norfolk 2 scenario does the highest number of staff hours (401) correspond with the highest number of individuals assisted per day (845). In fact, in the Gloucestershire scenario, the FIS strategy records the lowest number of staff hours (304) and the highest number of individuals assisted per day (687). Examination of the underlying model run data found that the relationship between staff hours and number of individuals assisted is more a function of the destination area's proximity to the distribution point and its population density, rather than, as expected, a simple positive relationship between staff hours and individuals assisted. The impact of this finding, as well as others outlined in this section, on resource allocation and strategy selection will be discussed further in the Discussion Chapter.

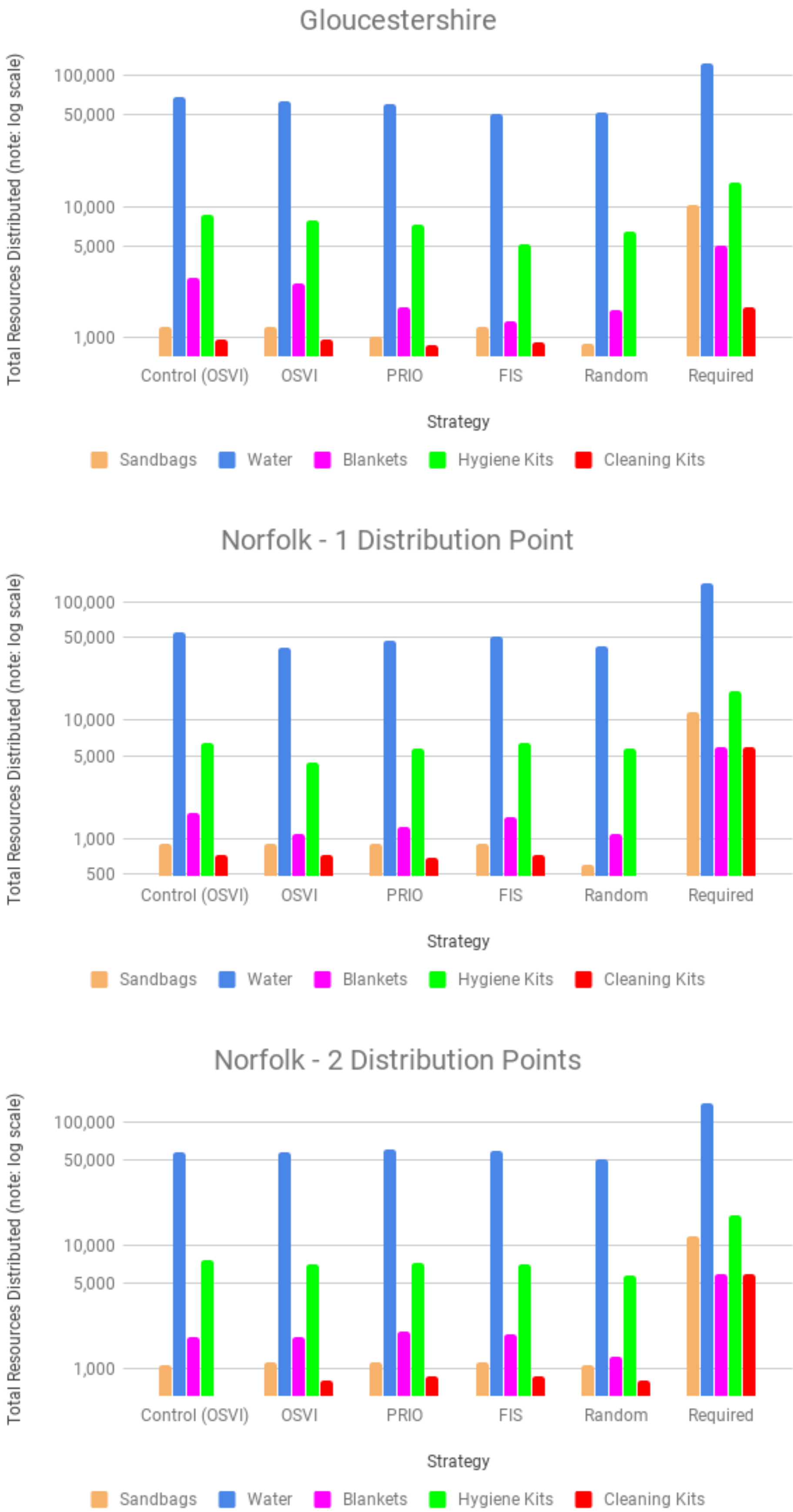

Figure 75: Total resources distributed by type for each distribution strategy for each case study area

Scenario	Strategy	Staff Hours	Number of individuals assisted in some way per day
Gloucestershire	Control (OSVI)	389	672
	OSVI	399	672
	PRIOS	**411**	638
	FIS	304	**687**
	Random	400	569
Norfolk 1 Dist. Point	Control (OSVI)	404	525
	OSVI	380	559
	PRIOS	429	525
	FIS	**457**	722
	Random	443	**766**
Norfolk 2 Dist Points	Control (OSVI)	390	797
	OSVI	370	633
	PRIOS	376	795
	FIS	370	837
	Random	**401**	**845**

Table 31: Total staff hours and individuals assisted per day for each strategy in each scenario.

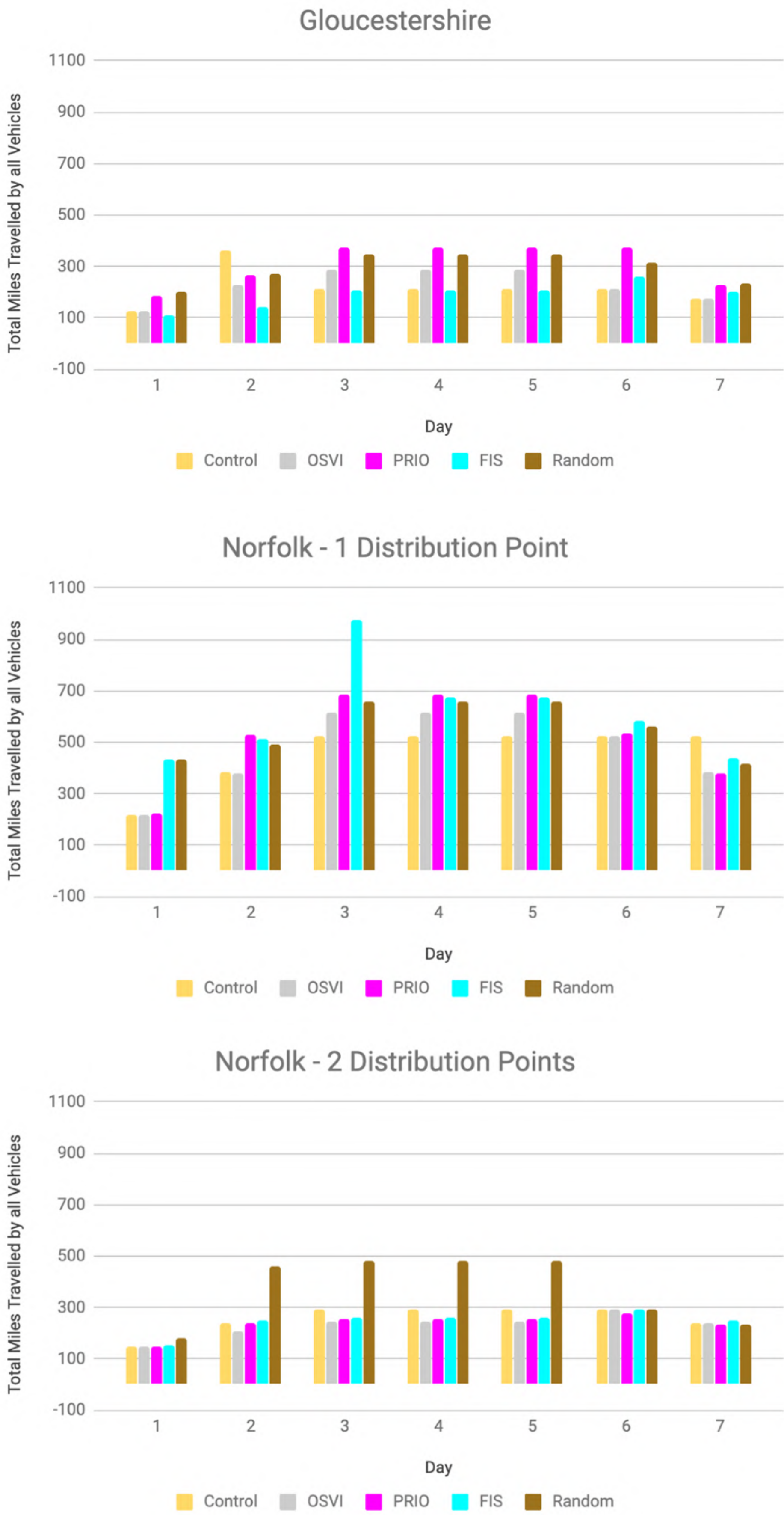

Figure 76: Total miles driven by all vehicles per day over 7-day model run by delivery strategy for each case study area.

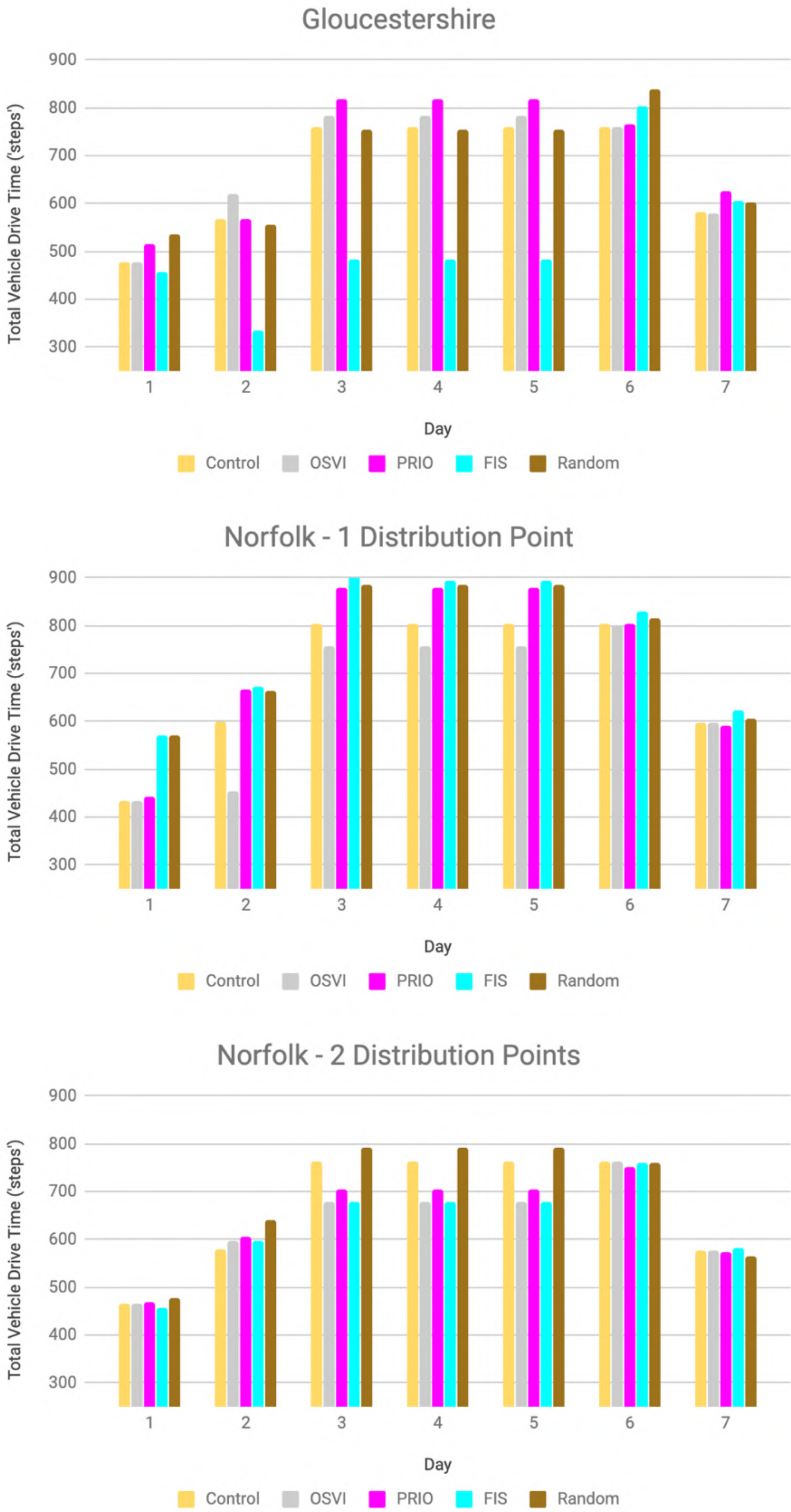

Figure 77: Total drive time (model steps) for all vehicles per day over 7-day model run by delivery strategy for each case study area.

To evaluate the performance of each strategy properly it is necessary to determine how long it would take to deliver resources to *all* likely affected persons as well as the staff and vehicles needed to do so. Each scenario and strategy were examined by running simulations with no time restrictions on resource distribution - 12-hour shifts remain, but resource distribution is not limited to, for example, one day for sandbags. Similarly, the number of vehicles needed to deliver resources to all likely affected persons *within* the time restrictions was also examined. Simulations were run and the number of available vehicles was increased until all required sandbags were distributed.

As can be seen in Figure 79, using the default number of vehicles per day (as outlined in Table 26) requires just over eight days of response activity to provide all likely affected houses with sandbags. This would not be suitable given that, in the Gloucestershire scenario presented, peak flood water levels are reached across days three and four and the benefit of sandbags is reduced once flooding is underway.

To counter this unsuitable timespan, the number of vehicles available was increased until all sandbags required were delivered within one day - as set out in the Gloucestershire scenario. As can be seen in Figure 79, it was not possible to deliver the required number of sandbags (10,176) in one 12-hour shift using the standard BRC Volvo XC70 or 4x4 Land Rover Defender. Simulations were run using upwards of 80 vehicles (the equivalent of 160 staff/volunteers delivering resources plus staff/volunteers working at distribution points), but the capacity of the vehicles, the number of bays available at the Gloucestershire distribution point, and the time required to load and unload the vehicles means that the minimum time to distribute the required number of sandbags is just over one 12-hour shift.

Under each scenario tested the number of bays available at distribution points was larger than the number of vehicles. This meant that no vehicle was required to wait until another vehicle departed and a bay was freed up. The number of bays available at a distribution point is fixed and is unlikely to increase as space is often at a premium at distribution points. BRC staff noted that extra resource deliveries and extra staff and volunteer vehicles often utilise vehicle loading space during emergencies. Thus, to test if the number of loading bays was the major constraining factor, the number of bays available at the Gloucestershire

distribution point was reduced to four – one fewer than the fewest number of vehicles available in the simulation – while all other parameters (vehicle numbers, loading/unloading times, capacity *etc*) were kept at their default levels (see Table 23, Table 26 and Table 28). As can be seen in Figure 78, the cumulative number of resources distributed for each resource type is reduced and the rate at which resources are distributed is reduced. This is due to the delay in departure and delivery times caused by vehicles without access to a bay when looking to load/reload having to wait and limiting the overall number of rounds possible in the time available.

It was not possible to simulate all potential scenario variations – using larger capacity vehicles and/or increasing available bays and/or altering loading and unloading times – to reach the distribution target in the timescale available, but these examples illustrate the value of being able to run such simulations and test the value of distribution strategies and resource allocation. This issue will be discussed further in the Discussion Chapter.

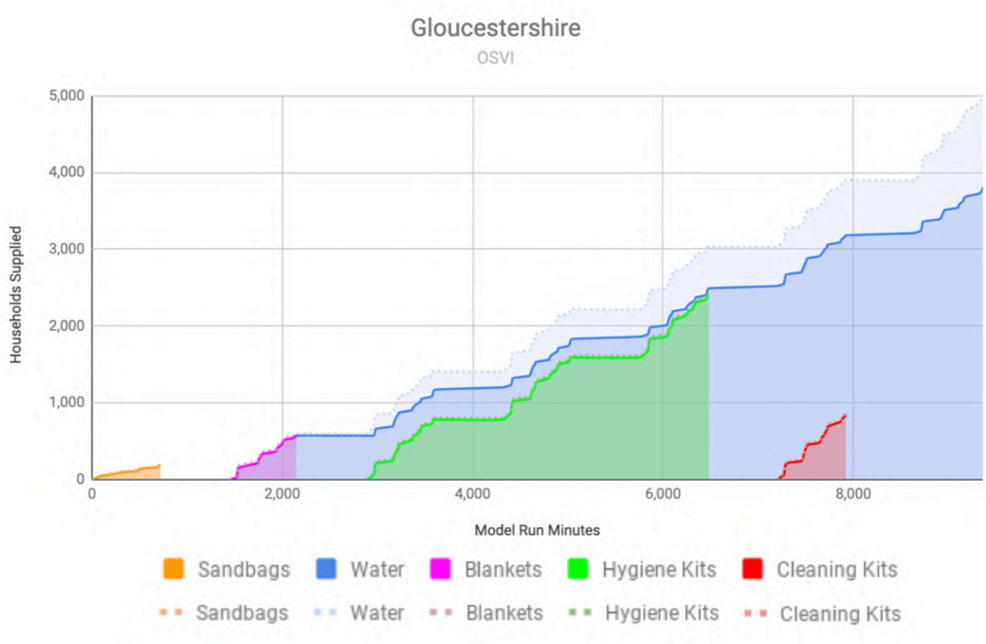

Figure 78: Cumulative number of households provided with resources by resource type over 7-day model run for OSVI strategy within the Gloucestershire scenario – solid lines represent test simulation with reduced bays, dotted lines and faded areas represent simulations with the default number of bays as seen in Figure 67

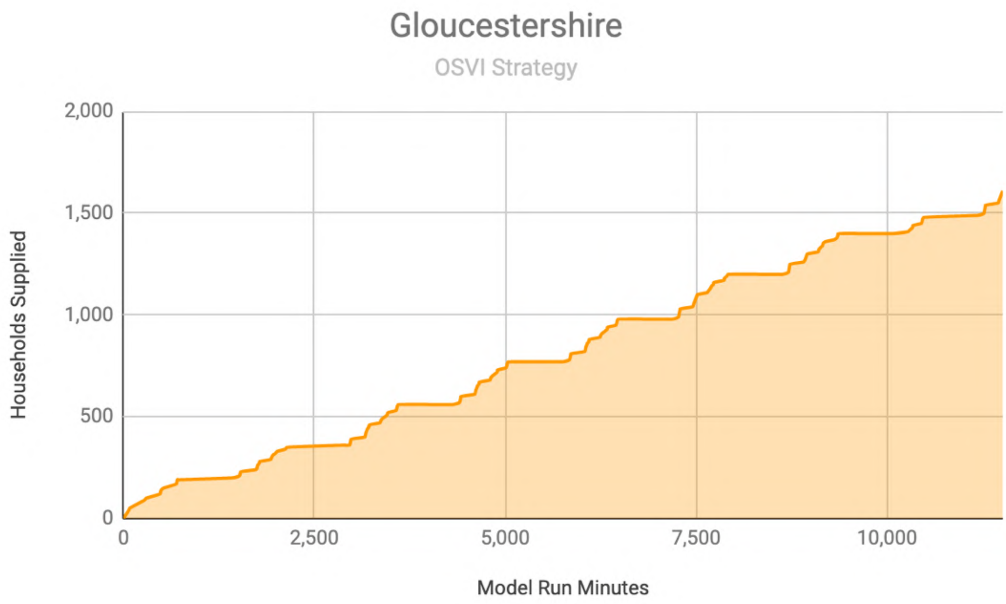

Figure 79: Cumulative sandbag distribution over time using default number of vehicles under the OSVI strategy within the Gloucestershire scenario.

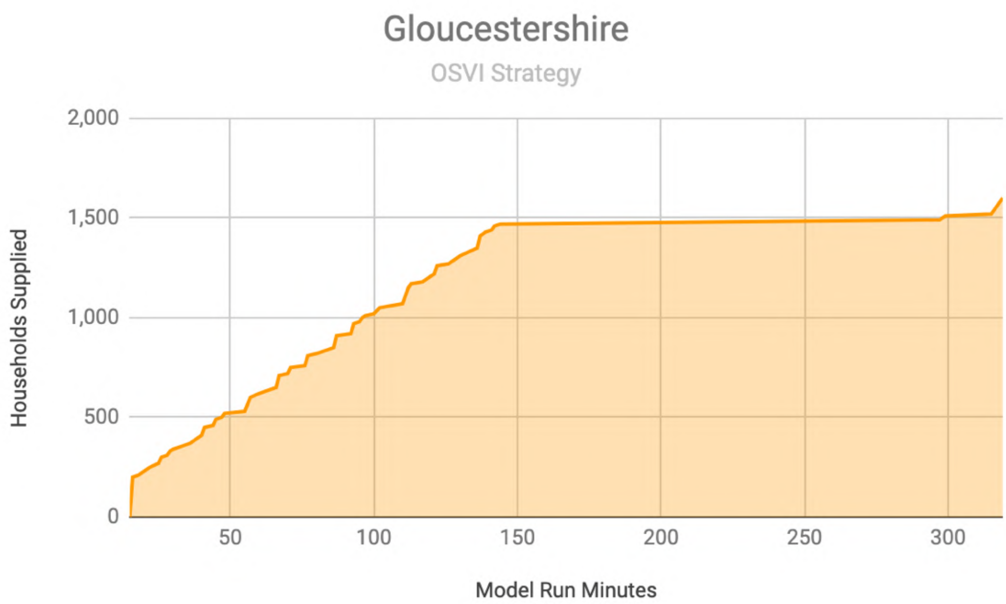

Figure 80: Cumulative sandbag distribution over time using 80 vehicles under the OSVI strategy within the Gloucestershire scenario.

9 DISCUSSION

Introduction	Literature Review	Stakeholder Engagement	Methodology OSVI	Results OSVI	Stakeholder Engagement	Methodology Model	Results Model	**Discussion**	Conclusion
Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5	Ch. 6	Ch. 7	Ch. 8	**Ch. 9**	Ch. 10

"[S]ome of the most desirable information…is data generated by government, especially geographic information which can often be used like glue to bind together disparate information."

~ Mayo & Steinberg, 2007: 13

This chapter expands upon the findings presented in both the Results: OSVI and Results: Model chapters and interprets those findings in relation to the research question and objectives, as well as to previous research in the field.

9.1 MAPPING VULNERABILITY

As previously outlined in Chapter 5, the OSVI draws considerable influence from the "unsafe conditions" phase of Blaikie *et al*'s (1994) Pressure and Release (PAR) Model as well as Cutter *et al*'s (1996; 2008) hazards of place model by focusing explicitly on place vulnerability within the OSVI, particularly relative local vulnerability within the Local OSVI. The inclusion of both vulnerability indicators and a measure of risk potential via the flood hazard zone within the OSVI provides a comprehensive picture of social vulnerability and allows for the examination of the interaction between socio-economic and biophysical vulnerabilities.

The OSVI not only displays the flood zones and therefore those areas at increased risk of flooding, it provides a means of highlighting those populations that are potentially more vulnerable to the impact of flooding due to their demographic characteristics. We term this the *demographics of flood vulnerability*: populations that are potentially more vulnerable to the identified flood risk due to its potential to exacerbate the local vulnerabilities identified by their demographics. This may be due to the area having a high proportion of elderly people or residents with health problems or the potential loss of key services during flooding, or, more likely, a combination of such vulnerabilities.

Flooding was found to impact one-third of LSOA within Norfolk and three-quarters of LSOA in Gloucestershire and a link between the presence of flood hazard in an area and its overall vulnerability was noted. Those areas with a high or moderate-high vulnerability rating are disproportionately affected by flooding, whereas no LSOA in Gloucestershire with a low vulnerability rating and only four in Norfolk were found to have the majority of their area within the flood zone. Furthermore, of those LSOA impacted by flooding, our analysis suggests that residents are also more likely to live alone and be aged 65+; be retired; have an income below the national median; be in receipt of a key benefit; lack central heating in their home; have bad or very bad health; have limited actions due to a long-term health problem/disability; provide care to another in excess of 50 hours a week; and are more likely to live in an area where travel time to key services is in excess of the national average. This suggests an underlying causal relationship between proximity to the hazard and socio-economic and health vulnerabilities – a trend noted by other authors (see: Alexander, 1993; Blaikie *et al*., 1994; Watts & Bohle, 1993) – although the relationship is unclear and further study is needed. This finding supports the hypothesis outlined in section 1.3 that social vulnerability, understood as a consequence of social inequalities, is, on average, higher for those living in a flood zone even when flood-related indicators are ignored.

Vulnerability is a contentious issue with an abundance of definitions and intertwining elements. The working definition of vulnerability utilised by any one organisation is likely to be different to that of another organisation. Any index created will undoubtedly have its detractors as it may appear to overlook individuals, groups or factors that they feel are fundamental to understanding vulnerability based upon their own experiences (Mustafa *et al.*, 2011). The benefit of the method presented is that these changes in definition and/or focus can be incorporated into the VI through the inclusion/exclusion of variables and the application of weightings (as detailed in section 5.6). It must be remembered that the OSVI, as well as others such as SoVI® (Cutter *et al.*, 2012), SVI (Koks *et al.*, 2015), and VCI (Mustafa *et al.*, 2011), are aggregated versions of reality, not reality themselves and that the goal of their creation is often to facilitate discussion and the development of work to assist the most vulnerable in society (*ibid*).

The analytical approach utilised provides a mechanism whereby freely available, quality data can be used by a local council or NGO to identify communities that may require added assistance to improve their standard of living. This can be done through the mapping of simple demographics data (age, income *etc*.) but the production of a vulnerability index, and vulnerability maps, provides a much more comprehensive and accurate picture of social vulnerability.

The vulnerability mapping approach presented does appear to function effectively as a method for identifying potentially more vulnerable communities within society, as well as providing a method for customising vulnerability maps to better suit the service requirements of an organisation. As has been demonstrated, vulnerability mapping is a useful tool for uncovering the disparities within society that make a community more or less vulnerable. More importantly, however, the effective utilization of vulnerability mapping can lead to the successful identification, monitoring and reduction of those disparities. Vulnerability mapping is also a useful part of hazard and emergency preparation. Where a flood map can identify those areas likely to be impacted by a flood, vulnerability mapping can identify those populations that are likely to require particular response and recovery services, be it extra medical equipment for an area that has an above average proportion of sick and/or elderly inhabitants living within a flood zone.

The relatively small LSOA unit used throughout the VI provides a workable unit to identify vulnerable communities and neighbourhoods but also local emergency planners and civic leaders who can provide local knowledge. Such identification allows for the targeting of services and programmes by practitioners, be it awareness and education programmes, planning by emergency services to ensure services/staff/supplies can match extra demand, or the location of shelters and evacuation routes/pick-up points.

Vulnerability is a highly variable and dynamic aspect of life that changes in space and time (Müller *et al.,* 2011). As such, no one variable can be used to validate the VI produced. Instead, the factors that may influence the VI must be examined. The production of multiple indicators (Norfolk average, England and Wales average, 50% of maximum), changes in index construction (different category weightings) and changes in the scale of analysis were used to test the VI and gain a greater understanding of how the VI changes. More work is needed to understand fully the VI and confidently implement the findings. It is necessary to examine the sensitivity of the VI to changes in variables used and indicators applied, as well as the impact of alterations in construction and geographic locale. Ultimately, it was not possible to undertake fully such examination in the timescale available.

9.2 MODELLING RESPONSE EFFORTS

9.2.1 SCENARIO & STRATEGY DISCUSSION

The scenarios presented were designed and modelled to be as representative of past events, in the case of the Gloucestershire scenario, and potential future events, in the case of the Norfolk scenario. Multiple variations of both case studies were simulated, with model parameters and input data tested and experts consulted throughout the development process in an effort to capture the key parameters and outcomes of each case study. However, despite best efforts, it is not possible to replicate perfectly a large-scale and complex event in silico – and as discussed in section 2.3, nor should that be the goal of the modeller.

One aspect of scenario development that was problematic was the impact of edge effects on analysis. Also known as a 'boundary problem', edge effects impact spatial analysis where geographical patterns are delineated by the boundaries placed upon the study area (Fortney, Rost & Warren, 2000; Stewart Fotheringham & Rogerson, 1993). For example, the use of administrative boundaries – census districts (LSOA) or county boundaries, for example – to define the limit of a study area and restrict routing options. Within the related literature it is often hypothesised that a failure to account for edge effects will lead to considerable errors in analysis (Rodeiro & Lawson, 2005). However, a reliable method for doing so remains elusive, though recent research into the impact of edge effects on access to healthcare providers suggests the impacts may be minor (Gao *et al.*, 2017). During development of the model, it was noted by BRC staff and volunteers that navigating within the county boundary was overly restrictive and that routes and distribution points they knew to be available were restricted as they crossed the boundary. It was also noted during accessibility analysis (see section 4.4) that omitting services close to, but outside, the county boundary (such as West Suffolk Hospital that is less than 12 miles from the Norfolk county border and represents the closest hospital for most of those in the southwest of the county) likely impacted travel times to key services, and as such impacted overall vulnerability ratings of border areas. The edge effect must be considered on a case-by-case basis as its impact is dependent upon the indicator used, the spatial distribution of facilities under examinations, and the organisation of the area being studied (Gao *et al.*, 2017). Given the project's reliance on established administrative boundaries and the BRC's semi-autonomous regional service provision, it was decided that the issue was likely limited but worth consideration in future work.

During response performance analysis (see section 8.2) it became apparent that the number of bays available at distribution points for vehicle loading and the time taken to un/load vehicles were two of the main distribution constraints. One might assume that an increase in available vehicles would increase the performance of distribution efforts and that an increase in the available resources would ensure that all those affected would receive assistance. This is not the case. As detailed in section 8.2.2, the relationship between staff hours and number of individuals assisted is more a function of the destination area's proximity to the distribution point, and not the relationship between staff hours and individuals assisted. Organisations such as the BRC, as well as any organisation that undertakes distribution activities, are effectively competing for space – space to store resources, space to perform activities, and operating space close to their likely distribution points. Given the maximum availability and refresh rates detailed in Table 18 for each resource type, it is unlikely individual BRC locations can store all the resources they may need to respond to the large-scale flood emergency being simulated here – this is undoubtedly the case for bulky items such as bottled water, sandbags and cleaning kits. However, blankets are sufficiently compact, and have a long shelf life, that it may be possible to store the likely required number (5,088 blankets for Gloucestershire and 5,901 for Norfolk) at regional distribution points to ensure all affected residents receive one. Like blankets, hygiene kits are compact and have a lengthy shelf life and a sufficient number can likely be stored locally to provide one to each affected person. However, unlike blankets, hygiene kits often need to be distributed daily during large-scale floods and so, under the scenarios presented, the required number triples and stocks would need to be refreshed daily. This addition of daily deliveries *to* the BRC and the ramification on deliveries *by* the BRC perfectly exemplifies the complexity of emergency logistics. Although it was not possible to factor such complexity into the model presented, it is hoped to do so in the future.

Given the constraints on distribution efforts listed above, prioritising *what* resources get distributed *when* and to *whom* is an important issue. Of the strategies examined – OSVI, PRIOS, FIS, Random – no single strategy performed better than all others across all the scenarios. Results presented in section 8.2 suggest that the performance of a given strategy is more context specific than first thought. It is possible that basing strategy choice on the resource being distributed or the location of the distribution point may prove beneficial. For example, on day one of the scenarios presented when sandbags are being distributed, and need to be distributed before flood waters peak, the FIS strategy could be used to target those areas with the greatest flood vulnerability. Similarly, strategy choice could be based upon the location of the distribution point. Under the Norfolk 2 scenario, where two distribution points are available, each point could utilise a different strategy depending on, for example, the geography or demographic makeup of the surrounding area. The FIS strategy could be used in Great Yarmouth, a heavily flood affected area on the coast, and PRIOS could be used by the Norwich distribution point which is closer to areas predominantly populated by the elderly and young families. Further work is needed to adequately affirm that, as stated in the hypothesis in section 1.3, that *the use of social vulnerability indicators when prioritising aid distribution can improve aid distribution performance.* It is hoped that further strategy and scenario testing will be performed by the BRC themselves when evaluating the serviceability of the model.

9.2.2 APPROACH USED

Participatory research has been shown to reduce quantitative uncertainties in simulations through the inclusion of stakeholders early on and the utilisation of their domain knowledge to guide all aspects of modelling: from data collection and input to model calibration and validation (Ritzema *et al.*, 2010). The iterative participatory modelling process and the problem evaluation and discussions that come from such work have also been shown to benefit both researchers and participants through knowledge sharing and have proven useful methods of examining community disaster planning and adaptation (Henly-Shepherd *et al*., 2015) and natural resource management (Naivinit *et al*., 2010). The research presented here responds to the challenge of adequately collaborating with stakeholders and interested parties and using their implicit understanding to develop, refine and validate a model of flood vulnerability, as detailed in section 2.2.6.

While the recommendations set forth by Leiras *et al*., (2014), namely the strengthening of NGO/academia relations and data collection, are commendable, the complexity and uncertainty within global supply chains during emergencies due to infrastructure and logistics disruptions, as well as the inherent confusion and urgency on the ground, severely limit the availability of data and opportunities for collaboration. It could be argued that, in such instances, collecting more data is not the solution, and the collection of better data over bigger data is more beneficial (Dominitz & Manski, 2017). For example, the lack of firm distribution data for BRC responses was a problem, but not an unsurmountable one. A detailed list of how many resources were distributed when and where could have allowed for better testing of the model and its outputs, but the engagement process and the model development and evaluation methods used made up for this. As discussed in the section 2.3.3, the acquisition of domain knowledge when building ABMs is often difficult as those who are most knowledgeable of the processes being modelled are often not those doing the modelling (Crooks *et al*., 2008; Hall & Virrantaus, 2016). However, the stakeholder engagement that took place throughout this entire project allowed domain experts to guide model development and led to the development of model details that the modeller may not have known to include (such as restrictions on volunteers entering flood waters and needing to factor in ‘chatting’ time when unloading resources at destination points – see section 6.3.3).

The benefit of ABM is that it is relatively easy to alter inputs and model strategies and tweak parameters. For example, BRC staff found it useful to be able to determine the number of responder agents as well as the volume of resources available, but also the parameters of those objects to create suitably realistic classes of agents and resources. For example, although not utilised in the model, BRC staff defined a number of different agents that could be used in future models:

- BRC Staff Agents: these Agents should have full autonomy, knowledge of the affected area, and decision-making skills.
- BRC Volunteer Agents: these Agents should defer to staff Agents for decision-making.
- BRC Car Agents: these Agents should not be able to traverse flood waters, can hold a limited volume of supplies depending on the resource being distributed, and can travel at the maximum speed allowed by law.
- BRC 4x4 Agents: these Agents should be able to traverse certain flood waters, can hold larger volumes of supplies, and have a slower maximum speed compared to cars. Not all Staff and Volunteer Agents should be able to drive the 4x4s.

The modular design of the model allows for extensions, like the additional entities listed above, as well as processes (evacuation, for example) and environments (different case study areas or additional hazards), and operational procedures (additional management structures to represent other NGOs or emergency responders, for example).

The principal values of using ABMs in social sciences are theory development, discovery of relationships, mechanisms, patterns and rules of the social reality, not the production of predictions (Gilbert & Terna, 2000: 59). To this end, the model was made as open and adaptable as possible and designed in a way so that its key elements – the agents, environment, hazard, and development framework – can be quickly and easily modified to fit the rapidly developing on-ground situations that need to be examined. The results produced during multiple runs of user defined model strategies should aid BRC decision-making in regard to the optimum ratio of staff-to-volunteers, as well as the volume of resources required to maximise 'impact' and limit increases in vulnerability.

Geospatially explicit ABMs, once thoroughly developed and validated, could offer humanitarian relief workers a real-time decision support tool that can simulate an emergency event and analyse response strategies; providing insight and guidance into, for example, the likely movements of affected persons and the ideal location of resources. As sources of spatial and demographics-related information continue to improve in quantity, quality and availability (see, for example, the work done by the Humanitarian OpenStreetMap Team (Soden & Palen, 2014; Poiani *et al.*, 2016) and modelling techniques and the knowledge of how people act in emergency situations improve, it will become quicker and easier to rapidly and accurately map, model and understand quickly developing situations (Crooks & Wise 2013). Further, the potential for the use of ABM within emergency relief goes beyond the modelling of post-disaster relief distribution. ABMs can, for example, be used to forecast the development of emergencies, be it disease outbreaks, civil unrest or the impact of hazards (Crooks & Wise 2013).

9.3 RESEARCH CONTRIBUTION

The major contribution of this work is the novel synthesis of three core research methods: demographics analysis, vulnerability mapping and ABM. These individual methods have been examined separately at length, but to the author's knowledge, there are no models that integrate geo-demographics into a spatially explicit ABM of emergency response. The method used to create the VI: the detailed analysis of socio-demographic characteristics at such a granular level but across an entire country and the combination with hazard and exposure analysis provides new methodological insights into the assessment of social vulnerability. Further, the creation of a dynamic model that integrates a vulnerability index is both innovative and novel.

Much of the ABM research previously undertaken has been abstract in nature, with a focus on grid-style representations of a geographical area, rather than the integration and presentation of real-life geography. However, there is a growing interest in utilising GIS and geospatial data to improve the applicability and use of ABM. Very little work exists that marries GIS and ABM to model emergency relief efforts (Crooks & Wise, 2013). Of the work that does exist, its focus has been on the movement of those affected by an emergency, namely those seeking aid distribution points, whereas this thesis focuses on the classification of an affected community's vulnerability and the subsequent distribution of aid. As detailed in section 2.2.2 of the Literature Review, applied research in humanitarian logistics and emergency response operations is limited and partnerships between academia and humanitarian organizations were scarce. Further, within the literature, there is a focus on pre- and post-disaster supply chain management, specifically the logistics of getting resources from manufacturers or stockists to disaster zones or distribution points. Few studies focus on 'last mile' logistics *during* the event. This thesis does that.

This project follows the growing trend of using open source data and software. The project relied almost exclusively on open source data and software, a rare undertaking for a project of this nature, and in doing so highlights the original nature of the project within the wider ABM, GIS and open source literature as well as its contribution to understanding the strengths and limitations of using such data in this context. In addition, the project aims to contribute to the growing understanding of vulnerability and response management within the NGO sector by providing information, analysis and findings specifically geared towards the needs of the partner NGO.

In addition to the production and combination of the open-source vulnerability index and an applied ABM, the work undertaken contributes:

- towards the limited past work on NGO response effort research and academic-NGO collaboration.
- a greater understanding of NGO-based domestic UK floods response efforts and guidance to both academics and practitioners for developing alternative simulation methods;
- the application of the derived social vulnerability indicators *and* an ABM to provide guidance to both academics and practitioners for developing alternative simulation methods and management policies;
- a grounded and applied ABM developed for and in conjunction with humanitarian practitioners.

At all stages of the project, feedback was openly encouraged and was recorded along with findings from workshops, focus groups, interviews and participatory modelling sessions. This allowed for a continuous process of analysis and improvement that refined project outputs and increased their usability. For example, based upon interactions with BRC volunteers and staff, relatively simple changes were made to the model's graphical user interface (GUI) (map colours and overall design, model speed *etc.*) and reporting structure (graph style, chart update frequency and output file format) to make it more user friendly and appropriate to their needs.

Being able to engage fully with the BRC and encamp within the organisation opened many opportunities to interact with staff and volunteers that may not have been possible otherwise. Embedding oneself within an organisation can create a level of trust that helps to foster data sharing and improve participatory modelling (Lucero, 2013). The stakeholder engagement and participatory modelling approach used led directly to the development of two scenarios and a set of response strategies to aid development, verification and validation of the model, as well as the data needed to model such actions accurately. It is unlikely that these scenarios and strategies would have been developed without the focus groups, discussions and consultation made possible by the close engagement with the BRC.

ABMs can initially be difficult to understand, especially for those unfamiliar with modelling, but this work has shown that a participatory modelling method can lead to a wider engagement with the models, particularly if the models are made relevant and potential users have an input. Models such as the one presented here, which are built for scenario exploration, can promote discussion and lead to the exchange of institutional learning.

Finally, on a personal level, the work helped me to develop a much greater understanding of the BRC's operating methods and standards as well as its future plans in UK response work. The process allowed for a first-hand experience of flood response work in the UK to be gained. The work has firmly secured a long-lasting bilateral relationship between the BRC and UCL, and has provided the project, and UCL more broadly, access to data and policy guidance on issues such as humanitarian aid, development, and international governance that were previously unavailable. The work has made possible the generation of a considerable research/professional network within the NGO sector and beyond that will undoubtedly improve future research collaborations.

9.4 CHALLENGES, LIMITATIONS & OPPORTUNITIES

The principal challenge of creating a vulnerability index is the selection of variables that adequately represent vulnerability. This task is complicated by the availability of data, the scale of the data available and agreement on what indicators are important. The OSVI has been shown to offer a novel and comprehensive view of social vulnerability that includes the often-overlooked measures of accessibility and risk potential. However, there is room for improvement.

One aspect of the OSVI production method utilised that could be examined further is its use of binary indicators. After cumulating the data for each variable and determining the averages for each, the data was normalised and reduced to a binary format: with zero representing no vulnerability where the score was below the local or national average and one representing the presence of vulnerability when the score was above that average. It is possible that, in using this method, the data is converted to a binary format *too* early and that unnecessary errors may be introduced. For example, say one LSOA had the following three variable scores:

- variable A = 1%
- variable B = 51%
- variable C = 51%

If the national average for each is 50% then variable A is below the threshold and is classified as zero, or no vulnerability, whereas variables B & C are above the threshold and are classified as one, or vulnerable. The LSOA would therefore be determined to be vulnerable. If, however, the variables are kept in their raw form and *then* averaged, the LSOA would be classified as having no vulnerability as the combined average is below the national average of 50%:

$$\frac{(1\% + 51\% + 51\%)}{3} = 34\%$$

It is unclear if keeping variables in their "raw" form presents a more accurate representation of vulnerability when compared to the binary method used. The binary method used to create the OSVI presents users with a simple vulnerable/not vulnerable classification for each variable, and an easy to understand cumulative vulnerability score for each area. Although this simplicity was intentional so as to aid understanding and usage, it could also be a limitation. Future work could examine the use alternative indicator methods.

Limiting the study areas by their county boundaries undoubtedly led to erroneous results with regards to measures of accessibility. For example, there are a number of hospitals in the neighbouring counties of Cambridgeshire and Suffolk that are within closer proximity to a number of Norfolk LSOAs than those Norfolk hospitals examined. Similarly, the impact of flooding on accessibility was examined by removing those roads within the flood zone and then routing from LSOA Centroids to the closest hospital. This routing was limited to the road network within the boundary of both counties examined. Had the wider road network been utilised, as well as key services in neighbouring counties, it is likely that routes produced would have been able to circumnavigate the flood zone and accessibility figures would have been drastically different. It was out of the scope of this project to examine the consequences of these edge-effects on analysis and to consider alternative methods.

The central challenge of agent-based modelling is to simulate adequately the behaviours, attributes and scales of the phenomena under examination and ensure that the resultant behaviours and interactions resemble real-world examples. Given the complexity of the underlying model, model validation is a non-trivial task that extends far beyond the scope of this thesis and, as shown in sections 2.3.2 and 7.4.6, model validity is a particularly challenging aspect of ABM research that requires more attention. However, it is hoped that the information presented in the preceding chapters – particularly the focus on participatory modelling – helps to alleviate concerns as to the validity of the model and demonstrates that efforts were taken to create as accurate a model as possible given the information, time and resources available.

A number of technological restrictions limited the work. The reliance on open source software, although lauded, did restrict options, and the requirement that the BRC or other such NGOs be able to run the model was limiting. A number of software options exist that could provide the BRC with a similar model with much less effort and in a much shorter time, but such software is expensive. Similarly, the hardware required to run the model with the number of agents first envisioned is expensive – the final model with a reasonably limited number of agents requires 32GB+ RAM to run efficiently. Further, despite extensive testing and verification, it is possible that errors exist in the model code.

Although it is felt that the participatory modelling method used was challenging, it was ultimately successful and rewarding. When discussing vulnerability and emergency response with NGO staff, different perspectives and overlapping expertise is likely to lead to misunderstanding and even conflict. This was noted in larger group settings that were held early on during the project scoping phase. However, later modelling workshops with smaller groups were easier to manage and more efficient. This is likely due to the more contentious issues having already been discussed or participants feeling more empowered once they can interact with the model directly and share their own knowledge and integrate it into the model. The participatory modelling process used represents just one example of how knowledge integration and exchange can assist in the development and validation of ABMs.

The following are the challenges and limitations of the project as identified by me and BRC staff during project workshops:

- Information gathering was found to be a difficult and complex task. Information and data sharing amongst BRC teams is limited, unless team members have direct contact with one another or shared goals. The BRC is actively looking to improve this situation using large data repositories and a data standard (*e.g.* HXL) to encourage and improve the sharing of information within the organisation as well as with others. To gather data for this project, it was necessary to contact lots of staff and volunteers individually to ask for their help. Often data was found to be stored on personal computers or offline. In most cases, data was only supplied after the person had been fully briefed on the project and had been given assurances from managers. It was found that face-to-face interviews and focus groups resulted in data being supplied as members were reminded of past events. Discussions often led to the interviewee or focus group member remembering that they had useful information (stock orders or personal notes) printed and filed or recorded electronically but not on the organisation's network. This process resulted in data being provided quite late in the project timeline.
- Anonymity is a major issue for the BRC given its work with vulnerable people. Understandably, staff and volunteers are reluctant to share information without consent. However, this has led to a culture where little-to-no information is shared in case it breaches trust or causes legal concerns, even if that information has been anonymised or contains no personal information. This overly cautious approach made gaining access to contacts and data a lengthy and convoluted process of introductions and requests.
- The BRC is made up of hundreds of staff and thousands of volunteers in dozens of offices across the UK. To navigate this large and semi-

autonomous network and ensure that one is talking to the most knowledgeable member requires a lot of time. Much of the onsite time spent at the BRC involved emailing and telephoning staff and volunteers and repeating the same information and asking for assistance or for details of someone who may be able to help. It was found that several key managerial staff members were well connected and could provide introductions to others who worked directly on case study emergencies.

- It was recognised during the engagement process that most staff and volunteers were focused on short-term projects, the maximum of which was usually 6 months. This is common within the NGO sector, but was found to be contrary to the processes and projects undertaken in response to flood emergencies, particularly post-disaster recovery operations. For many, the lengthy timeframes involved in academic work (4+ years in this instance) was not suitable for their work.
- Some staff and volunteers perceived the research to be an evaluation of their work and were initially reserved in their interactions. It required the assistance and assurances from management before some staff members felt comfortable providing information.
- Several staff members saw parts of their work as confidential and were not willing to share information that could eventually be published. This was particularly present when discussing donations (either monetary, in-kind or stock), response strategies, or beneficiaries. Again, the assistance and assurances from management were required before some staff members felt comfortable providing information.
- Much of the work the BRC does concerns qualitative, socio-economic issues that are highly changeable. Such issues are often accompanied by a wide array of definitions, theories and schools of thought. It became apparent, through focus group sessions, that staff and volunteers had a wide-ranging set of views and opinions on emergency response topics. This was expected, but the time needed to suitably address the scale and range of such issues was not suitably allotted. This resulted in lengthy meeting overruns and follow-up sessions. It also resulted in overly broad sets of goals and objectives that were required to be refined due to time constraints.

- Although the model was praised, it was felt the learning curve required to understand its methods and complexities was too high. Similarly, the model's data structure was felt to be too complex for an average user to set up and would need considerable refinement and simplification.
- Although the use of open source mapping data was commended, users reported a desire for the model to run on Google Maps, a mapping tool that almost all were more comfortable using.
- Although the level of detail within the OSVI was praised, it was widely felt that the data was likely out of date due to its reliance on 2011 Census data. It was felt fewer, more recently updated data sources could provide a comparable result. Conversations were had around the use of 'non-traditional' data sources and indicators of vulnerability. Although a great deal of research has focused on the study of proxies of wellbeing and vulnerability and the creation of related indices, much of the work has focused on 'formal metrics', particularly Census data and data produced by the UN, IMF and ADB (see: Cutter *et al*., 2003). The use of 'non-traditional' metrics, particularly crowdsourced and citizen reported data and social media, remains largely unexamined. The increasing use of digital communications and the Internet, particularly mobile Internet and social media, in developing countries is opening up opportunities to move away from 'formal metrics' and 'traditional' data. The 'formal metrics' that are available to development agencies and that they rely upon most heavily (namely those produced by national statistics agencies, the United Nations (UN) and IMF World Bank) are often incomplete, generalized, have a resolution that results in entire towns or villages being assigned the same metrics, and more often than not reference one another in a circular fashion (Srinivasan, 1996; UNDP, 2003; Morse, 2004; Redy & Heuty, 2008; Holt, 2013).

9.4.1 POTENTIAL END-USERS & WIDER APPLICABILITY OF THE APPROACH

The work presented here is aimed at one organisation: the British Red Cross. The model produced is specifically tailored towards the work of the BRC following flood events in the UK. However, the concept of resource distribution is sufficiently generic and the model suitably adaptable that it could be utilised more broadly: other areas of the UK or internationally, different distribution strategies, transport methods or hazards, for example.

It is believed that the user group for the index and the model (or improved versions of both) is relatively large within the NGO and public sectors. With sufficient training and an improved understanding of what the OSVI and model actually do and do not do or show, particularly with regards to outputs, it is believed that both, as well as the wider stakeholder engagement process more broadly, could be valuable across a range of sectors.

The BRC is a large organisation with dozens of regional offices and teams. These teams are not present in all offices/areas and the priorities and requirements of each is different. In addition to the BRC teams referenced in section 5.6 (*Fire & Emergency Support, Support in Emergencies, Independent Living, Support at Home, Transport Support, Mobility Aid,* and *Hand, Arm, & Shoulder Massage*) there is potential for the OSVI and the model to be of use to the *Ambulance Support, Distribution & Driving, Connecting Communities, Refugee & Asylum Seeker Support, People Operations,* and *Retail & Fundraising* teams. For example, the *Connecting Communities* team offers tailored support to individuals who are socially isolated. The OSVI could be used to identify areas where individuals may be isolated, and the team could target outreach work to those areas. The *Ambulance Support* team could use the model to simulate, for example, winter NHS crises where they may be called in to assist NHS ambulances services. The team could identify areas where NHS hospitals are likely to require increased resources due to regional demographics. It is likely that the OSVI and model would need to be adapted for each team, but the examples presented in section 5.6 show the opportunities available for customising the work.

If the model is to be used in a different setting, then the key consideration must be the data used. The data used to create the model presented was chosen specifically for the case study presented. Although OSVI data is available for England and Wales, replicating it for an international setting, for example, would be difficult. A meeting was held with members of the BRC International emergencies team where the model was demonstrated, and feedback was requested. Although the team recognised the value of the model within a domestic setting, it was determined that the methodological framework, the overall data structure and sources, and the conceptual vulnerability model would need to be heavily refactored, likely for each region or country, for the model to be of use, but the team did see potential for the use of such bespoke models during training sessions. Similarly, although the GIS and model data used, such as road networks and flood zones, are wildly available throughout the world, the work undertaken to prepare them, and the specific values needed for analysis, for creating the CFPS for example, would require considerable reassessment for an international setting.

The model can largely be split into three parts: flooding, vulnerability, and distribution. The wider applicability and transferability of each part is given below:

Flooding: the floods data used in the model is representative of the data that is available in other developed nations. Further, the way the data was used in the model was straight-forward: a simple binary flooded/not flooded shapefile. It is probable that the flood analysis undertaken could be replicated in an international setting and that the FIS could be replicated. However, the work presented here focuses on surface water flooding. Coastal flooding is not included in this modelling and represents a very different form of flooding that would require significant examination before the model could be transferred to areas concerned with predominantly the impact of coastal flooding.

Vulnerability: the formation of the OSVI as presented is not easily transferred to an international setting. The values required for the overall vulnerability analysis outlined are far from universal, however the variables used to create the OSVI are near-universally accepted to represent elements of social vulnerability. As such, vulnerability analysis could be transferred to an international setting, but would likely require significant research and refactoring, assuming the data are available at all. The data used, or similar, are widely available throughout developed nations, but it is likely that an alternative list of indicators and variables would be required for use in a developing nation (this issue is discussed further in section 4.2).

Distribution: the distribution modelling technique used is straight forward and easily replicated. This was intentional, as it was expected that analysis would be undertaken in multiple locations. The BRC's logistics and distribution operations undertaken during flood emergencies in the UK are not that complex – that is to say, in the grand scheme of logistics operations undertaken in the UK by the likes of, for example, the Royal Mail, Amazon or BBA Aviation, the scale of the BRC's operations are relatively small. That is not to diminish the challenges posed by the situations the BRC face – changing and dangerous access issues, limited resources and the desire to help as many people as possible as quickly as possible – it simply shows that the distribution model created could easily be transferred to another country or organisation, assuming that a basic road network is available.

The work was discussed with representatives from the wider NGO sector, including AgeUK, local councils, and the emergency response and management sector, including UKPN, the Environment Agency, and individuals with experience of ambulance and police response. Not all organisations respond to domestic emergencies like the BRC and so discussions with representatives focused on how the OSVI and the model, as well as the stakeholder engagement process used, could be adapted for their case studies. For most it was felt that the model would need to be altered to focus on transport or outreach, not necessarily resource distribution. For example, early talks with UKPN, an electricity distribution network operator, considered how best to use the OSVI to highlight areas where their 'Priority Services Register' could be advertised to improve uptake. Similarly, the OSVI and stakeholder engagement process could be adopted by local councils and used to better understand community composition and aid service targeting and provision, outreach work and service advertising. For emergency response and management, the techniques presented could offer a way to improve situational awareness of local communities impacted by emergencies and provide teams with information on community makeup and potential needs – allowing for better preparation in terms of equipment required and scenario testing.

All those approached noted the potential for using the methods and tools presented here within their respective regions and remits. The use of stakeholder engagement in particular was seen to have great potential for increasing beneficiary engagement and improving service provision. However, all recognised the complexity of the model as a potential hindrance – a lack of technical knowledge or source data was a key concern as well as whether they need a model for their work. It was also noted during conversations that potential users often requested a high level of model fidelity – requesting more detail and specific attributes for agents and case studies – so that the model was "more real" but were dismayed when such exactness increased both model complexity and the need for more source data. In addition, it was noted that modelled outputs were often taken as exact guidelines, rather than potential recommendations. To this end future work will focus on outreach and guidance, before further research is performed, or the work adapted. It is planned to produce guidance notes for the BRC on how to approach the kind of interdisciplinary research presented here in the future. Focus will be on explaining the processes and tools used as well as best practices and how to avoid common pitfalls.

9.4.2 FUTURE RESEARCH

The entire range of processes, tools and data sources used throughout this project could be expanded upon in future work. So too could different elements of the OSVI and model be explored in greater detail. Reflection upon the work done and discussions with the BRC raised several key areas for further work.

The OSVI is the first step in imagining a dynamic and customisable platform that can provide added context to complex situations and the targeting of resource and service allocation, be it the provision of programmes to address an identified vulnerability stressor or the location of new facilities to improve accessibility. Future work would ideally focus on further refining the variables and indicators used as well as examining the underlying dimensions of social vulnerability and risk and its changes over space and time.

Following completion of the project and presentation of the findings it was pointed out that little focus was paid to the impact that disabilities and health problems play in vulnerability during flood events. The OSVI contains a *Health and Special Needs* sub-category that itself includes variables on incapacity benefit claimants, those who reported very bad health or limited actions due to a long-term health problem or disability, and those who accessed adult mental health services. OSVI analysis presented in Chapters 4 and 5 highlights where these variables were found to play an important role in an area's level of vulnerability. For example, the number of residents of an LSOA reporting long-term health problems or a disability is highlighted as one of the top variables contributing most to the vulnerability scores of both case study areas (see sections 5.1.1 and 5.1.2) and is a factor used to calculate the Cumulative Flood Score (see section 5.3). In addition, section 5.6 presents the findings of OSVI weighting changes by BRC departments when calculating each vulnerability category in the index, including the Health, Self and Support category that contains the Health and Special Needs sub-category. Although limited, the analysis presented does highlight the importance of considering disabilities when examining social vulnerability and responses to emergencies. Given the BRC's focus on helping those with health problems and disabilities, particularly the Independent Living, Mobility Aid and Support at Home departments, future work focusing on the impact of disabilities on social vulnerability and response efforts should be a priority.

One interesting angle of future research would be to move from the 'formal metrics' that were used to create the OSVI and explore the use of 'non-traditional', crowdsourced and citizen reported data. This would be particularly interesting in an international context where many of the countries where development agencies work do not have well-established programmes to collect the required data in a consistent and repetitive manner (Ghosh, *et al*. 2015), and what is collected may be based upon idiosyncratic methods, and is likely to be highly generalized over a large area with no baseline available (Prabhu, 2005). Previous work has also shown the power of social media data, particularly Twitter, search engine queries and online media content to track migration flows (UN Global Pulse, 2014), disease outbreaks (Cook *et al*., 2011) and to predict conflict (UN Global Pulse, 2015). Big (crisis) data can also assist development agencies in the immediate aftermath of natural disasters. For example, following Typhoon Pablo in the Philippines, the UN Office for the Coordination of Humanitarian Affairs (UN-OCHA) and the Digital Humanitarian Network examined 20,000 Tweets in 12 hours to provide damage estimates and location data based upon text, photo and video reports Tweeted by those affected. In addition, novel methodologies have used satellite data to highlight poverty through rooftop material identification (United Nations, 2018) and night-time light dispersion as a proxy for wellbeing (Ghosh *et al*. 2013). When we supplement such data with qualitative, on-ground reporting done by development agencies, (for example health surveys performed by MSF) a detailed, up-to-date image of the local conditions is created. It is my contention that these local, 'non-traditional' metrics of wellbeing that remain largely unexamined will provide development agencies with measures that may be better suited to the local-level, dynamic work they undertake.

One aspect of work that regretfully could not be undertaken due to time constraints, was the representation of those affected by flooding in the model. It was hoped to model the actions and interactions of those living in flooded areas and to fully 'agentise' the OSVI by having vulnerability levels change dynamically throughout the model process. It was decided that this work was far beyond the scope achievable during this EngD. Further exploring the representation of affected agents within a relief/response model would be an interesting continuation of the work. For example, representing individuals or households as agents within the model that can process and exchange information, interact with the Responder agents and whose needs and vulnerability change based upon their actions would be a fascinating way to test response strategies as the spatial and temporal layout of vulnerability and the needs of each individual or household would be more dynamic (and not as heterogenous – grouping by LSOA – or static – focus on set Centroids as delivery points – as presented). Incorporating a richer set of individual/household dynamics, behaviours and scheduling would improve the realism and validity of the model and add situational nuance. Do families remain at home? Or do they go about their usual business or move to the nearest non-flooded area and wait? How does the number of cars on the road at different points of the day affect distribution? Do those affected coordinate their response efforts? Further, generating a visual representation of these changes through the production of 'vulnerability profiles' – generalised profiles showing the changes in vulnerability over the course of an emergency and at key points (start of flood, first aid delivery, peak flood, subsequent aid deliveries, flood waters receding, for example) – for priority groups or areas, could provide a better way to display modelled changes.

An additional distribution strategy was discussed that would focus on targeted distribution of certain resources based upon demographics of areas. For example, an area identified by the OSVI as being predominantly elderly or having limited mobility and being within a flood zone would be a priority area for the distribution of medical supplies whereas areas with a high proportion of households with dependent children would be a priority for the distribution of family aid packages. Again, this was beyond the scope of this project, but would be an interesting use of the OSVI and a fascinating way to test response strategies.

Talks with BRC staff and a BRC partner, the UK Power Network (UKPN), led to the decision to develop a test scenario based on a fictional flood event in Norfolk that leads to blackouts due to significant water damage of one of the UKPN's electricity substations – an issue that occurred in Gloucestershire in 2007. The test strategy decided upon was the BRC offering preferential contact and support to those on the UKPN's vulnerability register and the impact this has on regular BRC response strategy efforts. However, regrettably, time constraints and data limitations meant this work could not be undertaken during the EngD process. It is hoped that this work will be pursued in the future and the partnership will continue.

Further, social networks have enabled civilians to organise relief efforts and exchange hazard knowledge following emergencies. So-called "unbounded helpers" who do not belong to a formal response effort or NGO but nonetheless organise themselves and their response efforts are of interest to the BRC given their network of over 35,000 UK volunteers (see: Detjen *et al. (2016),* Dressler *et al.* (2016) and Reuter and Kaufhold (2018)). Exploring how best to distribute information through affected communities using social networks and organising response efforts across large networks and if such efforts enhance the performance of emergency response and management would contribute to making the model more realistic and applicable to how the BRC operates.

Finally, improving the representation of flooded roads within the model and integrating that into the routing algorithm could add improved realism to the model. In the model presented, agents can only operate within the study area. It is likely that responders would utilise all available routes in the real-world but doing so vastly increased the computational time and resources needed during routing. This issue of edge-effects and boundary limitations is discussed further in section 9.4. Future work could address this issue by expanding the available road network, but issues around which roads to include and when to apply restrictions would likely be complicated. Further, the flood maps used do not represent flood depth, an important aspect of flooding that determines if a road is passable or not. How does pathfinding – the most computationally demanding task in the model – change as knowledge of impassable flooded roads disseminates or does destination choice change depending on past experience? Work was undertaken to develop further the A* routing algorithm used and include a scaled journey cost that would be applied to every road segment and include parameter weightings for use in parameter sweeps when determining a route, but time constraints meant it could not be fully tested or verified:

$$
\begin{aligned}
&scaledJourneyCost \\
&\qquad = (weightedDistance\ x\ distanceToTravel) \\
&\qquad + (weightedSpeed\ x\ segmentSpeedLimit) \\
&\qquad - (weigtedPopulation\ x\ areaPopulation) \\
&\qquad + (weightedFloodImpact\ x\ floodImpactScore)
\end{aligned}
$$

Where $\mathrm{distanceToTravel}$ represents the individual road segment length, $\mathrm{segmentSpeedLimit}$ represents the maximum speed limit permitted for that segment, $\mathrm{areaPopulation}$ represents the potential users of that segment and therefore is a proxy for traffic, and $\mathrm{floodImpactScore}$ represents the specific impact of flooding on each segment using the FIS. $\mathrm{weightedDistance}$, $\mathrm{weightedSpeed}$, $\mathrm{weigtedPopulation}$, and $\mathrm{weightedFloodImpact}$ represent parameter values that would be used to examine the impact of each element.

Although the current model has proven to be a robust and illustrative tool to explore the impact of distribution strategies, the extensions outlined above would contribute to making the model more "realistic" and more useful within the NGO sector. These additions would increase the level of stochasticity within the model and in turn better represent the potential disruptions and system changes that can occur during complex events.

10 CONCLUSION

Introduction	Literature Review	Stakeholder Engagement	Methodology OSVI	Results OSVI	Stakeholder Engagement	Methodology Model	Results Model	Discussion	**Conclusion**
Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5	Ch. 6	Ch. 7	Ch. 8	Ch. 9	**Ch. 10**

"In a disaster, accurate information, like clean water, is an indisputable good."

~ Keen, D. and Ryle, 1996: 4

This chapter reconsiders the research question, detailing how it has been addressed, and provides a brief summary of the work.

This thesis aims to provide emergency response managers with a method of identifying social vulnerability and a tool to support the strategic and operational understanding of relief distribution during flood emergencies. The main research question was:

> Can an open source index of geodemographic vulnerability be created and used in a model in order to better understand the dynamics of vulnerability and the capacity of different relief response strategies in an evolving emergency?

The objectives broke down as follows:

- To **identify a set of proxy indicators of vulnerability** and **produce a vulnerability index** based upon those indicators.
- To **create a spatially explicit agent-based model of BRC relief distribution** that incorporates the vulnerability index, real-world resource quantities and locations, and models likely emergency scenarios.
- To **test the performance of different relief distribution strategies and scenarios.** Distribution strategies will be guided by BRC practices and past emergency responses as well as best practices from the wider emergency response sector.
- To **develop a greater understanding of the influencing factors of vulnerability (both endogenous and exogenous) and the performance of humanitarian response efforts** under a domestic context.

Researchers including Cutter, (1996; 2003; 2011; 2012), Mustafa *et al.* (2011) and Koks *et al.* (2015) have worked extensively on the topic of vulnerability measurement and others including Kovacs and Moshtari, (2018) and Das and Hanaoka (2014a) have focused on examining and modelling the many different aspects of humanitarian resource distribution. The research presented in this thesis combines and enhances the work in these two fields. There have been few examinations of comparative indicators of social vulnerability that incorporate measures of accessibility and flood risk. Fewer studies still have integrated a broad spectrum of vulnerability indicators available at the national level but with a resolution that allows for the representation of local-level vulnerability. The approach presented here addresses these limitations. Further, despite the significant spatial dimension to emergency response work, and the growing humanitarian modelling field, there are few studies that utilise geographical data to aid planning and assessment work, with few studies having focused on slow-onset emergencies, such as floods, within a UK context (Bozorgi-Amiri, Jabalameli & Mirzapour Al-e-Hashem, 2013). Moreover, there is a lack of grounded and applied work that coordinates with emergency responders (Menth, 2016). Past studies of emergency response work within the humanitarian sector that have focused on vulnerability assessment and operational decision making have featured limited, if any, academia-NGO collaboration and stakeholder engagement (Leiras *et al.*, 2014). Academics, policy makers and responders have been shown to operate within different frameworks with divergent timescales and goals, but increased collaboration can improve the work of all (Mustafa *et al.*, 2011). Finally, limited attention has been paid to the use of open-source data and technology, with proprietary sources preferred.

The goal of this project was to utilise free and readily available secondary data to identify communities that may require added assistance before, during or after a flood event, and test a range of distribution strategies that could be used by the BRC, or other NGOs or local councils in the future, to reach those identified. The methodological approach presented, as well as the two main project outputs, can be divided into two distinct, but connected, components that go to meeting this goal and answering the research question (outlined in section 1.3):

1. The OSVI provides a method whereby quality data on the core drivers of vulnerability can be used to create a versatile vulnerability index that provides information at a national level but at a sufficiently fine resolution so as to identify pockets of vulnerable communities. The OSVI focuses on common core drivers of vulnerability across spatial scales and rural and urban environments and can indicate areas where vulnerable communities live for which special emergency response strategies may need to be designed. The OSVI provides information in an informative and intuitive way that can be combined with other tools and knowledge to facilitate community emergency planning and anticipate an area's needs before, during and after an emergency.
2. The model provides responders and policymakers with an adaptable means of using available data to model and test response strategies and prioritise resource distribution. The model will provide a visual, open-source and data-focused way of improving organisational development and strategic planning. The model provides a spatially-explicit emergency exploration and planning support tool that facilitates decision making and builds our knowledge of humanitarian response processes and furthers the progress of ABM within future emergency response management and other related domains.

In the short-term, the main project outcome is the production of institutional learning and awareness, and the development of knowledge, skills and opinions relating to vulnerability and flood response procedures. Medium- to long-term outcomes will be a greater understanding of response practices and decision-making processes; and an increased awareness of the links between the socio-cultural characteristics of a community and the impacts of a flood hazard on their vulnerability; and an increased knowledge of the power of modelling for humanitarian relief planning and decision making. This will lead to greater policy and strategy development.

The OSVI was found to be a useful supplementary tool for the BRC, with the measurement and visualisation of vulnerability and potential hazard impact providing context and aiding response service planning and capability assessment. Further, by working closely with the BRC and asking questions of staff and others when creating the OSVI and the model, issues and questions around the recording and use of response statistics, or lack thereof, were raised and discussions were had that led to future research questions and ideas being generated that may not have occurred otherwise.

Two issues remain to be addressed – firstly, the underlying demographic data imposes a boundary effect which could be limiting as the BRC regularly work across county boundaries and with other NGOs. The modular setup of the model allows it to be extended with different management structures, scenarios and response processes and future work will address both the edge-effect and model scaling by examining service locality, catchment zones and mutual aid. Secondly, although the analysis suggests that underlying vulnerability (poor health, age, low income) could be correlated to an increased probability of living in a flood zone, further investigation is required.

The methods used throughout this thesis are scalable and adaptable and the project's reliance on open-source data and technology significantly reduces the associated costs and encourages use by NGOs and other parties involved to coordinate and share information, potentially improving local knowledge and reducing vulnerability (Trujillo, Ordones & Hernandes, 2000).

10.1 FINAL REMARKS

The identification of vulnerability is an important part of NGO work and relief distribution. Pinpointing where those most likely to be adversely affected by an emergency are located as well as how they are likely to be impacted and what their likely needs may help responders to plan service provision effectively.

For organisations like the British Red Cross, it is increasingly important that they can provide 24/7 operational support in response to ad hoc emergencies on top of the regular provision of essential social care and support programmes (Adamson, 2014). In addition, with NGOs required to defend and demonstrate the outcomes of their work (Proudlock, Ramalingam & Sandison, 2009; Van Wassenhove, 2006; Hofmann *et al.*, 2004; International Development

Committee, 2006), an increase in the number of organisations offering assistance and vying for donations, and increased pressure on governments to reduce spending (Clarke, 2018), improvements in relief planning and modelling could greatly improve the value and performance of emergency relief.

During an emergency, such as a flood, the efficient distribution of relief is essential to reducing risk and saving lives. Emergencies are complex, constantly developing situations, with response capacity and overall knowledge changing minute by minute. It is my belief that the ‘virtual lab’-style, explorative ABM approach used to develop the model presented best suits the way development agencies work: changeable approaches and procedures, adaptive methods and resources, fluctuating timescales, and with work often governed by the environment. The potential operative utilisation of tools such as vulnerability indices and ABM to simulate an evolving emergency could provide responders with the knowledge needed to adapt and improve real-life response strategies, response preparedness, and overall capacity and capability. The research described here may benefit humanitarian organisations beyond the sponsor organisation, the British Red Cross.

The OSVI and the model described are the first steps in imagining a dynamic and customisable platform that can provide added context to complex situations and the targeting of resource and service allocation, be it the provision of programmes to address an identified vulnerability stressor or the location of new facilities to improve accessibility. Both can be seen as proofs-of-concept with more work needed before they are operationalised. Future work will focus on further refining the variables and indicators used as well as examining the underlying dimensions of social vulnerability and risk and its changes over space and time, as well as improving the applicability and usability of the model within the wider emergency response sector.

11 APPENDIX

11.1 FLOODING

Flooding is a natural and complex process and is a near-constant part of British life[33]. Most areas in the UK have been affected by flooding at one point. Flooding in the UK is not restrained to any particular season or location; it can and does occur at any time of the year and all geographies in the UK can be impacted by it: rural or urban, highland or coastal.

Floods are caused by:

- Weather phenomena, such as rain or snow or a tidal surge.
- An overflow or inundation that comes from a river or other body of water.
- Any relatively high flow of water that overtops the natural or artificial banks of a watercourse[34].

WHAT ARE THE TYPES OF FLOODING?

Floods can originate from a variety of sources. The most severe flooding often occurs when these sources combine.

RIVER (FLUVIAL) FLOODING

River flooding (also known as fluvial flooding) occurs when a river, or similar watercourse, cannot accommodate the volume of water draining into it from the surrounding land, during or after a heavy downpour for example. Such floods are generally infrequent and can be predicted to some extent.

Rivers are more likely to be overwhelmed in areas where rainwater cannot be absorbed into the land onto which it falls, such as steep slopes, waterlogged

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[33] The information presented in Appendix 10.16 is adapted from the EA website: http://www.environment-agency.gov.uk/homeandleisure/floods/

[34] Definitions adapted from the USGS definition: http://ks.water.usgs.gov/waterwatch/flood/definition.html

areas or built over land (paved or tarmacked, for example). Rapid melting of snow can also lead to river flooding.

SURFACE (PLUVIAL) FLOODING

Surface water flooding (also known as pluvial flooding) occurs when heavy rainfall overwhelms the capacity of local drainage systems (both natural and man-made) or when there is a blockage in the system (blocked pipe or a build of silt and debris in a stream, for example) and water flows across the ground.

The route the water takes, and the depth of flooding, depend on local features and can be difficult to predict.

COASTAL FLOODING

Coastal flooding results from high tides or tidal surges.[35] The most severe coastal flooding occurs when the two coincide and a surge occurs at high tide.

SEWER & WATER MAINS FLOODING

Similar to pluvial flooding, sewer flooding occurs when an area's sewers are overwhelmed by heavy rainfall or when pipes become blocked. In urban areas, surface water flooding and sewer flooding often combine, polluting the floodwater and causing serious health concerns.

In comparison, flooding from burst water mains is not related to rainfall and occurs when water mains are damaged or faulty. Such flooding can cause localised disruption and damage to buildings, particularly basement properties.

GROUNDWATER FLOODING

Groundwater flooding occurs when water levels underground rise above the land surface.

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[35] A storm surge is a rise in sea level at the coast which is caused by low atmospheric pressure and the high winds of a storm.

This type of flooding is most likely to occur in areas above an aquifer.[36] Groundwater levels within an aquifer generally rise and fall according to an annual cycle, but periods of prolonged rainfall may cause water levels to rise above the land surface. This type of flooding can last for weeks or months.

PITT REVIEW

Following the widespread floods of June and July 2007, which resulted in 13 deaths, Sir Michael Pitt was commissioned by the Secretary of State for Environment, Food and Rural Affairs, the Secretary of State for Communities and Local Government and the Chancellor of the Duchy of Lancaster to carry out a review of the country's flood defences. *The Pitt Review: Lessons learned from the 2007 floods* was published on 25 June 2008. The review focused on:

- flood risk management
- the resilience and vulnerability of critical infrastructure
- the emergency response
- emergency planning and the recovery phase.

RECOMMENDATIONS

The full report contained 92 proposals that Pitt stated must be implemented if communities are to be better protected from future flood events. Key recommendations of his final report included:

- Establishing a cabinet committee to address the risk of flooding.
- Adopting a long-term approach to flood risk management, with priority given to adaptation and mitigation, and above inflation increases in the resourcing of flood resilience measures.
- Establishing a National Resilience Forum to facilitate emergency planning at a national level.
- A presumption against building in high flood risk areas.

[36] An aquifer is a water bearing rock such as chalk that holds and permits the passage of water. Large portions of Southern England are underlain by chalk.

- Pre-planning financial arrangements for responding to exceptional emergencies.
- Action to ensure the resilience of critical infrastructure such as power, water and transport (in particular dams and reservoirs).
- A wider brief for the Environment Agency, taking a national overview of all flood risk.
- A ‘step change in the quality of flood warnings ‘with the Environment Agency and the Met Office working to improve forecasting, modelling and warning systems.
- Establishing a national capability for flood rescue.
- Using armed forces personnel to provide logistical advice during civil emergencies.
- Providing better information, awareness and advice.
- Preventing householders from laying impermeable surfaces on front gardens.
- Removing the automatic right to connect surface water drainage from new developments to the sewerage system.
- Local authorities leading on the management of local flood risk.
- Preparation of emergency flood kits by the public.
- A Director in Defra overseeing the programme of delivery and issuing regular progress updates.
- The Environment, Food and Rural Affairs Select Committee assessing progress after 12 months.

AFTER THE REVIEW

The final progress report, published January 2012, reported that 43 of the 92 recommendations in the Pitt Review had been implemented and a further 46 were progressing, although no deadlines were given for the remaining recommendations.

The report presented 92 proposals to better protect communities from future flood events, including:

- a 25-year plan to address the issue of flooding, along with the creation of a dedicated Cabinet committee
- an overhaul of building regulations for homes built or refurbished in flood-prone areas
- definitive electronic maps of all drainage ditches and streams, including details on who is responsible for maintaining them
- more investment by utility companies to protect key infrastructure sites
- a national flooding exercise at the earliest opportunity

A final progress report was published in 2012 that suggested that 43 of the 92 recommendations in the original Pitt Review had been implemented, including:

- a 25-year plan to address the issue of flooding, along with the creation of a dedicated Cabinet committee
- a presumption against building in high flood risk areas and developers should make a full contribution to the costs both of building and maintaining any necessary defences
- all local authorities should extend eligibility for home improvement grants and loans to include flood resistance and resilience products for properties in high flood-risk areas
- in flood risk areas, insurance notices should include information on flood risk and the simple steps that can be taken to mitigate the effects.

A further 46 recommendations were reported as progressing, although no deadlines were given:

- the Met Office should continue to improve its forecasting and predicting methods to a level which meets the needs of emergency responders
- the Environment Agency should further develop its tools and techniques for predicting and modelling river flooding, taking account of extreme and multiple events and depths and velocities of water.
- householders should no longer be able to lay impermeable surfaces as of right on front gardens and the Government should consult on extending this to back gardens and business premises

- an overhaul of building regulations for homes built or refurbished in flood-prone areas.

A further two recommendations had not been taken forward or completely implemented:

- Flood risk should be made part of the mandatory search requirements when people buy property and should form part of Home Information Packs.
- The Risk and Regulation Advisory Council should explore how the public can improve their understanding of community risks, including those associated with flooding, and that the Government should then implement the findings as appropriate.

A number of responses, progress reports and legislative changes have been made since the Pitt Review:

- The government response to the Pitt Review was published in December 2008 accepting all of the Report's recommendations and undertaking to implement them.
- In 2008, the government published Future Water, The Government's water strategy for England.
- Progress reports were published in June 2009 and December 2009.
- The Flood and Water Management Act was introduced in April 2010.
- The National Flood Emergency Framework was published in July 2010.
- The National Flood and Coastal Erosion Risk Management Strategy for England was published in July 2011.
- The first UK Climate Change Risk Assessment was published in January 2012.

11.2 BRITISH RED CROSS: FUNDAMENTAL PRINCIPLES

As a member of the International Red Cross and Red Crescent Movement, the BRC is committed to, and bound by, its seven fundamental principles. These were used to guide the project, its development and its deliverables. For example, all public reports produced were politically neutral and impartial; and it is the intention that all the deliverables of this project be made available to all volunteers and staff of all Red Cross and Red Crescent societies, as well as external stakeholders within the wider GIS and humanitarian community, if deemed permissible. The seven fundamental principles are:

Humanity

- Born of a desire to bring assistance without discrimination to the wounded on the battlefield, the BRC endeavours to prevent and alleviate human suffering wherever it may be found.

Impartiality

- The BRC makes no discrimination as to nationality, race, religious beliefs, class or political opinions.

Neutrality

- The BRC may not take sides in hostilities or engage at any time in controversies of a political, racial, religious or ideological nature.

Independence

- The BRC is independent and must always maintain its autonomy so that it may be able at all times to act in accordance with these Fundamental Principles.

Voluntary service

- The BRC is a voluntary relief movement not prompted in any manner by desire for gain.

Unity

- There can only be one Red Cross or Red Crescent Society in any one country. It must be open to all. It must carry on its humanitarian work throughout its territory.

Universality

- The International Red Cross and Red Crescent Movement, in which all Societies have equal status and share equal responsibilities and duties in helping each other, is worldwide.

11.3 AGENT-BASED MODELLING DEVELOPMENT TOOLKITS

The ABM research cited hitherto is possible due to the continued development and experimentation of approaches to ABM and a number of ABM toolkits, the ever increasing availability of granular and longitudinal data, and the improvements in computing performance in both terms of speed and affordability (Macal & North, 2005; Hashemi & Alesheikh, 2013). Dozens of software platforms and programming languages exist that support ABM. Well supported examples include MASON, Repast, AnyLogic, NetLogo and Swarm, and R and Matlab. Depending on the requirements of the model and the skills of the modeller, there are multiple options available and practical guides available (see: Macal *et al*., 2010; Hashemi & Alesheikh, 2013).

Due to the focus on heterogeneous agents and the modelling of emergent systems, careful agent design, model planning and calibration, and validation is a priority (Deffuant *et al.*, 2012). Advances in ABM toolkits and modelling approaches, the growing availability of quality data, and the improvements in computing have helped the development of the aforementioned ABMs (Macal & North, 2005). ABMs are routinely developed in either native code or within an existing ABM toolkit. Several toolkits exist (see Nikolai and Madey (2009) and Gilbert (2008) for a comparison of toolkits):

- **AnyLogic**: a proprietary ABM package, with full GIS and 3D support, a general-purpose ABM with support for discrete event and system dynamics simulations, developed by the AnyLogic Company.
- **Cormas** (Common-pool Resources and Multi-Agent Systems): with GIS integration, a focus on natural resources management, rural development and ecology, developed at CIRAD.
- **MASON** (Multi-Agent Simulator of Networks/Neighbourhoods) (Luke *et al.*, 2005), is a multi-agent simulation toolkit developed at George Mason University's Evolutionary Computation Laboratory and the Centre for Social Complexity (Luke *et al.*, 2005). It is made available under an open-

source academic license. It is aimed at users who need to model multi-agent simulations with large numbers of agents. It has full GIS and 3D support and includes social complexity, physical and artificial intelligence, and machine learning applications. It also includes a number of extensions for Social Network Analysis (SNA; (Wasserman & Faust, 1994)), evolutionary computation (DeJong, 2006; Luke, 2009), physics modelling and geo-spatial data analysis through GeoMASON.

- **NetLogo**: an open-source, cross-platform ABM toolkit, aimed at teaching modelling and simulation, with GIS and 3D support, focus on social and natural sciences and getting users started with simulation and models.
- **Repast** (Recursive Porous Agent Simulation Toolkit): an open-source, cross-platform ABM toolkit, with GIS integration, a focus on the social sciences, developed at the University of Chicago.
- **Swarm**: an open-source ABM package, with no GIS support, developed at the Santa Fe Institute.

After extensive examination (see Agent-based Modelling Development Toolkits for a detailed comparison of ABM toolkits), MASON was chosen for this project for the following reasons:

- MASON is made available under an open-source academic license, allowing for data and code to be made available to other academics and NGO researchers.
- MASON is written in Java, a coding language my supervisors and I are familiar with and ensures MASON is not platform dependent.
- MASON is guaranteed duplicable, meaning that the same simulation parameters will produce the same results regardless of platform.
- MASON is optimised to process simulations very fast, paramount when running computationally intensive simulations.
- Simulations in MASON can be serialised to easily recoverable *checkpoints*, allowing for simulations to be paused and restarted at will.
- MASON has an extensive, yet fast, visualisation toolkit that allows for 2D and 3D visualisation, a GUI for model manipulation, as well as image and video output.

- MASON simulations can be decoupled from real-time visualizations, allowing for simulation batched to be run much faster.
- MASON has multiple extensions, including a Social Network Analysis (SNA) extension (Wasserman & Faust, 1994) and a GIS extension, GeoMASON (Coletti, 2012), that adds support for vector and raster geospatial data import, spatial reasoning, distance calculations, coverage determination and other functions.
- Output files can be created and exported in formats that can be used by third-party analysis packages.
- MASON comes packaged with an extensive tutorial guide, online support network and user group.

Platform / Tool **-----------** **License**	**Primary Domain**	**Type of Agents / Interaction Behaviour**	**Source Code** **-----------** **Operating Systems Supported**	**GIS Capability**	**Modelling Strength / Scalability**	**Model Development Effort Needed**
AnyLogic www.anylogic.com **-----------** Closed source, Proprietary	General purpose. Supports Discrete Event and System Dynamics Simulations	Agents / Objects implemented as Java classes	Java **-----------** Windows 8, 7, Vista; Mac OS X 10.7.3; Ubuntu Linux 10.04	Yes: supports tile maps from online providers and shapefiles	High / Large-scale	Moderate
CORMAS https://cormas.cirad.fr **-----------** MIT	Social and Natural Science Simulations of evolving multi-Agent systems	Agents / Objects implemented as class constructs	VisualWorks **-----------** Windows; Mac OS X; Linux	Yes: supports both vector and raster shapefiles	Medium- to Large-scale	Moderate
MASON https://cs.gmu.edu/~eclab/projects/mason/ ----------- Academic Free License (open source)	General purpose, social complexity, abstract modelling	Agents / Objects implemented as Java classes	Java **-----------** Windows; Mac OS X; Linux	Yes	Medium- to Large-scale	Complex/Hard

NetLogo http://ccl.northwestern.edu/netlogo/ ----------- GPL	Social and Natural Science	Active objects as mobile Agents with simple goals	Any JVM v.5 or later ----------- Windows; Mac OS X; Linux, Unix	Yes	Medium- to Large-scale	Simple/Easy
Repast (Simphony) https://repast.github.io/repast_simphony.html ----------- GPL	Social sciences	Reactive/Belief-Desire-Intention object-orientated Agents	Java ----------- Windows; Mac OS X; Linux	Yes	High / Large-scale	Complex/Hard
Swarm www.swarm.org ----------- GPL	General purpose	Collections (swarms) of independent object-orientated Agents, Discrete Event interactions	Java; Objective-C ----------- Windows; Mac OS X	No	High / Large-scale	Complex/Hard

Table 32: Comparison of various agent-based modelling and simulations (ABMS) tools (adapted from Abar et al. (2017)

11.4 INFORMATION ON ALTERNATIVE MODELLING METHODS

MATHEMATICAL MODELLING

Mathematical modelling represents the 'traditional' approach to examining systems within the social sciences (Diaz, 2010). These macro-simulations utilise differential equations, for example, to minimize route complexity (Yuan & Wang, 2009), analyse evacuation routes in transportation networks (Stepanov & Smith, 2009), examine the impact of population demands and routing capacities on evacuation routes (Ng & Waller, 2010), optimise disaster response logistics operations (Afshar *et al.*, 2012), and examine the pre-positioning of hurricane supplies in commercial supply chain logistics (Lodree, Ballard & Song, 2012).

However, the majority of models listed are limited by the difficulty of deriving model constraints and the complexities and inaccuracies inherent within mathematically representing project elements. In addition, Grüne-Yanoff (2017) points to the assumption of homogeneity within many mathematical models. The author illustrates this with the example of Kaplan *et al*. (2002) who simulate an attack of 1,000 initial smallpox cases on a population of 10 million agents that all share the same probability of having contact with non-infected agents and the same movement attributes. It is this contact pattern and implausible population homogeneity that motivated the development of agent-based models.

DISCRETE EVENT SIMULATION (DES)

A modelling methodology often utilised by studies focusing on temporal aspects is discrete-event simulation (DES), which is a process-orientated methodology where events are arranged as a discrete sequence in time and is well-suited to study relationships/entities that are affected by such events and in turn create new events. This is, arguably, how crisis events evolve and DES has been shown to be a useful technique for modelling explicit situations within restricted systems (Gonzalez, 2012). For example, Aaby *et al*., (2006) examined the geospatial optimization of points of delivery of health products during an influenza epidemic using DES. DES has been used extensively within operations management of emergency rooms (see: Jun *et al*., 1999; Connelly & Bair, 2004; Duguay & Chetouane, 2007) but has seen limited use within the simulation of broader scale events that impact multiple systems.

DES represents a chronological sequence of events that mark changes in state within the system under review; it is most easily understood as a queuing model. It is this focus on the temporal aspects of a system, to the exclusion of the spatial, that limit the use of DES within the emergency management sector, where spatial context is paramount (Crooks & Wise, 2013).

SPATIAL DECISION SUPPORT SYSTEMS (SDSS)

Spatial decision support systems (SDSS) are interactive GIS-enabled decision support systems (DSS) that graphically display database management systems and analytical models to evaluate and support complex spatial problems (Densham, 1991). Much of the related SDSS literature focuses on determining optimal site locations for, for example, shelters and emergency service sites during urban evacuation planning (Esmaelian *et al.*, 2015) or landfill and waste disposal sites (Ferretti, 2011). Others have utilised SDSS to evaluate vehicle or evacuee routing. For example, Castle and Longley (2005) utilized SDSS coupled multiple pedestrian movement simulations to model and evaluate a number of evacuation scenarios during a range of crises, including fires and terrorist attacks. Similarly, (Ling *et al*., 2009) developed, Blue Arrow, a web-based SDSS to aide emergency response personnel during evacuation planning by providing highly customisable route planning with turn-by-turn instructions. More recently, SDSS has been utilised to monitor hazardous areas and assist decision making during emergency situations. For example, Horita *et al*., (2015) developed a web-based SDSS that integrates volunteered geographic information (VGI), specifically Twitter content, for flood risk management that was tested during a real-life flood event in in São Calos, Brazil.

de Silva (2001) discusses the complexities related to creating SDSS and identifies challenges that are not exclusive to SDSS but are prominent within its use to model crises. Particularly, the author points to the challenges inherent within the integration of multiple technologies (GIS, simulation models, and database management), data streams (geospatial, volunteered, and temporal) and managerial and behavioural processes when aiming to achieve a "realistic, usable and reliable decision-support tool" (de Silva, 2001: 12) that can be used in complex evolving emergencies. Further, de Silva (2000) highlights challenges related to the generation of realistic crisis scenarios, in particular evacuee behaviour, within SDSS;, the limited inclusion of agent-to-agent relationships; and the validity of assumptions made during the design of SDSS and SDSS themselves.

SYSTEMS DYNAMICS (SD)

Systems dynamics (SD) is an equation-based modelling technique used to examine the dynamic behaviours and mechanisms of complex systems over time to better understand cause and effect. SD models often focus on system element interactions and non-linear relationships and incorporate feedback loops and temporal elements such as time delays. Although SD models are increasingly including the examination of space and time, SD models are inherently aspatial and generally lack the ability to simulate agent-to-agent interaction (Gilbert & Troitzsch, 2005), a critically important aspect of many emergency scenarios (Crooks & Wise, 2013). Fawcett and Oliveira (2000) present a SD model of casualty treatment after an earthquake that aims to capture the impact of both time *and* space, but spatial context is limited to statistical data of populations and resources in administrative areas.

Keenan and Paich, (2004) use SD to examine General Motors' *Enterprise Model* of the North American car market. In their model they are required to simulate the engineering, manufacturing and marketing processes but also consumer demand and market competition. The authors outline their design processes and model results, namely forecasts of production volume, market share and profitability. The authors conclude that SD is too restrictive for their model needs. Uncertainty is a key issue in the car industry and must be factored in to the model and the authors explain that given the scale of the problem being examined (10^9 consumer options [assuming up to 3 cars per household], 10^7 consumer choice computations with a further 10^3 alternatives) an SD approach is unwieldy and time consuming (both programmatically and in terms of model processing and run times). The authors then outline a hybrid SD/agent-based approach to their model and conclude that using ABM to model cars and households individually will improve the model's processing and applicability without the need to sacrifice model complexity.

SD models are well suited for many research questions, particularly those focusing on non-linear temporal system elements, but are not appropriate for the spatiotemporal emergency response systems where interaction is important (Crooks & Wise, 2013).

MICROSIMULATION MODELS (MSM)

Microsimulation models (MSM) simulate the actions and interactions of low-level entities, such as individuals and vehicles, and can be dynamic or static in nature. Each entity within the MSM is assigned a set of attributes (*e.g*. age, speed *etc*.) and rules and then the aggregate changes are examined (Dawson, Peppe & Wang, 2011). MSM are therefore commonly used to examine the impact of policy changes within systems. MSM have been used to simulate, for example, disease transmission (Brouwers, 2005; Sander *et al.*, 2009), evacuation (Chen, 2008), and flood management (Brouwers, 2005; Saadi *et al.*, 2014). However, while MSM do focus on individuals, they rarely consider the relationships between individuals and the evolution of these interactions and the resultant changes in behaviours (Gilbert & Troitzsch, 2005). MSM utilises a "top-down" approach, with modelled behaviours based upon statistical estimates from aggregated data and are not the result of local rules (Epstein & Axtell, 1996). Further, although MSM do exist that include a detailed and explicit spatial dimension (*e.g*. Birkin & Clarke, 1987; Clarke & Holm, 1987) few such models were found that focused on emergency response and relief.

COMPANION MODELLING

Companion modelling (or 'ComMod'), which is essentially a clone of participatory modelling developed by (Bousquet *et al.*, 1999) while developing multi-agent simulations for resource management, has been particularly well received in studies that focus on the process of modelling or co-learning exercises in developing countries (see: Becu *et al*., 2003; Voinov & Bousquet, 2010; Campo *et al.*, 2010; Worrapimphong *et al.*, 2010). ComMod studies engage with key stakeholders and co-produce research questions and develop models via workshops where stakeholders often interact directly with the model during its development. Salvini *et al.* (2016) utilised participatory rural assessment exercises and interviews to develop a role-playing game (RPG) to understand land-use choices among farmers in rural Vietnam. Farmers then played the RPG and researchers examined the decisions they made following various scenarios and interventions and adapted the findings to produce a set of behavioural rules for their ABM. Le Page *et al*. (2015) examined bushmeat hunting in Cameroon. The authors started with a small-scale abstract model and used participant feedback from a series of workshops to develop an increasingly detailed and large-scale ABM of the entire forest system. Such ethnographic approaches to modelling (see also: Barreteau *et al.*, 2014; Moglia *et al.*, 2010; Naivinit *et al.*, 2010; Souchere *et al.*, 2010; Washington-Ottombre *et al.,* 2010) can capture detailed decision-making structures within small groups that can be used to construct a decision-tree for the resultant model (Gladwin, 1992; Orr, Mwale & Saiti, 2002). In contrast, standardised surveys, such as censuses, can provide context to decisions that are made by a larger number of individuals across a broader context. However, the decision-trees created from such data are invariably open to scrutiny as they capture only a small component of an individual's decision-making process, offering up an incomplete and imperfect representation of real-life and the gaps that are present within the decision structure are open to interpretation (Bell, 2017).

Results of ComMod studies have shown the value of participatory or co-production modelling, namely the facilitation of discussions and presentations, the feedback process and the expedient model amendment and development process that this provides (Voinov & Bousquet, 2010). However, as noted by Bell (2017), this richness of data and input is likely to increase project costs, extend the time needed and result in a project that may only be representative of the system and participant group being examined.

11.5 FURTHER ABM INFORMATION

Schelling's (1978) segregation model is a perfect example of how to balance abstraction with realism. The model consisted of two groups of agents that sort themselves across a grid-based environment based upon their preferences on neighbourhood composition. Despite the model being abstract, it demonstrated the complex societal phenomena of self-segregation when even tolerant agents chose to self-segregate over time. As ABM has developed so too have Schelling's Dynamic Models of Segregation, with researchers expanding the number of agent classes in the model and utilising real-world demographics. For example, Paolillo and Lorenz (2018) extended Schelling's model by introducing a range of value- and ethnicity-oriented agents to examine ethnic segregation, value segregation, and population density and Fossett and Dietric (2009) included realistic geography to test the effects of city/neighbourhood size, shape, and form. Similarly, Epstein *et al.* (2008) took a simple epidemic model that assumed perfect mixing and fixed behaviour of the environment and endowed agents with adaptive behaviour whereby they move to disease free zones to avoid the disease. The behaviour that emerged from this simple model was found to closely mirror the dynamics observed during the 1918 Spanish flu and other historical epidemics (Bruch & Atwell, 2015).

For example, Schelling's (1971: 149) microeconomic "spatial proximity model" of neighbourhood segregation is ABM's formative study and demonstrated the power of computer simulation to represent populations, interactions and socially relevant processes and computationally model recognisable emergent macro-level social phenomena from few predefined low-level interactions. Later, Epstein and Axtell (1996) developed their 'Sugarscape' model which extended the earlier work of Schelling to develop entire artificial societies that demonstrated rudimentary societal characteristics such as death, disease, trade and conflict. In contrast to Schelling's work, Epstein and Axtell's models utilised much greater behavioural specificity at the individual level to understand macro-level patterns (Silverman *et al.*, 2013). Such "low-dimensional realism" models incorporate one or more elements of realism, but keep other aspects of the model, particularly it's graphical representation, abstract (Bruch & Atwell, 2015).

These models are primarily used for the testing of assumptions or exploring the implications of wider empirical research (*ibid*).

Within urban planning, UrbanSim (Waddell, 2002) represents a highly developed "virtual laboratory" to analyse city infrastructure and investment policies (Borning, Waddell & Förster, 2008). The model is built upon a vast range of empirically grounded process modules that cross the many levels of the urban environment (Bruch & Atwell, 2015). For example, at the individual level, data is provided to improve the realism within agent decision-making regarding work and home location, transport choices and employment decisions. Moving up a level, the development and relocation of organisations within the model is based upon real-world business data. Infrastructure within the model, including transport and land use, is grounded in real-world data and produces a realistic geographically-accurate simulated landscape (Bruch & Atwell, 2015).

When first developed in the late 1990s, UrbanSim departed from the trend of modelling high-level aggregated geography and large homogenous groups of agents and focused on representing individuals within the model. As demands on the model increased with the need to include more data and represent increasingly complex and growing urban areas, researchers had to balance the desired level of spatial aggregation and agent representation with the need to effectively visualise and model urban systems and the availability of computational power. UrbanSim remains an agent-level simulation, but unlike most ABMs, does not focus on the interactions of adjacent agents, instead favouring to represent key agents (households, buildings *etc*.) and locations (land areas) as parcels (gridcells or zones) within the model. This raster-like modelling allows for easier inclusion of location-based socioeconomic factors at a disaggregate level, but can complicate model validation (Dasigi, 2015). UrbanSim has been used to guide urban decision-making in major US and European cities, including land-use zoning and transportation accessibility in Utah, US (Waddell & Nourzad, 2002), housing market analysis in Paris, France (de Palma *et al.*, 2007; de Palma, Picard & Waddell, 2007, 2005) and sustainability policies in Brussels, Belgium, Zurich, Switzerland (Bierlaire *et al.*, 2015).

11.6 FINAL MODEL FOLDER STRUCTURE

```
EngD_ABM/
  src/
    comparators/                    // distribution strategies
      AidLoadDistanceComparator.java
      AidLoadOSVIComparator.java
      AidLoadPriorityComparator.java
      AidLoadRandomComparator.java
    objects/
      AidLoad.java                  // defines basic load functions
      Driver.java                   // main model Agents
      Headquarters.java             // home base/depot
    sim/
      EngDModel.java                // main model code
      EngDModelWithUI.java          // GUI mode for main model
      Polygon.java                  // reads, displays OSVI polygons
      ScenarioRunner.java           // model run scheduling
    utilities/
      DriverUtilities.java          // defines basic Agents functions
      HQUtilities.java              // defines basic HQ functions
      InputCleaning.java            // cleans and tests shapefiles
      RoadNetworkUtilities.java     // cleans and tests road network
  data/                             // shapefiles and CSVs
    BRC_HQ_Gloucestershire.shp
    Flood_Zones.shp
    Gloucestershire_Centroids.shp
    Gloucestershire_Road_Network.shp
    OSVI.shp
    …
  lib/                              // required Java archives
    mason.jar
    openCSV.jar
    geomason.jar
    …
```

11.7 MODEL PROCESS & STRUCTURE DIAGRAMS

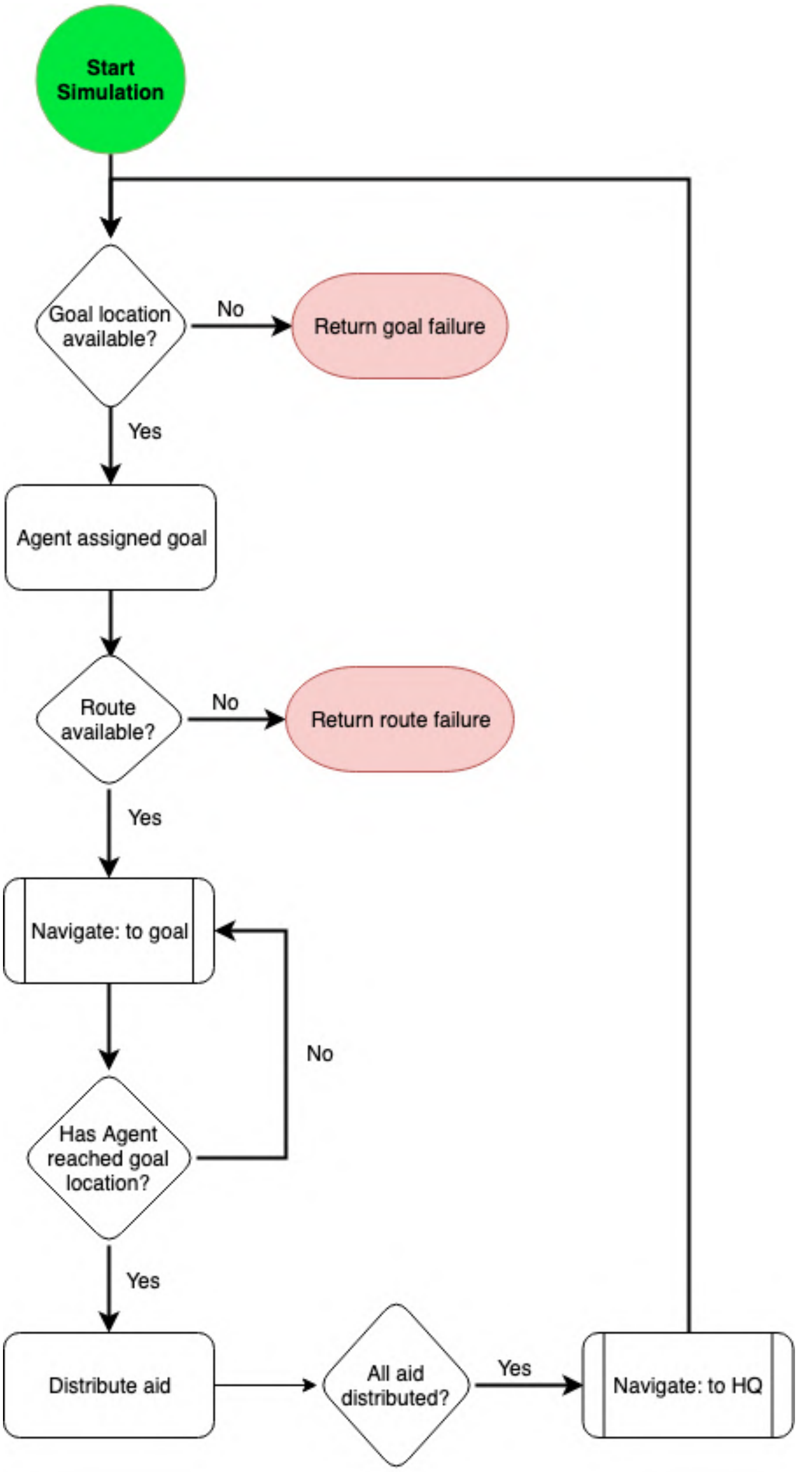

Figure 81: Outline of generic relief distribution model process used in model iterations MK_0 to MK_5

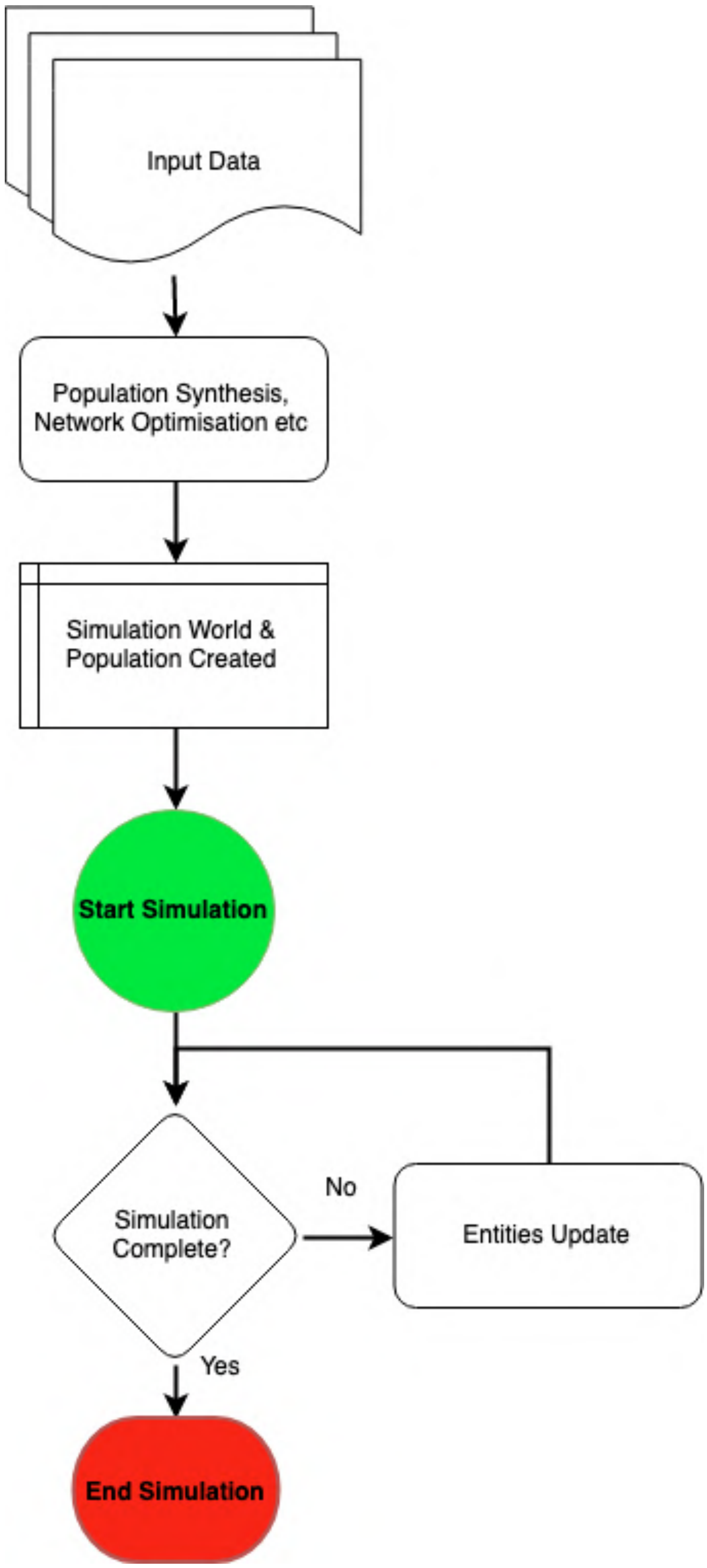

Figure 82: Outline of generic model structure used in model iterations MK_0 to MK_5

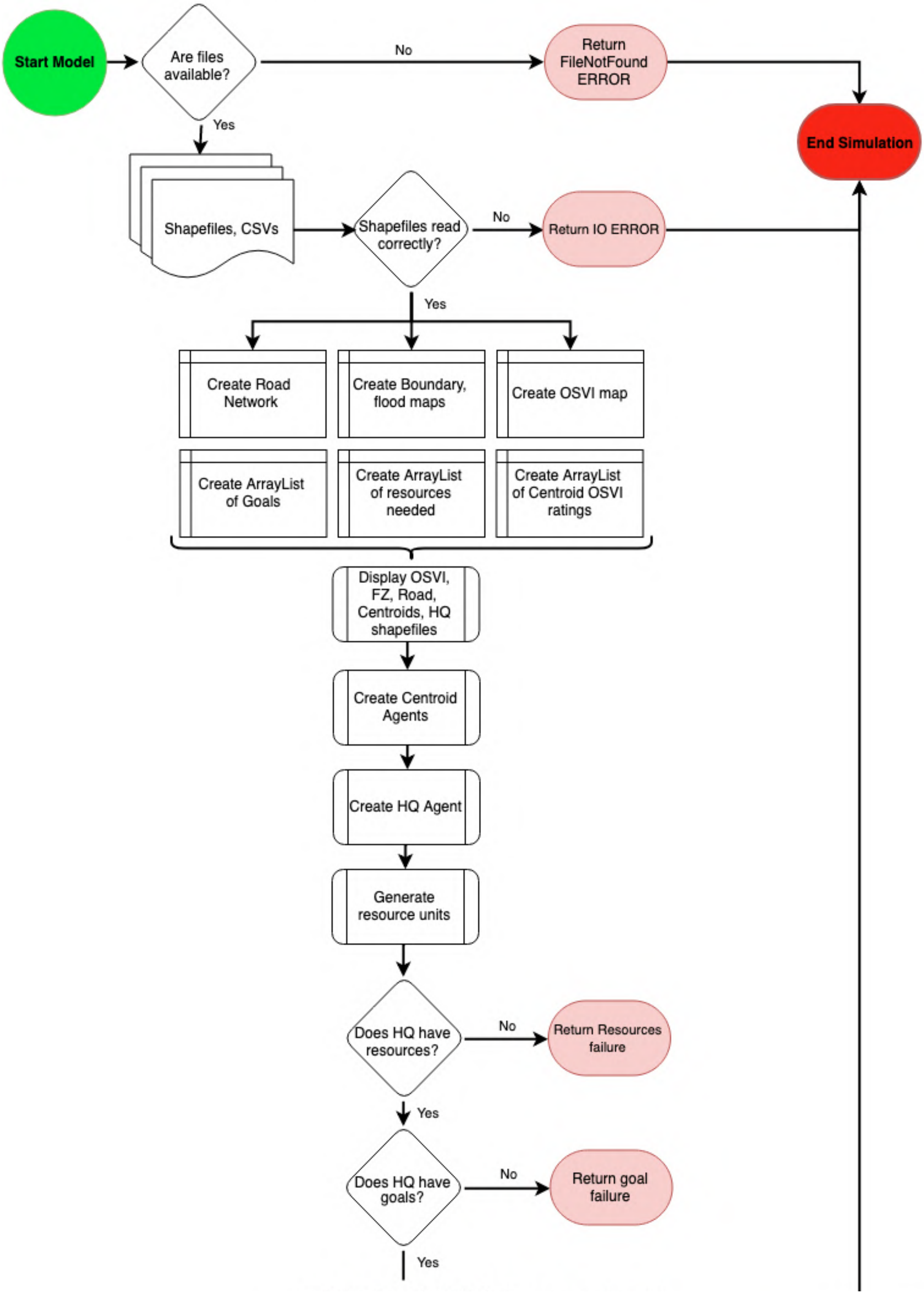

Figure 83: Redesigned model process used in model iterations MK_6 to MK_8 (continued on next page)

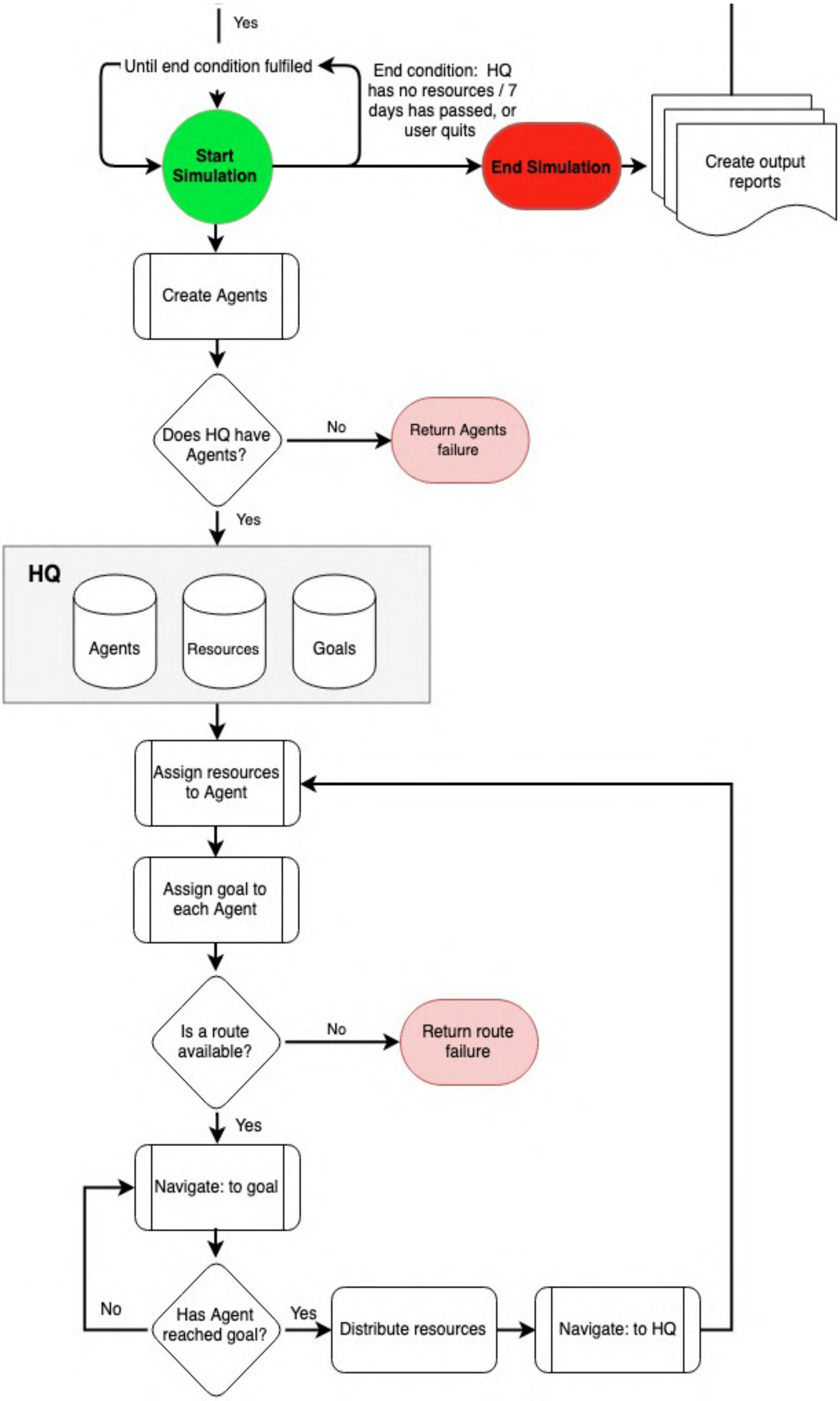

Figure 84: Redesigned model process used in model iterations MK_6 to MK_8 (continued)

11.8 A FRAMEWORK FOR VALIDATION

Bayarri *et al.,* (2007) present a six-step procedure that enables computer model evaluation oriented towards answering the question: *Does the computer model adequately represent reality?*

Understanding the Model and Its Uses

1. **Specify model inputs and parameters with associated uncertainties or ranges - the Input/Uncertainty (I/U) map**. This step requires considerable expertise to help set priorities among a (possibly) vast number of inputs. As information is acquired through undertaking further steps of the validation process, the I/U map is revisited, revised and updated.
2. **Determine evaluation criteria**. The defining criteria must account for the context in which the model is used, the feasibility of acquiring adequate computer-run and field data, and the methodology to permit an evaluation. In turn the data collection and analyses will be critically affected by the criteria. Moreover, initially stated criteria will typically be revisited in light of constraints and results from later analyses.

Data Collection

3. **Data collection and design of experiments**. Both computer and field experiments are part of the validation (and development) processes; multiple stages of experimentation will be common. The need to design the computer runs along with field experiments can pose non-standard issues. As noted above, any stage of design must interact with the other parts of the framework, especially the evaluation criteria.

Model Approximation

4. **Approximation of computer model output**. Model approximations (fast surrogates) are usually key for enabling the analyses carried out in Step

5; fast surrogates are essential also when the model is used for optimization of *e.g.,* a manufacturing product design.

Analysis of Model Output

5. **Analyses of model output; comparing computer model output with field data.** Uncertainty in model inputs will propagate to uncertainty in model output and estimating the resulting output distribution is often required. The related 'sensitivity analysis' focuses on ascertaining which inputs most strongly affect outputs, a key tool in refining the I/U map.

   Comparing model output with field data has several aspects.

   - The relation of reality to the computer model ("reality = model + bias")
   - Statistical modeling of the data (computer runs and field data where "field data = reality + measurement error")
   - Tuning/calibrating model input parameters based on the field data
   - Updating uncertainties in the parameters (given the data)
   - Accuracy of prediction given the data

   The methods used here rely on a Bayesian formulation; the details are in Section 5. The fundamental goal of assessing model accuracy is addressed there.

Feedback; Feed Forward

6. **Feedback information into current validation exercise and feed-forward information into future validation activities.** Feedback refers to use of results from Step 5 to improve aspects of the model, as well as to refine aspects of the validation process. Feed-forward refers to the process of utilizing validations of current models to predict the validity of related future models, for which field data are lacking.

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