Risk Analysis for Flood Event Management: Integrated Modelling of Hydrodynamics and Human Responses

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Dedication

I DEDICATE THIS THESIS TO GOD, THE LORD

The Lord is my shepherd, I lack nothing.
He makes me lie down in green pastures,
he leads me beside quiet waters,
he refreshes my soul.
He guides me along the right paths for his name's sake.
Even though I walk through the darkest valley,
I will fear no evil,
for you are with me;
Your rod and your staff,
They comfort me.
Psalm 23:1-4

Abstract

Flood risk management seeks to reduce flood consequences and probability by considering a wide range of options that include non-structural measures such as flood event management. Quantitative flood risk analysis has provided a powerful tool to support appraisal and investment in engineered flood defence. However, analysing the risks and benefits of non-structural measures have been limited making it difficult to compare the benefits of a wide range of options on a shared assessment platform. A major challenge to understand the performance of non-structural measures during a flood event is the complexity of analysing the human responses in the system that determines the successful operation of flood event management.

Here presents a risk analysis approach that couples a multi-agent simulation of individual and organizational behaviour with a hydrodynamic model. The model integrates remotely sensed information on topography, buildings and road networks with empirical survey data and information on local flood event management strategies to fit characteristics of specific communities. The model has been tested in Towyn, North Wales, and subsequently used to analyse the effectiveness of flood event management procedures, including flood warning and evacuation procedures in terms of potential loss of life , economic damages and the identification of roads susceptible to congestion. The potential loss of life increases according to the magnitude of a storm surge (e.g. 11 for 1 in 100 years surges as opposed to 94 for 1 in 1000 surges). Providing 3 hours flood warning can reduce this by 67% if individuals take appropriate action. A global sensitivity analysis shows that hydrodynamic processes are only responsible for 50% of the variance in expected loss of life because actions taken by individuals and society can greatly influence the outcome. The model can be used for emergency planners to improve flood response in a flood event.

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Acronyms

ABM	Agent-Based Model
ANUGA	A hydraulic model developed by Geoscience Australia
CA	Cellular Automata
CCA	Civil Contingencies Act
CCBC	Conwy County Borough Council
CCU	Civil Contingencies Unit
CFD	Computational Fluid Dynamics
CREAM	Cognitive Reliability and Error Analysis Method
DEFRA	Department for Environment, Food & Rural Affairs
DEM	Digital Elevation Model
EA	Environment Agency
Egress	Pedestrian evacuation simulation software developed by ESR Technology
Esri	ArcGIS software company
ERS-1	European Remote-Sensing Satellite
EXODUS	evacuation simulation and pedestrian dynamics/circulation analysis software by University of Greenwich
FA	Fire Authority
FCR	Flood control room
FEM	Flood Event Management
FHRC	Flood Hazard Research Centre
FIPA ACL	The Foundation for Intelligent Physical Agents (FIPA) Agent Communication specifications deal with Agent Communication Language (ACL) messages, message exchange interaction protocols, speech act theory-based communicative acts and content language representations

FIM FRAME	A research project was undertaken by HR Wallingford Ltd
FLOODSite	EU Project on Integrated Flood Risk Analysis and Management Methodologies
Flowroute-i_{TM}	A hydraulic model developed by Ambiental Ltd.
FRM	Flood Risk Management
GIS	Geographic Information System
GridFlow	Evacuation simulation software developed by BRE Ltd.
GSA	Global sensitivity analysis
HBS	Human Behaviour Simulator
HCM	Highway Capacity Manual
HDS	Hydrodynamic Simulator
HEP	Human Error Probability
HLLC	Harten-Lax-van Leer-Contact Riemann solver
HR	Hazard rating
HRA	Human Reliability Analysis
InfoWorks ICM	A hydraulic model developed by Innovyze company
ISIS	A hydraulic model developed by Halcrow
JFLOW+	A hydraulic model developed by JBA Consulting Ltd.
LA	Local Authority (agent)
LandMap	Dataset provided by GeoInfomation Group
LISFLOOD-FP	2D diffusion hydrodynamic simulation model developed by Dr Paul Bates, Bristol University
LOS	Level of service
LRF	Local Resilience Forum
MACG	Multi-Agency Control Group
MAFP	Multi-Agency Flood Plan
MASSVAC	A mass evacuation simulation software

MCM	The Multi-Coloured Manual and Handbook by FHRC
MIKE FLOOD	A hydraulic model developed by DHI
Netlogo	Agent-Based Model software chosen as the development platform for this research developed by North Western University, USA.
NewChan	Shallow 2D hydrodynamic simulation model developed by Dr Qiuhua Liang, Newcastle University
NWFS	North Wales Fire Service
OAT	One-at-a-time sensitivity analysis
OD	Ordnance Datum
OS	Ordnance Survey
PA	Police Authority (agent)
PPS25	Planning Policy Statement 25: Development and Flood Risk
PSA	Probabilistic Safety Assessments
RAM	Risk Analysis Module
RAM	Random-access memory
RFSM	A hydraulic model developed HR Wallingford Ltd
SA	Sensitivity Analysis
SES	Social Economic Status
SAR	Synthetic Aperture Radar
SCG	Strategic Co-ordinating Group
SOBEK	A hydraulic model developed by Deltares
SPRC	Source-Pathway-Receptor-Consequence model
SWE	Shallow Water Equations
TRC	Time Reliability Correlation
THERP	Technique for Human Error Rate Prediction
TUFLOW suite	A hydraulic model developed by BMT WBM
UA	Uncertainty Analysis

UIM	A hydraulic model developed by University of Exeter
UNISDR	The United Nation Office for Disaster Risk Reduction
USDA	United States Department of Agriculture
XPSTORM	A hydraulic model developed by Micro Drainage Ltd

Chapter 1. Introduction

1.1 Research background and the context of the study

Flooding is one of the most significant risks to people and the economy in the UK and internationally. The magnitudes of the impacts from any given flood are heavily modulated by the response of individuals and organisations. The research presented in this thesis explores human factors as important components of flood risk management. This is no simple task because:

Human responses in the event of a flood are complex. They not only include residents' individual responses but also multi-organizational responses to the flood. The complexity of analysing the human system responsible for the emergency management means the research in this area is very limited.

Human factors impacting on flood risks are implicit. As important mediators, human factors are pervasive within the whole flooding system, from flood defences maintenance to flood rescuing. On many occasions, human factors are tightly coupled with structural measures.

The impact of human factors is rarely quantified or integrated into the probabilistic flood risk analysis process due to its close relationship with the social, economic and demographic characteristics of the flooded area.

Quantifying the impact of human factors is achieved through considering the possibility and practice of using social simulation techniques to integrate the human responses and actions undertaken during a flood event into a risk-based framework. Moreover, this approach enables non-structural flood event management measures to be appraised on the same basis as more traditional structural flood risk management measures.

The introductory chapter first introduces the key challenges and relevant background information to the research presented in the rest of this thesis, before setting out the aim and objectives and finally describing the structure of the thesis.

Impacts of floods

Flooding is a recurring disaster that threatens people's lives and homes. In the UK, flooding is the second highest natural disaster risk after a flu pandemic (Harvey, 2013). Over 5 million people in more than two million homes are at risk of flooding in the UK, with 1.6 million people at high risk. Further, one in six homes is at risk of flooding (Environment Agency, 2011). Under the circumstances of climate change and social-economic development, this has become an even more serious issue. Climate change models show that floods that occur once in every 100 years today may happen once every ten years by the end of the century (Adaptation Sub-Committee, 2012). Meanwhile, due to population growth and spatial expansion, the flood vulnerability of our society is also set to increase (Siegrist and Gutscher, 2006). In October 2000, extremely heavy rainfall led to flooding inundation which seriously devastated South East England. Infrastructure and roads were destroyed; traffic and power supplies were interrupted, and the total economic loss was estimated to be 100 million pounds. In June and July 2007 the extreme flooding that affected England and Wales was ranked as one of the most expensive occurrences in the world, as 55,000 properties were flooded. Around 7,000 people were rescued by the emergency services and 13 people died (Pitt, 2008). Between 1998 and 2005, the insurance industry paid out £7.2bn in weather damage claims in the UK, of which £3.5bn was for storm and flood damage (Natural Environment Research Council, 2011). Furthermore, in 2007 alone more than £3bn in claims was processed due to the flood. In 2012, an exceptional flood struck the whole of the UK, from Yorkshire to Devon, Wales to Tyne. The floods overwhelmed more than 8,000 homes and businesses after one of the wettest years on record. Reports show that 2012 was the costliest flood year for insurers since 2007 (Benfield, 2012). The severe floods that have affected many areas in recent years remind us of the rising flood risk in the UK (House Of Commons, 2013).

Flood risk management

In ancient times, people took measures to mitigate flood risks. In China, legendary ruler Da Yu (2200-2100 BC) made great efforts to dredge river beds and devised a system of irrigation canals that guided floodwater into fields instead of directly damming the flow of rivers. The flood control system was crucial to establishing the prosperity of the Chinese heartland (Sima, 109-91BC). In the 13th century, in the Netherlands, flood defences (dykes) were constructed and the organisational structures to maintain these dykes, the so-called water boards, were introduced (Jonkman, 2007). Throughout this period, the development of flood protection systems and regulations was accompanied by the lessons learned from the floods as well as the introduction of new technologies.

The technique of quantitative risk analysis has been applied in flood management for decades. A flood risk is defined as a product of hazard, exposure and vulnerability (Kron, 2003) and flood risk management (FRM) starts from a depiction of the whole flood system and then the key elements of the flood system are defined and explored (Hall and

Solomatine, 2010). For quite a long time, flood risk management was limited to flood defences until the most recent integrated risk-based frameworks were developed (Sayers *et al.*, 2002b; Hall *et al.*, 2003b).

Risk analysis provides a rational basis for appraising different flood protection options in terms of expected damage and expenditure and has become a prerequisite for major policy and decision-making in relation to flood management. For example, PPS25 requires flood risk to be taken into account at all stages of the planning process to avoid inappropriate development (Department for Communities and Local Government, 2009). The 2010 Flood and Water Management Act is set within the context of the overall flood risk management hierarchy.

For this study, the most significant influence of the integrated flood risk management concept is that it initiates flood risk analyses on the people and assets that are impacted – often referred to as 'Receptors'. People learn about and respond to flood risk in ways that can increase or mitigate impacts. This should be taken into account when assessing the flood risk – although this requires the use of approaches that are not familiar to flood risk managers as people do not follow physical laws in the same way as water. In addition, for flood risk mitigating measures, non-structural measures such as government policy, land-use planning, flood warning and insurance should also be considered (Meyer *et al.*, 2012). To date, there has only been limited the development of approaches that can appraise both structural and non-structural measures quantitatively using a common platform.

Finally, integrated flood risk management highlights the dynamic and continuous approach of flood management. Flood risk reduction during a flood event is a significant mediator of flood impacts. Thus, there is an urgent need to align flood event management into a broader flood risk management framework which is currently focused on long-term strategic decision-making (Evans *et al.*, 2004a; Evans *et al.*, 2004b; Woodward, 2012). Knowledge of short-term risk analysis for flood event management has to be improved (Vat *et al.*, 2007).

Flood event management

Flood event management (FEM) is increasingly recognised as an important component of flood risk management. Flood event management refers to the human response to mitigate flood risks during flood events, and pre-flood preparations closely related to human emergency responses in the flood event such as planning and flood warning. FEM is a complex system because it involves the interactions among the physical processes of a flood, individuals and multiple organisations involved in flood event management.

Human responses are important mediators of FEM, they alter the effectiveness of non-structural measures such as flood warnings and flood evacuations. Studies show that household behaviour is a significant factor that affects the efficiency of a flood evacuation plan; the evacuation rates are associated with households' demographic features such as age, gender, social class and even having children and pets or not (Enarson and Scanlon, 1999; Heath *et al.*, 2001). In New Orleans after the 2005 Hurricane Katrina, over 1,100 people died despite 80–90% of the population being evacuated (Wolshon, 2006). Among the people who do not evacuate, 77% of them had spent their whole life in the city, and more than one-third (34%) of them lacked a means of transportation. In his influential review after the 2007 UK floods, Sir Michael Pitt (2008) pointed out that flood risk management needed to move on from hard defences to softer approaches, the importance of emergency response should be particularly stressed.

Making decisions and taking action during a flood event is particularly challenging due to the limitations of time, resources and the uncertainties of flood hazards adding to the difficulties of multi-agency cooperation. A transparent and auditable risk-based tool, as proposed in this thesis, can help to support decisions and identify investment priorities.

Computer simulation of human agency

Computer simulation has been widely used to support disaster management to help identify the benefits of prevention measures and potential problems (e.g. overcrowded evacuation routes) through the analysis of simulation outputs. Computer simulation models offer the ability to test a wide range of different disaster scenarios and emergency plans that it may not be possible or too expensive to field-test. Some reliable and efficient computer models have been successfully applied to simulate disaster evacuation such as Egress, GridFlow and EXODUS (Johnson, 2005). However, these models have focused on small areas such as an airport, ship or building. Few models can simulate mass evacuation movements in large spatial areas such as a town.

Even less work simulated human response in the context of a flood event. Meanwhile, it is not appropriate to directly transfer fire (or another disaster) models because human behaviour in a flood event has its unique features by comparison. Unlike the occurred in a fire, people's decision making in a flood event is often well thought out. Panic only sets in when their stress exceeds their psychological strength (e.g. perhaps in a flash flood). Some notable efforts to simulate flood evacuation will now be considered briefly. MASSVAC simulates population evacuation under the threat of flooding as a result of dam failure (Alsnih and Stopher, 2004). It looks at the evacuation process on the network by focusing on major road arteries at the macro level. The research implies that the computer simulation would significantly enhance the potential for flood emergency management. However, the simulation represented a different type of flood, a dam failure and only represented a limited part of the transportation system. Simonovic and Ahmad (2005) implemented a computer-based dynamic simulation model for flood evacuation emergency planning; the model simulated the procedure of Red River Valley citizens' flood evacuation behaviour. People's decision processes and flood responses were simulated. Similarly, Kanno (2006) set up a multi-agent simulation system to simulate organizational behaviour in the flood event. However, due to the nature of these models, the emergent character of human behaviour and their spatial features in flood events are not captured. For example, they are unable to identify roads that are likely to be congested in the flood evacuation.

Notably, these existing models do not accurately take into account flood water dynamics and possible interactions between flood and human behaviour. Modern 2D hydraulic models with different numerical solutions can now yield accurate and fast simulations for urban flooding (Liang and Marche, 2009). The integration of the human behaviour model with the hydrodynamic model is a challenge in this thesis.

In summary, FEM has been recognized as an important component in flood risk management. However, existing flood risk analysis methods are mainly for long-term strategic flood risk management and lack of capabilities of quantitatively evaluating non-structural measures that are mainly used in the flood event. Therefore, for integrating FEM into FRM, a method that can quantitatively represent the role of non-structural measures should be developed, which hinges on how to quantify the effect of human factors attached to non-structural measures.

1.2 Research aim and objectives

The aim of this research is, therefore, to develop an approach to appraising the benefits of flood event management that is compatible with existing risk-based approaches to appraising structural flood defences and thereby answer the following questions:

1. Can the effectiveness of non-structural flood event management be measured quantitatively?

2. How much can human actions during a flood event affect flood impacts?
3. Can the flood risk management benefits of human, structural and other factors be compared within the same framework?

To achieve this aim and to answer these questions this work has the following key objectives:

1. Review emergency flood management planning and previous flood event response studies to understand the different actions and interactions that occur during a flood.
2. Review approaches to representing human behaviour from a wide range of applications, which are not just limited to flood event management.
3. Develop a conceptual model to describe human behaviour during a flood event.
4. Constructing a coupled hydrodynamic human behaviour simulation model that can explore a wide range of flood scenarios and test a range of individual and organisational flood event responses.
5. Adapt methods to calculate flood risk to be appropriate to the short (relative to the usual approach of Expected Annual Damages) time horizons relevant to flood event management.
6. Evaluate the benefit of non-structural measures using the FEM and appraise the emergency flood decision-making options.
7. Conduct a sensitivity analysis to explore the relative importance of different flood event management actions.

As will be shown in this thesis, the research supports flood event management in four ways. First, the new approach helps to identify the benefit of non-structural measures and the importance of human factors in the flood event. Second, it supports the development of FEM plans through the identification of vulnerable parts of the road network and areas that are liable to congestion during evacuation. Third, the risk analysis tool can provide a framework for assessing the benefits of flood event management decisions involving non-structural measures. Finally, this type of simulation tool can be used for emergency training and exercise with the aim of improving responders' capabilities in flood emergency response. A cogent motive for developing the simulation-based approach is because FEM is a procedure that involves many organisations and potentially thousands of residents, any "real-world" simulation exercise is costly and time consuming (e.g. Exercise Triton) (Environment Agency, 2004).

1.3 Scope and limitations

The research focuses on risk analysis during a flood event, so the flood event is not equal to the duration of the flood but rather the time of the pre-flood preparation such as flood warning to post-flood emergency responses. The type of flood investigated in the research is limited to coastal flooding. Therefore, the flood simulation model developed is not explicitly for other types of flooding such as ground water flooding or fluvial flooding. Furthermore, limited by the data collected, the flood scenarios are simplified simulations, and specifically only the result of the flood defence breaches and rising sea water level are emphasised.

The human travel behaviour model is based on England and Wales travel behaviour data. The model does not take into account the travel behaviour variability that exists in different areas.

This research takes Towyn in North Wales as a case study area. However, the work presented a conceptual model and model development as well as an example of model applications rather than practical risk-based flood emergency planning for Towyn, although this might be possible given more practical data.

1.4 Thesis structure

The thesis begins with a literature review (Chapter 2) that provides the background to and the problem domain of the study. The concept of flood risk, flood risk management (FRM) and flood event management (FEM) in England is also reviewed to analyse the challenges of integrating FEM into the FRM framework. Chapter 3 is a technical literature review of the methods that are relevant to the study, which includes: flood risk analysis process (section 3.2), flood simulation methods (section 3.3), human behaviour study and human behaviour simulation (section 3.4), the flood risk measurement methods (section 3.5), and the uncertainty analysis methods (section 3.6). Chapter 4 introduces the new methodology of risk-based human responses simulation by integrating the flood simulation model with the human behaviour model. Chapter 5 presents the application of the new method in a case study in Towyn, North Wales. The case study demonstrates how the simulation model helps to appraise some non-structural measures and the roles human factors play in the flood event. Chapter 6 further analyses the behaviour of the model and case study result by diagnosing the importance of particular model parameters through sensitivity test. Chapter 7 summarises key findings and conclusions from this study and identifies key priorities for future research.

Chapter 2. Research Background

2.1 Introduction

This research aims to develop an approach to appraise the benefits of non-structural measures in flood event management. Therefore, it is necessary to set the context in relation to flood risk management (FRM) and flood event management (FEM). This chapter sets out to review the following questions:

1. What is flood risk?
2. What is flood risk management (FRM) and why does it provide a useful framework?
3. What is flood event management (FEM)?
4. What are the challenges of incorporating FEM into an FRM approach?

In section 2.2 the flood risk concept is introduced and followed by a review of the flood risk management system. This section positions the study in the FRM research. In section 2.3, flood event management is reviewed in terms of its definition, current approach and the need for improvement. Section 2.4 considers how to align FEM with the FRM approach, which generates the aim of this research.

2.2 Flood risk management

2.2.1 Flooding system

The flooding system refers to the physical and organisational systems that have impacts on or are influenced by flooding (Hall *et al.*, 2003a). The physical systems involve the earth water cycle such as rainfall, runoff and marine storms; the man-made flood control systems such as drainage and flood defences; the social-economic and environmental assets in the flooded area such as lands and properties. The organizational systems involve the organizations that are responsible for managing floods, insurers providing insurance related to flood disasters and the stakeholders who play a role in the flood management.

In the flooding system, the hydraulic subsystem, which is shown in Figure 2-1, plays a key role in the result of flooding. Flooding can be categorised as fluvial and coastal flooding according to water sources; spatially the flood events can be at the scale of catchments or estuaries and coasts or the scale of urban areas.

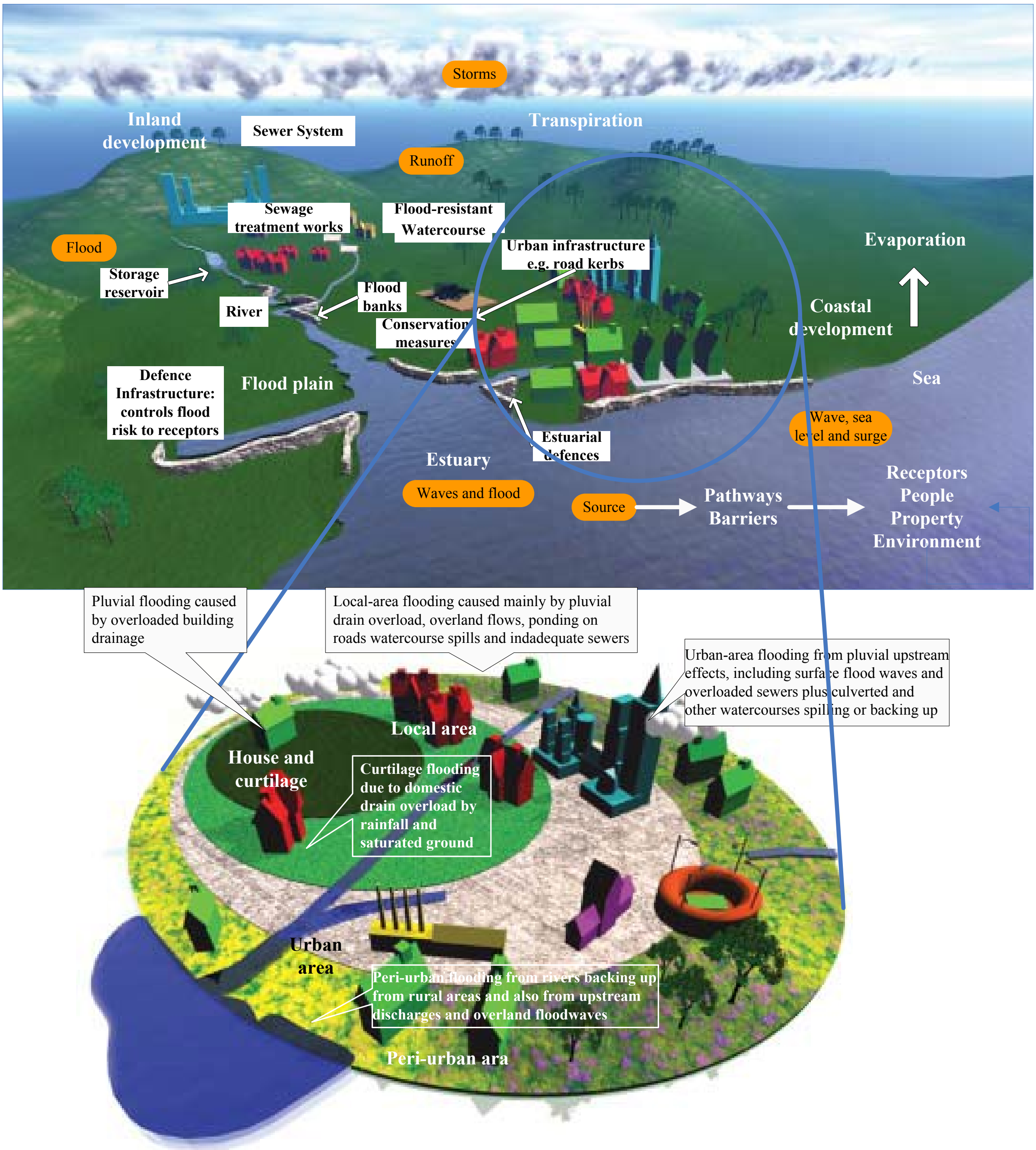


Figure 2-1 A hydraulic perspective of the flooding system (Evans *et al.*, 2004b)

2.2.2 Flood risk

Flood risk is identified as a combination of the probability of flood occurrence with its potential consequences (Hall *et al.*, 2003b; Gouldby and Samuels, 2005). It emphasises that the magnitude of flood risk is determined not only by the occurrence of natural disasters but also by the social-economic characteristics of the area exposed to the flood disaster. Schanze (2006) identifies flood risk as the convolution of flood hazard and flood vulnerability which refers to the characteristics of the elements exposed to the flood hazard. The vulnerability can be social vulnerability such as loss of life, health injuries or economic vulnerability such as direct and indirect financial losses. Although Schanze's definition of flood vulnerability is conventional, the measure of flood vulnerability is confused with flood risk measures that are widely used (Penning-Rowsell *et al.*, 2010). It is more acceptable that flood risk is defined as a product of hazard, exposure and vulnerability (Kron, 2003). Flood risk is often described by the Source-Pathway-Receptor-Consequence (SPRC) model (Gouldby and Samuels, 2005) (see Figure 2-2).

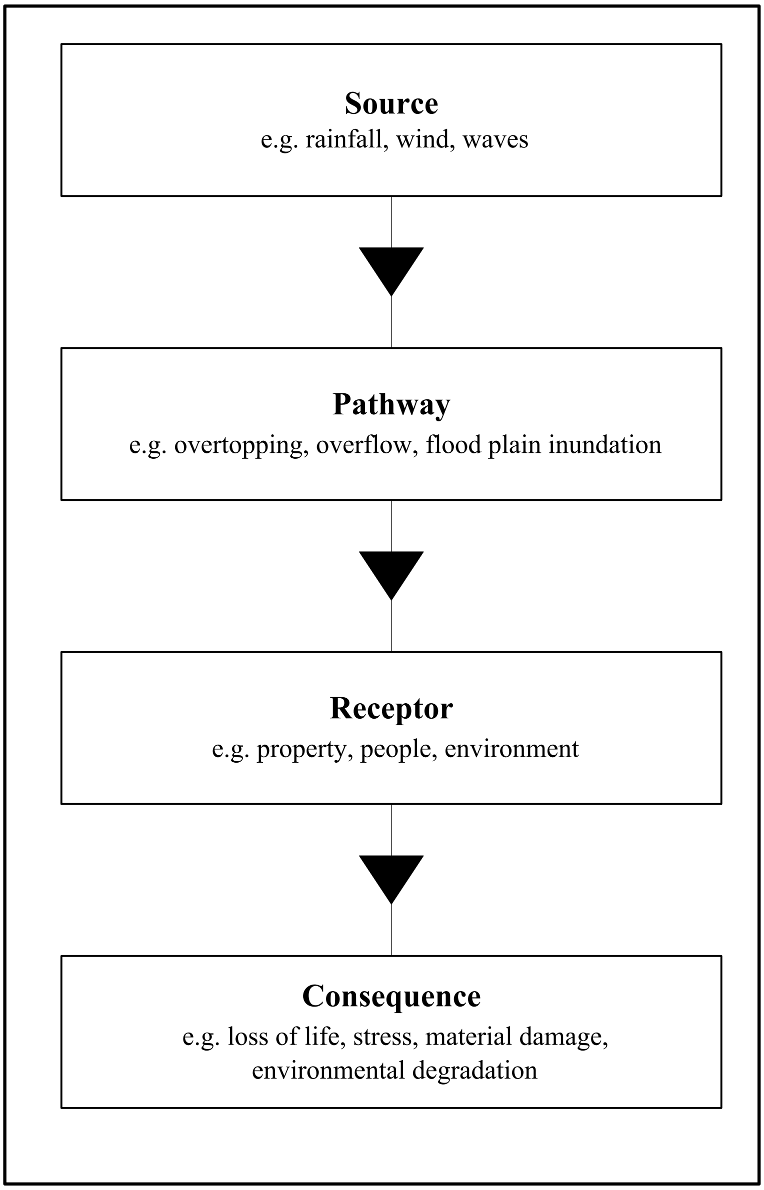


Figure 2-2 Source-Pathway-Receptor-Consequence Conceptual model helps with flood risk analysis

● Sources are weather events, or sequences of events that may result in flooding (e.g. heavy or sustained rainfall and marine storms).

● Pathways are the mechanisms that convey floodwaters that originate from weather events to places where they may impact on receptors. Pathways, therefore, include fluvial flows in or out of river channels, overland urban flows, coastal processes and the failure of fluvial- and sea-defence structures or urban drainage systems.

● Receptors are the people, industries and built and natural environments that flooding affects.

Consequences are flood risks, which can be expressed as:

$$\boldsymbol{R} = \boldsymbol{f}(\boldsymbol{\rho}, \boldsymbol{e}, \boldsymbol{s}, \boldsymbol{\omega}) \quad (2\text{-}1)$$

Where:

$\boldsymbol{R}$: The flood risk

$\boldsymbol{\rho}$: The nature and probability of the hazard

$\boldsymbol{e}$: The degree of exposure of the receptors to the flood

$\boldsymbol{s}$: The susceptibility of the receptors to the hazard

$\boldsymbol{\omega}$: The value of the receptors

Vulnerability ($\boldsymbol{V}$) is a sub-function of the risk function, which is a function of $\boldsymbol{s}$ and $\boldsymbol{\omega}$, as shown in equation 2-2.

$$\boldsymbol{V} = \boldsymbol{f}(\boldsymbol{s}, \boldsymbol{\omega}) \quad (2\text{-}2)$$

The flood risk definition based on the SPRC model demonstrates the interrelations in the flooding system and emphasises the importance of the receptors' vulnerability. Because this research emphasises human factors, this is an appropriate definition of flood risk in the thesis.

2.2.3 Flood risk management

Recent decades have witnessed flood management shifting to a flood risk management approach in which flood risk analysis is a core technique. Evidently complete flood protection against flooding is unachievable. Instead risk management has been widely regarded as a more suitable approach for handling flood hazards (Plate, 2002; Hall *et al.*, 2003b; Hooijer *et al.*, 2004) because risk analysis provides quantitative methods for appraising different flood protection decision-making options in terms of expected damage and expenditure, which forms a rational basis for the flood management.

Flood risk management was at first limited to the flood defences. The crest levels of defences were set according to design water levels, which are established through statistical analysis with little consideration of potential impacts. In most cases, design water levels just aim for individual flood defences instead of considering the whole defence system (Voortman, 2003). In the 1950s a risk-based cost-benefit analysis that took into account both flooding probability and the consequences was used in the design of water defences in the Netherlands, in which only exceedance probability, the height of the sea level and economic flood damages were involved and non-economic consequences were not considered (Van Dantzig, 1956). Although simple, this early research paved the way for the quantitative risk analysis approach for flood management. Quantitative risk analysis methods are reviewed in detail in Chapter 3.

With a further understanding of flood risk management, an integrated risk-based framework for flood management is established (Sayers *et al.*, 2002b; Hall *et al.*, 2003b). Supported by process-based, parametric and statistical models, an integrated depiction of the whole flood system from sources, pathways and receptors is drawn and the key elements of the flood system are defined and explored (Hall and Solomatine, 2010).

The holistic flood risk management concept makes dramatic changes to the flood risk research. First of all, it discloses that flood management is holistic and systematic (De Bruijn, 2005) and that all the miscellaneous aspects related to flood risk should be organized under a holistic framework. In the foresight project (Evans *et al.*, 2004a), drivers of the national flood risk 2050 and the response measures are logically categorized in the framework of the SPRC model. The comprehensive consideration of different types of flooding such as coastal and fluvial floods (Evans *et al.*, 2004b), the variety and range of flood risk management styles from urban to catchment, national or even international scale (Hall *et al.*, 2003a; Hooijer *et al.*, 2004; Gouldby *et al.*, 2008) are discussed. A further literature review on the methodology of the holistic flood risk management will be described in Chapter 3.

In the source part, the holistic flood risk management concept directed the research studies towards the extreme flood event that has a lower probability but significant consequences (Apel *et al.*, 2004; Büchele *et al.*, 2006). Future uncertainties that impact on the flood event are also assimilated into the flood risk management framework (Evans *et al.*, 2004a; Lavery and Donovan, 2005; Næss *et al.*, 2005).

In the pathway part, which is the traditional flood risk research field, integrated flood risk assessment brings the advantages of considering the entire flood defences system for strategic planning at different levels (Dawson, 2003; Gouldby *et al.*, 2008; Harvey *et al.*, 2013)

The research presented in this thesis contributes most towards the concept of integrated flood risk management through improved representation of the receptor and consequences. When assessing the flood risk, it is not only the physical natural flood hazard but also the social-economic, environmental and even ecological impact of flood hazards that should be taken into account. The receptors, especially humans, are not only the receptors of floods but also have subjective initiatives of learning, response and sociality that increase or mitigate the flood risk. In terms of flood risk mitigating measures, both structural and non-structural measures should be considered (Meyer *et al.*, 2012). The structural measures refer to physical constructions or engineering techniques to mitigate hazard impacts (The United Nations Office for Disaster Risk Reduction, 2009), while non-structural measures refer to the measures where structural engineering works are not included. Hutter et al. (2007) summarise non-structural measures as follows (Figure 2-3). It is also suggested that non-structural measures can be categorized into three aspects: regulatory/legal instruments, financial instruments and communicative instruments (Hooijer *et al.*, 2004; Olfert and Schanze, 2009; Dawson *et al.*, 2011b).

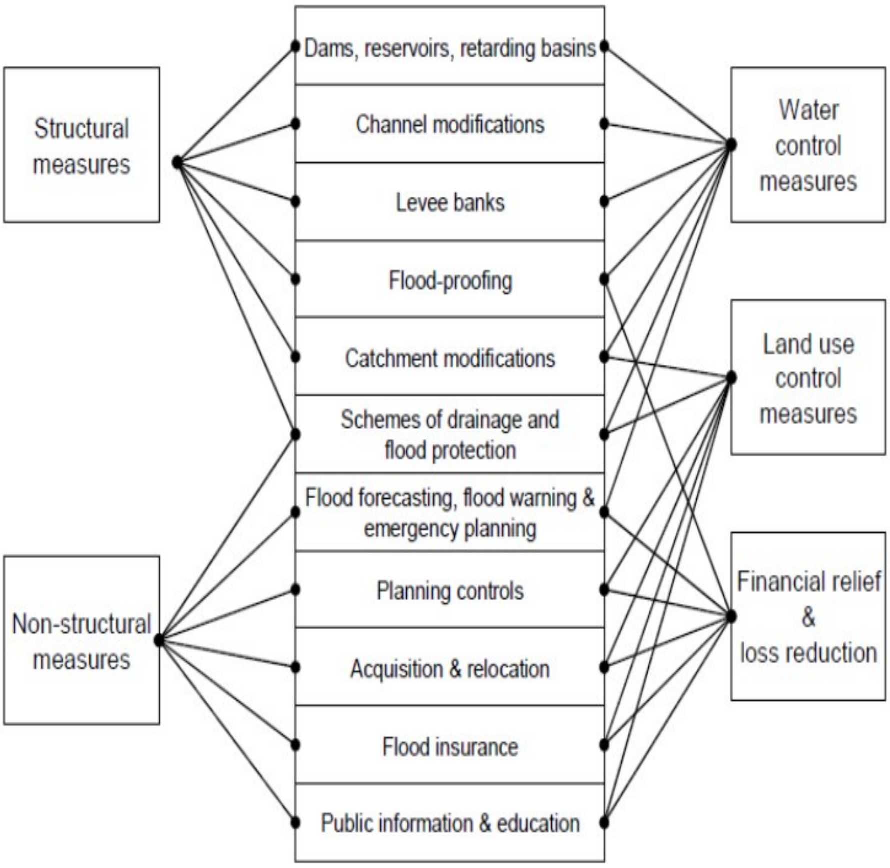


Figure 2-3 Structural and non-structural measures (Penning-Rowsell and Peerbolte, 1994)

In recent years, a wider range of non-structural interventions are studied, including land-use planning (Brath *et al.*, 2003; Pottier *et al.*, 2005), flood warning (Handmer and Parker, 1989; McCarthy *et al.*, 2007; Parker *et al.*, 2007a; Parker *et al.*, 2007b; Lany *et al.*, 2009; Parker and Priest, 2012), insurance (Hsu *et al.*, 2011), improving the flood resistance of property (Cutter *et al.*, 2003; Joseph *et al.*, 2011). Resilience (Bruijn, 2005; Merz *et al.*, 2010) and social vulnerability (Steinführer *et al.*, 2007).

However, most of the analysis of the non-structural measures is limited to qualitative disclosure of the relationships between the interventions and the flood impacts. Some quantitative economic evaluations were attempted for one or two specific non-structural measures such as flood warning or land use planning. The literature reviews in Chapter 2 and three highlight lack of methods that can appraise both the structural and non-structural measures quantitatively on the same platform.

Secondly, integrated flood risk management highlights the dynamic and continuous approach to flood management. Flood risk varies over time. The risk scenario changes continually with various physical and social-economic drivers such as climate change or population increase. Therefore, flood risk management is a continuing cycle of assessing, implementing and maintaining flood risk management measures to achieve an acceptable residual risk in view of sustainable development (Klijn *et al.*, 2008). For this reason, the components of flood risk management are described in Figure 2-4.

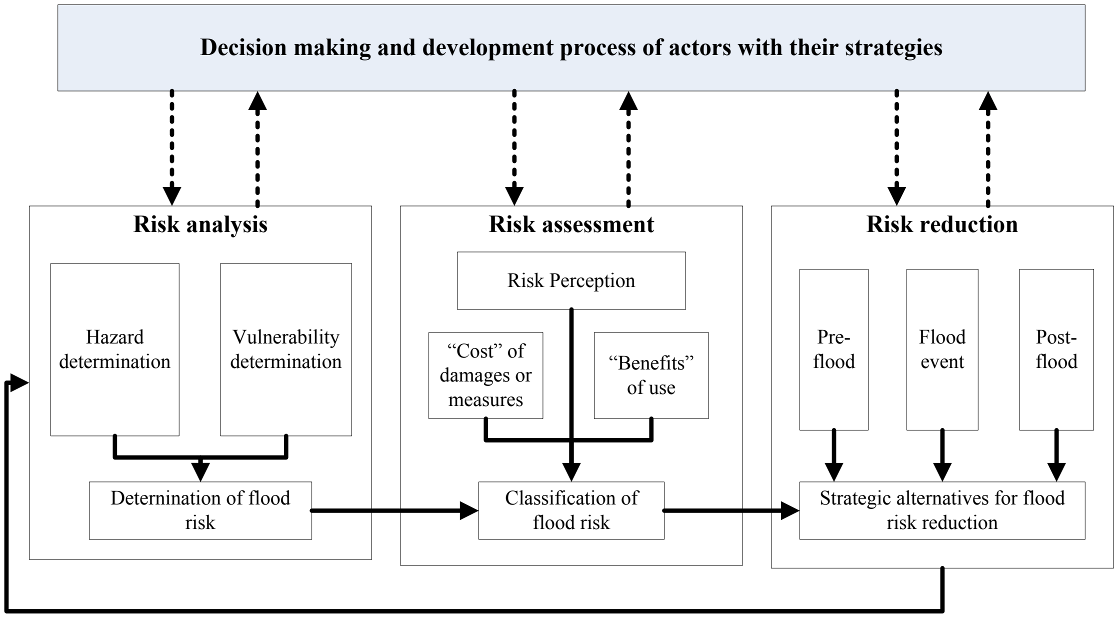


Figure 2-4 Framework of flood risk management (Schanze, 2006)

The flood risk reduction is distinguished as pre-flood mode, flood event mode and post-flood mode in the time dimension (Rosenthal and Hart, 1998). Pre-flood interventions cover measures of flood prevention, protection and preparedness. Flood event management includes forecasting, warning and emergency responses and operations to the flooding situation. Post-flood management involves recovery and the assessment of the flood impact. It is stressed that flood event management is a vital component of flood risk management.

However, so far flood risk analyses are more utilized for the long-term strategic flood risk management process (Evans *et al.*, 2004b; Evans *et al.*, 2004a; Woodward, 2012). Knowledge of short-term risk analysis for flood event management has to be improved (Vat *et al.*, 2007). In section 2.3, flood event management will be described in detail, in order to explore the challenges of integrating flood event management into the flood risk management framework.

2.3 Flood event management

2.3.1 Introduction

In recent decades, the UK has suffered quite a few major flood events including those in Carlisle (1999), Cumbria (2005 and 2009), and a flash flood due to heavy rainfall in Boscastle (2004). Severe floods hit most of the UK in 2007, there were floods in Cornwall in November 2010, and in 2012 a series of floods affected parts of Great Britain (September in Yorkshire and the North East, November in Somerset). Recent disorganized flood responses to the flood events highlighted the importance of improving flood event management (Pitt, 2008), which applies science, technology, planning and management during the flood event (Drabek, 2007).

There are two reasons that make flood event management an important issue. One reason is that uncertainties are associated with the source of the flooding, such as waves and storm surges as well as the pathways, such as flood defence breaches (Hall and Solomatine, 2010). In most cases, the uncertainties of flood hazard make it difficult to anticipate and prepare for all eventualities, even though, a flood plan may have been carefully designed (Woodward, 2012). Therefore, real-time decisions that can be adapted to the realistic flood situation have to be made during the flood event.

Another reason is that during a flood event many flood mitigation response and rescue activities require complex organizational management. To guarantee that the rescue resources are available at short notice is quite a challenge. Dealing with the impacts of flood events through emergency planning and response has become a core activity of flood risk management organizations (DEFRA, 2008). It has been recognized that both the probability of flooding and the damage caused can be significantly reduced by managing flood events in real time (Evans *et al.*, 2004b).

This section reviews the flood event management concept and the process of flood event management, and is followed by a description of the legal and policy framework of flood event management in England, before finally discussing the main risk reduction measures associated with flood event management.

2.3.2 Flood event management process

It is widely accepted that the emergency management approach can be described as a four-phase cycle: mitigation, preparation, response and recovery (Drabek, 1986). Mitigation aims at reducing the probability of the hazard include three parts: anticipation, assessment and prevention (Great Britain, 2004). It is a long-term strategy that follows the recovery process after a disaster occurs. Preparedness is pre-planning (DEFRA, 2011b) for an effective response and management to emergencies for regulating human behaviour and responsibility in flood events (Drabek, 1986). The response phase is the rapid implementation of emergency plan arrangements in a relatively short period. It encompasses the decisions and actions taken to deal with the immediate effects of an emergency (Cabinet Office, 2013). Collaboration and communication are key issues of this phase. The recovery is defined as "the process of rebuilding, restoring and rehabilitating the community following an emergency. It is a complex social and developmental process rather than just a remedial process" (Cabinet Office, 2013). It is a long-term development process after the onset of an emergency.

Although it is disputed for its ambiguous divisions since the four phases are often overlapped in practical situation (Haas *et al.*, 1977)， the four-phase cycle points out the emergency management tasks heuristically, which establishes the foundation for the emergency planning framework for both researchers and practitioners.

Marjolein (2009) suggests that flood event management only takes place in the half of the disaster cycle, the preparation and response phases, and mid-long term management activities before and after the flood event should not be in the process of flood event management, which places more emphasis on the emergency management in the flood event. Foresight report (Evans *et al.*, 2004b) also suggests that flood event management (managing flood events) involves some pre-event measures such as flood planning, forecasting and warning, flood fight actions, collective damage avoidance actions and individual damage avoidance actions. In this research, the flood event management is defined to include not only human behaviour at the response phase but also some pre-flood preparations that are closely related to human emergency responses in the flood event such as planning and flood warning.

It has been noticed that the FEM is a complex system, which is composed of two interacting sub-systems: the physical properties of a flood and society's risk-taking and vulnerability. The application of a complex system is therefore recommended for analysing flood risk during a flood event (Environment Agency, 2007d).

2.3.3 Legislation and policy

The Flood and Water Management Act 2010 and the Civil Contingencies Act 2004 are the most relevant legislation for flood event management (DEFRA, 2011b).

The Flood and Water Management Act 2010 sets up a statutory framework of flood risk management in the form of legislation, in which the leading power and duty of the Environment Agency and local authority for flood emergency management are defined (Schneiderbauer and Ehrlich, 2004).

The Civil Contingencies Act 2004 (CCA) (2013) establishes a statutory framework of roles and responsibilities, which is based on the principles of integrated emergency management. The organisations involved in emergency preparation and responses are divided into two categories (Table 2-1). Category 1 responders such as the emergency services, local authorities and a number of government agencies are at the core of the responses to most emergencies. Category 2 responders are co-operating bodies (DEFRA, 2011b). The CCA requires Category 1 responders to fulfil their civil protection duties such as risk assessment, emergency planning, business continuity management, warning and public awareness and providing advice and assistance to commercial and voluntary sectors. Category 2 responders are obliged to co-operate and share relevant information. The Local Resilience Forum (LRF) is the main mechanism for cooperating and information sharing.

Table 2-1 Responders in Civil Contingencies Act 2004

Category	Type	Responders
Category 1	Emergency services	Police forces British Transport Police Fire authorities Ambulance services
	Local authorities	Local authorities Public health authorities
	Government agencies	Environment Agency Scottish environment protection agency Maritime and Coastguard Agency
	Health bodies	Primary care trusts Health protection agency NHS Acute Trusts Foundation Trusts Local health boards (Wales, Scotland) Port health authorities
Category 2	Utilities	Gas and electricity transmitters and distributors Water and sewerage undertakers Fixed and mobile telecommunications providers
	Transport	Rail Highway Airports

Category	Type	Responders
		Harbours
	Health	Health and Safety Executive (HSE)

Under the CCA 2004 and Flood Act 2010, DEFRA and the Environment Agency and local authorities have leading roles in flood risk management and flood emergency management (DEFRA, 2013). The implementation of FEM is a multi-agency process founded on a bottom-up approach in which operations are managed, and decisions are made at the lowest appropriate level. In all cases, local agencies are the building blocks of response and recovery operations. Indeed, the local level deals with most emergencies with little or no input from the regional or national levels (Cabinet Office, 2013). Within the different magnitudes of emergency, the leading role varies. Information sharing and communication is a key issue for carrying out the FEM tasks.

The National Flood Emergency Framework is the strategic policy for managing a flood event, which provides a detailed operation policy on the aspects of preparedness, planning and response (DEFRA, 2011b). Multi-Agency Flood Plans (MAFP) are produced by the Local Resilience Forum as part of the National Flood Emergency Framework. There are currently 47 Local Resilience Fora covering England and Wales, which are based on the administrative boundaries of the police forces. Each Local Resilience Forum has to consider the flood risk across the whole area for which it is responsible. For areas where the risk is higher, more detailed MAFPs are required. To date, there have been some 323 MAFPs produced in England and Wales (Lumbroso and Vinet, 2012).

The flood emergency rescue policy is also created to guide flood rescue operations (DEFRA, 2011b). It provides an organisational capability and structure to enable the delivery of a co-ordinated national response for rescuing during the flooding incidents. One of the unique features of this project is that it not only clarifies each organization's responsibility, but also sets the trigger condition of fulfilling these responsibilities.

2.3.4 FEM measures

During the flood event, possible policies and interventions used for risk mitigation are listed in Table 2-2.

Table 2-2 Flood risk reduction measures for managing flood events adapted from Evans (2004a)

FEM response type	FEM measures
Pre-event measures: To ensure that people and stakeholders are prepared to mitigate negative impacts and to facilitate the efficient management of the event	Flood plans Preparation by regional authorities, organizations, communities and individuals
	Flood risk mapping to identify highly vulnerable areas
	Education and awareness raising
Forecasting and Warning: To provide sufficient time for people and organizations to take effective mitigating action prior to flood water arriving	Flood-forecasting systems: Improved sensing, forecasting and real-time modelling during the event
	Warning dissemination systems (including their take-up by residents and businesses)
Flood fighting actions: To manage floodwaters and defences during the event	Demountable/temporary defences deployed before and during the event
	Water level control structures: Controllable weirs and sluices
	Emergency repair and reinforcing of defences
	Emergency diversions: Cut-through channels, deliberate breaching dikes
Collective damage avoidance actions: Organized or spontaneous removal of people, assets or livestock to a safe location	Evacuation
	Emergency rescue
	Demountable flood defences
	Medical preparedness to reduce health and social impacts
	State aid, compensation
Individual damage avoidance actions: Actions taken by individuals to reduce flood losses, including preventing or delaying flood water from entering buildings and moving people, assets or livestock to safety	Temporary flood proofing
	Moving assets to safety

Flood planning is a traditional routine strategy to reduce flood risk for local authorities. However, appraising the quality and completeness of a local flood plan is challenging. A framework known as the FIM FRAME method was developed for assessing, improving and drafting emergency plans (Lumbroso *et al.*, 2011). In FIM FRAME, twenty-two matrices for making or assessing a flood emergency plan are introduced, which give a detailed systematic overview of non-structural measures that should be considered in a flood plan, providing a template for drafting flood event management manuals.

Flood forecasting and warning is another main measure. It has been widely accepted that a successful flood warning does mitigate the flood damage directly and indirectly. Methods of evaluating the benefits of flood warnings are developed (Parker *et al.*, 2007a; Parker *et al.*, 2007b; Penning-Rowsell *et al.*, 2010; Parker and Priest, 2012). The challenge of flood forecasting is no longer the accuracy of flood water extent but the real time flood hydro-dynamic evolution to offer longer lead times and to provide warning against flood disasters with a lower threshold of probability so that responders can exploit the warning to mitigate flood risk (Anquetin *et al.*, 2004). More details will be discussed in Chapter 3.

Evacuation is a key issue for collective damage avoidance behaviour. Methods to find the optimal time for evacuation, evacuation routes, traffic management and shelter selection are explored (Lumbroso *et al.*, 2009). More details will be discussed in Chapter 3 as part of the technical literature review.

Social vulnerability and community resilience have recently attracted great attention. It has been realized that the consequence of flood risk is a product of exposure and vulnerability (Schneiderbauer and Ehrlich, 2004). Some social groups within communities are more likely to need specific targeting and support and the social awareness of flood risk and the construction of a social structure in the flood event is quite important for building a resilient community (Steinführer *et al.*, 2007). The nation-wide flood exercises were held to enhance the flood awareness of both individuals and organizations. The exercises tested the management arrangement, and many lessons were learned from it (DEFRA, 2012). The importance of social-media, evacuation planning, rescue coordination, information sharing and community engagement are emphasised by flood exercises.

Individual damage avoidance action has been reported recently, and some research studies explored the flood impact on individual health such as drowning, trauma and injury. Gender, age and mobility affect vulnerability to health related impacts of flooding such as stress (Tapsell *et al.*, 2002; DEFRA, 2003; Great Britain, 2004). Individual awareness and preparedness has recently been surveyed by Hopkins (2012) which shows that human responses to the flood event are associated with the level of knowledge and experience of past flood events, namely flood hazard perception as well as demographic, socio-economic and attitudinal factors.

2.4 Challenges of integrating FEM into FRM framework

From the analysis of FEM measures, it is noticeable that FEM measures are mainly non-structural measures. When a flood event is underway, the opportunities for physical construction are limited by that point. In flood event management, flood risks are entirely human concerns (Klijn *et al.*, 2008). Responses must be considered for how to manage people and reduce social vulnerability.

Non-structural measures are more related to human factors. People play a pivotal role in mitigating or increasing flood risks at all stages of FEM. However, because the non-structural measures are influenced by human factors, its impact is very difficult to quantify. Firstly, unlike engineering work, human factors influence flood risks by coupling with other measures. For example, although spatial planning is very important, its effect impinges on the reduction of residential properties in a flood plain. Secondly, some human behaviour does not have a significant impact on the current flood event but might have a huge influence on the subsequent flood events. It has been demonstrated that residents with flood experience have better flood preparations for any subsequent flood events (Pitt, 2008; Hopkins, 2012). Human behaviour has typically been described as a "Known to be important but not quantified" element in flood risk management (Evans *et al.*, 2004a).

Thus, a critical challenge for integrating FEM into FRM is to develop a method that can quantitatively represent the role of non-structural measures. This hinges on how to quantify the effect of human factors attached to non-structural measures. This research aims to explore the possibility of this.

2.5 Summary

This chapter first reviews the flood risk and flood risk management approach, and points out that integrated flood risk management is a quantitative risk-based holistic approach. However, with the shifting of flood risk management to the whole flooding system, which includes the social, economic and ecologic elements, the integrated quantitative risk analysis becomes very complex and challenging. The methods for quantitatively appraising non-structural measures are not very well developed.

As a dynamic system, flood event management is an important component of flood risk management. However, in terms of time scale, long-term strategic flood risk management is always important. Short-term flood risk analysis for flood event management is comparatively rare, whilst the demand for assessing flood risk in a flood emergency is pressing. For example, it is regulated in the UK that risk assessment is a key duty that falls to the Category 1 responders such as the Police and Fire and Rescue Services (Cabinet Office, 2013).

The interventions used in FEM are mainly non-structural measures, which are closely related to human factors. Therefore, taking human factor impacts into account is required to quantify non-structural measures.

For this reason, a short-term flood risk analysis method that can evaluate and quantify non-structural measures by taking human factor impacts into account is developed in this research. In Chapter 3, the techniques that are relevant to this topic are reviewed.

Chapter 3. Technical Literature Review

3.1 Introduction

This chapter is a technical review of the methods that are relevant to the research. In Chapter 2 it was shown that in order to integrate FEM into FRM, a method that involves human factors to appraise non-structural measures is needed. The key issue is how the input of human factors that impact on flood risk can be quantitatively calculated. Therefore, this chapter reviews the following questions in order to identify promising methods and approaches for this research.

5. What is the process of flood risk analysis?
6. What are the methods for flood simulation?
7. What are the methods of representing human behaviour in the flooded environment?
8. How are flood risks measured?
9. How uncertainties in risk analysis and flood event management models might be understood?

In section 3.2 the flood risk analysis process that forms the framework of this research is reviewed. Section 3.3 deals with the hydraulic simulation model. In section 3.4 the human factor theory that is widely used in other safety areas is analysed. This helps to determine the method for integrating human factors into a flood risk analysis approach. Then reviews on the sociology research as well as the social simulation are considered to identify the methods for representing human behaviour in the flooded environment. In Section 3.5 the methods for calculating flood consequences are discussed. Finally, the methods for controlling the uncertainty of the model are discussed.

3.2 Flood risk analysis

3.2.1 Risk analysis in the FRM

FRM is a systematic approach that includes flood risk analysis, flood risk assessment and flood risk reduction. Flood risk analysis provides information on previous, current and future flood risks (Schanze, 2006) and, therefore, provides the starting point for the FRM. Bruijn et al. outlined a risk analysis methodology for long-term strategy FRM (Bruijn *et al.*, 2008), with flood risk analysis involved throughout the FRM process. Firstly, system exploration screens the characteristics of the flood system; then risk analysis is used to analyse the flood risk in baseline conditions. Alternative strategies are assessed and compared with each other and the baseline before a preferred option is selected.

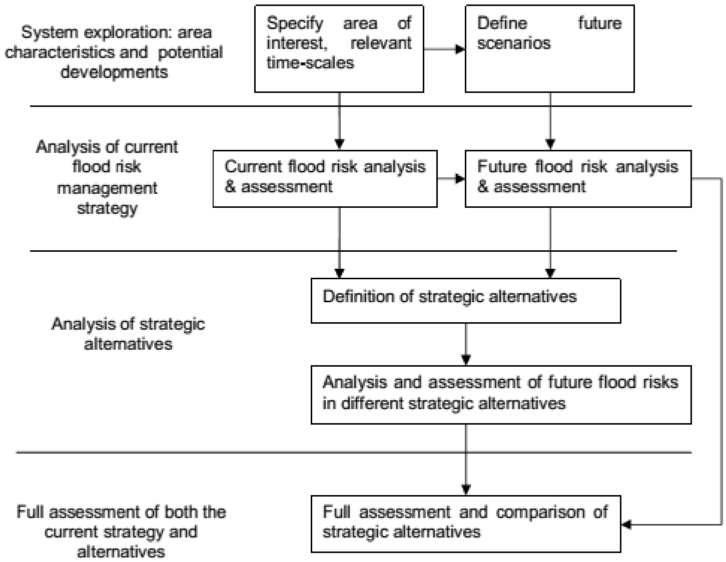


Figure 3-1 Schematic overview of the method for developing and assessing long-term flood risk management strategies in view of uncertain futures (Bruijn *et al.*, 2008)

Although the terminology is framed to consider long-term strategies, it captures the general process of flood risk management. It is the tool for quantifying flood risks under a given scenario of flood hazard and flood reduction measures in terms of metrics such as economic and other losses. This procedure of flood risk analysis involves setting up a baseline scenario as well as scenarios involving non-structural measures such as flood warnings and flood evacuations and then analyses and compares the flood risks under these different scenarios in order to evaluate the effectiveness of non-structural measures.

It has been noted that for the long-term and operational approaches to flood risk analysis different methodology are required (Plate, 2002). In terms of a risk analysis of flood event management, the future scenario might not be necessary because instead the dynamics of the flood and the flood risks during the flood event would be emphasised. However, most of the risk analysis research studies to date have focused on the long-term strategic flood risk management rather than the flood event emergency management operational level. This research attempts to contribute to the dynamic flood risk analysis in the flood event.

3.2.2 Comprehensive probabilistic approach of the flood risk analysis

With the establishment of the integrated flood risk management framework, increasing efforts to develop comprehensive probabilistic approaches that model the whole flood system are attempted. Tiered methodologies that are extended to various levels of risk analysis are used in quite a few projects such as the Foresight project, the FLOODSite

Consortium and the German Research Network Natural Disaster project (Sayers *et al.*, 2002b; Evans *et al.*, 2004a; Apel *et al.*, 2006). The comprehensive probabilistic approach provides a rational decision-making framework for flood risk management.

Flood risk calculation in the comprehensive probabilistic approach is expressed as the product of the probability and consequences. For example, for a given area the flood risk of expected annual flood damage R, is calculated by the equation (3-1)

$$R = \int_{0}^{y_{max}} p(y)D(y)dy \tag{3-1}$$

where y_{max} is the greatest flood depth from all flooding cases, $p(y)$ is the probability density function of flood depth and $D(y)$ is the damage in the area in a flood of depth y (Hall and Sayers, 2005).

The probability in the flood risk calculation is related to the flood hazard, and the consequence is the flood hazard's impact on the area. Flood risk analysis research is mainly carried out on these two aspects (Apel *et al.*, 2009; Smith and Petley, 2009), as shown in Figure 3-2.

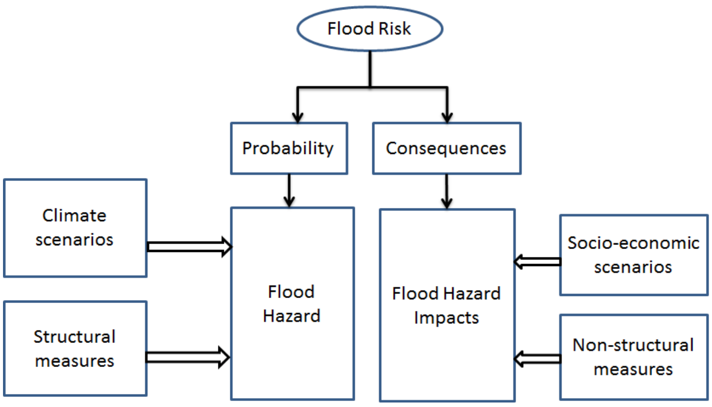


Figure 3-2 Overview of risk analysis framework, highlighting how the drivers of change and flood risk reduction measures interact with the risk calculation (adapted from (Dawson *et al.*, 2011b))

3.2.3 Flood hazard

Flood hazard is linked to the actual occurrence of the flooding. A large amount of research has been undertaken on the probability of the occurrence of flood hazard and the description of the characteristics of flooding. Probabilistic risk analysis methods are widely used in flood hazard occurrence analysis. These include both analyses of natural sources such as precipitations, coastal surge, river flows and of the pathways such as flood defence systems that lead to flooding. The simplest procedure is to connect the given records of discharge data with flood frequencies (Stedinger *et al.*, 1993). Many researchers have attempted to characterise the meteorological drivers of flooding. Based on UK historical rainfall data, it is observed that the frequency of extreme flood events peak in the summer months (Collier *et al.*, 2002; Hand *et al.*, 2004), however a trend of an increasing contribution of winter rainfall is also observed (Osborn and Hulme, 2002). Spatially, it was noted that extreme heavy rainfall events were increasing in northern and western parts of the UK (Fowler and Kilsby, 2003; Fowler and Wilby, 2010).

Probabilistic analysis is also carried out throughout the whole system of flood defences to assess the probability of flood defence failure. Advanced programmes for identifying the probability of each element in the system, such as hydraulic loads (river flow, coast surge), flood routing and the performance of flood defence structures (dams, dikes, levees) are studied (Vrijling, 2001; Apel *et al.*, 2006; Jonkman, 2007). A tiered risk assessment methodology was set up to analyse the flood defence system on different scales (Sayers *et al.*, 2002a; Dawson, 2003; Dawson *et al.*, 2003; Hall *et al.*, 2003a; Hall *et al.*, 2003b; Dawson and Hall, 2006). Possible levels in the tiered system of a flood defence system and the methodology for risk analysis are listed in Table 3-1.

Table 3-1 Possible levels in a 'tiered' approach to flood and coastal defence risk analysis (Hall *et al.*, 2003b)

Level	Decisions to inform	Data sources	Methodologies
High (Tier 1)	• National assessment of economic risk, risk to life or environmental risk • Prioritisation of expenditure • Regional planning • Planning of flood warning	• Defence type • Condition grades • Standard of service • Indicative floodplain maps • Socio-economic data • Land use mapping	• Generic probability of defence failure based on condition assessment and crest freeboard • Assumed dependency between defence sections • Empirical methods to determine likely flood extent
Intermediate (Tier 2)	As above plus • Flood defence strategy planning • Regulation of development • Maintenance management	As above plus • Defence crest level and other dimensions where available • Joint probability load distributions • Floodplain topography • Detailed socio-economic data	• Probabilities of defence failure from reliability analysis • Systems reliability analysis using joint loading conditions • Modelling of limited number of inundation scenarios • Simulation-based reliability analysis of system • Simulation modelling of inundation
Detailed (Tier 3)	As above plus • Scheme appraisal and optimisation	As above plus • All parameters required to describe defence strength • Synthetic time series of loading conditions	• Simulation-based reliability analysis of system • Simulation modelling of inundation

This comprehensive methodology very clearly shows the way for probabilistic analysis of flood defences at different levels and bridges the probabilistic analysis research method and the flood risk management practices. It significantly influences the establishment of the risk-based management framework upon the flood defences.

Flood modelling (hydraulic modelling) is another important subject for flood hazard research. It studies the characteristics of flooding (flood extent, water depth, velocity) under a given flood scenario. Computer based numeric 1D and 2D hydraulic simulation modelling methods have been developed to characterise a flood (Wang, 2011; Woodward, 2012). As it is one of the key issues in this research, a detailed review of inundation modelling will be introduced in section 3.3.

3.2.4 Flood consequence

The flood consequences analysis is normally limited to the flood hazard impact on the receptor such as people and properties in the flooded area. The measurement of flood risk varies according to different management goals, which often include loss of life, financial and economic damage (Apel *et al.*, 2009). This research is mainly focused on the receptor part of the flood risk. Measuring flood consequences is the foundation of the flood risk analysis in the FEM. (Schanze, 2006) Therefore, it will be reviewed in detail in section 3.5.

3.2.5 Evaluating structural measures and non-structural measures

Due to its ability to quantify the benefits of flood reduction options, flood risk analysis is often used for evaluating different structural measures such as flood defences. Structural measures work on the flood hazard part in the flood risk system. Calculating how structural measures affect the probability of the flood hazard occurrence is a key issue for evaluating the impact of structural measures. The probabilistic failure model is used for estimating the probability of flood defence failure. For example, in the dike system flood risk analysis, the performance of a flood dike is in terms of its fragility (Dawson *et al.*, 2005), the failure probability of a defence is calculated by integrating the fragility function over the loading distribution. Assuming the dike system state is S_j, j = 1,..n, the flow is Q and the equation (3-2) therefore changes to:

$$R = \int_0^\infty \sum_{j=1}^{n} P(S_j|Q) f(Q) D(Q, S_j)\, dQ \tag{3-2}$$

Where $P(S_j|Q)$ the failure probability of dike j is conditional upon loading Q, $f(Q)$ is the distribution of loading Q, and $D(Q, S_j)$ is the damage function given loading Q and the state S_j (Dawson *et al.*, 2005). The flood defence performances can therefore be calculated.

Different from structural measures, non-structural measures work on the consequences part of the flood risk system. Methods for evaluating the effect of non-structural measures are limited because the human system is quite complex. Human is responsible for the flood system maintenance and operation and is the first responder to the flood hazard (Dawson *et al.*, 2011b). Probabilistic failure models are not the most suitable model for human behaviour because human responses to the flood disasters are often trade-off activities based on their own experiences (Hollnagel, 1998). Humans' cognitive and non-linear complex behaviour is not easily quantified.

Dawson (2011b) designed a method to quantify the benefit of long-term non-structural measures by integrating the socio-economic and climate change scenario with long-term land use modelling. The creativity of this method is that instead of taking it as a pathway like structural measures, non-structural measures are integrated into the consequence part. The benefits of the non-structural measures are therefore embodied by the changing of the consequences of different scenarios and thus avoid the process of allocating the probability of human actions, which is impossible due to the lack of practical data support. Furthermore, this research opens up a way to not only simulate the characteristics of flooding, but also to use human social behaviour simulation models. It highlights the possibility of risk analysis on human-related non-structural measures based on the human behaviour simulation.

Dawson's risk-based human behaviour simulation has a significant meaning for this research. For the non-structural measures used in the flood event, the same approach can be adopted. The impact of non-structural measures such as flood warning and evacuation can be integrated into the flood risk analysis through simulating the human responses to the flood event so that the benefit of these measures can be quantified and compared with structural measures. In section 3.4, human factors and human behaviour will be reviewed in order to set up the human behaviour simulation model for risk analysis.

Simulation is widely used in the flood risk analysis, as setting up current and future scenarios are the first step in the flood risk analysis. It has become a tradition for the consequences of different scenarios to be estimated based on the output of flood simulation (Sayers *et al.*, 2002b; Jonkman, 2007). Some long-term human behaviour for flood risk reduction is also simulated in the flood risk assessment approach (Dawson *et* *al.*, 2011b). Following the previous research on the non-structural measure assessment, simulation is adopted as the main method for this research.

3.3 Flood modelling

Flood simulation is the foundation of the research because flood maps need to be provided as the simulation background for the human responses to a flood event. Here the computational fluid dynamics methods are first introduced, followed by the comments on the mainstream flood simulation models, and, as a result, the recommended full 2D shallow water model is introduced in detail.

Computational Fluid Dynamics (CFD) is an approach used to study fluid dynamics by developing accurate numerical methods and algorithms for solving practical fluid mechanical problems on a computer (Anderson, 1995). CFD is a very fast growing branch of fluid mechanics. Nowadays, high-speed computers have made it possible to use numerical methods and algorithms to simulate fluid flows in various practical conditions. 2D hydraulic models that incorporate different numerical solutions are now able to provide accurate and fast simulations for urban flooding.

3.3.1 2D shallow water equations for flood simulation

In modelling terms, water flow may be referred to as 'shallow' when its horizontal dimensions are much larger than the vertical extent; under such a condition, the vertical component of the water particle acceleration may be negligible to reinforce the assumption of hydrostatic pressure. Typical examples include those flows that are present in wide rivers, lakes, coastal lagoons, estuaries, and so on (Liang, 2004). Flooding can be generally categorized as a shallow flow.

Assuming the negligible vertical acceleration of the water particles and hence hydrostatic pressure distribution, the 2D shallow water equations may be derived by integrating the 3D Reynolds averaged Navier-Stokes equations in the vertical direction and expressed as follows:

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} = \mathbf{s} \qquad \textbf{(3-3)}$$

Where $\mathbf{u}$ is the vector representing the conserved variables; $\mathbf{f}$ and $\mathbf{g}$ denote the flux vectors in the *x* and *y* directions, respectively; $\mathbf{s}$ is the vector containing the source terms; t is the time and x, y are the Cartesian coordinates. The vectors may be given by (Liang *et al.*, 2004),

$$\mathbf{u} = \begin{bmatrix} \eta \\ uh \\ vh \end{bmatrix} \qquad \mathbf{f} = \begin{bmatrix} uh \\ u^2h + \frac{1}{2}g\left(\eta^2 - 2\eta z_b\right) \\ uvh \end{bmatrix} \tag{3-4}$$

$$\mathbf{g} = \begin{bmatrix} vh \\ uvh \\ v^2h + \frac{1}{2}g\left(\eta^2 - 2\eta z_b\right) \end{bmatrix} \qquad \mathbf{s} = \begin{bmatrix} 0 \\ -\frac{\tau_{bx}}{\rho} - g\eta\frac{\partial z_b}{\partial x} \\ -\frac{\tau_{by}}{\rho} - g\eta\frac{\partial z_b}{\partial y} \end{bmatrix}$$

where η is the free surface elevation above datum; z_b is the bottom topography elevation above datum; $h = \eta - z_b$ is the water depth; u, v are the *x* and *y* components of velocity, respectively; g is the gravitational acceleration; ρ is the density of water and τ_{bx}, τ_{by} denote the bed friction stresses in *x* and *y* directions.

Full 2D shallow water equations obey the conservation of mass and momentum principles.

3.3.2 2D flood inundation models

Different 2D flood inundation models/software packages are developed by seeking numerical solutions to these equations or one of its simplified forms. The EA had a thorough benchmarking on the main 2D flood inundation models for a variety of purposes in flood risk management (Néelz and Pender, 2013), in which 2D flood inundation models are categorized into 4 classes as shown in Table 3-2. Full Shallow Water Equations (SWE) models refer to the models that solve the shallow water equations by providing a full mathematical representation of the flood inundation process; '3-term' models such as LISFLOOD-FP solve the SWEs by neglecting the advective acceleration term; '2-term' models such as ISIS Fast Dynamic solve the SWE without acceleration terms; '0-term' models such as RFSM Direct only consider topographic connectivity and the continuity, and there is no time variation in the model.

Table 3-2 Categorisation of models based on the number of SWE terms considered (Néelz and Pender, 2013)

Category	SWE terms	Packages
Full SWE models	Convective acceleration, pressure, bottom slope, friction slope	ANUGA Flowroute-*i*TM InfoWorks ICM ISIS 2D and ISIS 2D GPU JFLOW +

		MIKE FLOOD SOBEK TUFLOW, TUFLOW GPU and TUFLOW FV XPSTORM
'3-term' models	Pressure, bottom slope, friction slope	LISFLOOD-FP RFSM EDA
'2-term' models	Bottom slope, friction slope	ISIS Fast Dynamic UIM
'0-term' models	N/A	RFSM Direct ISIS Fast

Although the simulation results of the final flood inundation extent based on models using simplified forms of SWEs are satisfying and there are computational cost savings (DEFRA, 2012), these models lack an accurate prediction of the velocity of the flood water, especially when predicting rapidly varying flows, which prevents the model from simulating the water dynamics.

Flood velocity is a very important factor in flood emergency management. For example, Dawson used LISFLOOD-FP for the flood simulation in risk-based flood incident management, in which the loss of life is only calculated by the depth of flood water (Dawson *et al.*, 2011a). However, it is observed that flood death depends on both flood depth and flood velocity (DEFRA, 2003). Therefore, full shallow equation models might be a better choice because of their capability to simulate the flood dynamics.

3.3.3 Numerical models for full shallow water equations

In order to simulate the velocity of the open channel flood water, a finite-volume Godunov-type method was used incorporated with Roe's approximate Riemann solver to extend HLLC approximate Riemann solvers. The vector terms in shallow water equations are reformed as follows:

$$\mathbf{u} = \begin{bmatrix} \eta \\ uh \\ vh \end{bmatrix} \qquad \mathbf{f} = \begin{bmatrix} uh \\ u^2 h + \frac{1}{2} g\left(\eta^2 - 2\eta z_b\right) \\ uvh \end{bmatrix} \tag{3-5}$$

$$\mathbf{g} = \begin{bmatrix} vh \\ uvh \\ v^2 h + \frac{1}{2} g\left(\eta^2 - 2\eta z_b\right) \end{bmatrix} \qquad \mathbf{s} = \begin{bmatrix} 0 \\ -\frac{\tau_{bx}}{\rho} - g\eta \frac{\partial z_b}{\partial x} \\ -\frac{\tau_{by}}{\rho} - g\eta \frac{\partial z_b}{\partial y} \end{bmatrix}$$

A finite-volume Godunov-type scheme has been used to solve the shallow water equations to achieve high-resolution simulations. By using the second-order Runge-Kutta integrating method (Liang, 2008), the explicit time marching formula is as follows:

$$\mathbf{u}_{i,j}^{n+1} = \mathbf{u}_{i,j}^{n} + \frac{\Delta t}{\Delta x}\left(\mathbf{f}^{n}{}_{i-1/2,j} - \mathbf{f}^{n}{}_{i+1/2,j}\right) + \frac{\Delta t}{\Delta y}\left(\mathbf{g}^{n}{}_{i,j-1/2} - \mathbf{g}^{n}{}_{i,j+1/2}\right) + \Delta t \mathbf{s}^{n}{}_{i,j} \quad \textbf{(3-6)}$$

Where the superscript n represents the time level, subscripts i and j are the cell indices in the x and y directions, respectively; Δt is the time step, Δy is the cell dimension in the y direction, $\mathbf{f}^{n}{}_{i-1/2,j}$, $\mathbf{f}^{n}{}_{i+1/2,j}$, $g^{n}{}_{i-1/2,j}$, $g^{n}{}_{i+1/2,j}$ are the fluxes through the west, east, south and north cell interfaces. By adopting the second-order Runge-Kutta integrating method, formula 3-6 can be rewritten as

$$\mathbf{u}_{i,j}^{n+1} = \mathbf{u}_{i,j}^{n} + \frac{1}{2}\Delta t\left(\mathbf{k}_{i,j}\left(\mathbf{u}^{n}\right) + \mathbf{k}_{i,j}\left(\mathbf{u}^{(1)}\right)\right) \quad \textbf{(3-7)}$$

$$\mathbf{k}_{i,j} = -\frac{\mathbf{f}_{i+1/2,j} - \mathbf{f}_{i-1/2,j}}{\Delta x} - \frac{\mathbf{g}_{i,j+1/2} - \mathbf{g}_{i,j-1/2}}{\Delta y} + \mathbf{s}_{i,j} \quad \textbf{(3-8)}$$

Herein $\mathbf{k}_{i,j}\left(\mathbf{u}^{n}\right)$ and $\mathbf{k}_{i,j}\left(\mathbf{u}^{(1)}\right)$ are computed by updated flux variables at each time step. $\mathbf{f}_{i+1/2,j}$ in equation(3-8) can be calculated by the following formula.

$$\mathbf{f}_{i+1/2,j} = \begin{cases} \mathbf{f}_{L} & \text{if} \quad 0 \le S_{L} \\ \mathbf{f}_{*L} & \text{if} \quad S_{L} \le 0 \le S_{M} \\ \mathbf{f}_{*R} & \text{if} \quad S_{M} \le 0 \le S_{R} \\ \mathbf{f}_{R} & \text{if} \quad 0 \ge S_{R} \end{cases} \quad \textbf{(3-9)}$$

where $\mathbf{f}_{L}$ and $\mathbf{f}_{R}$ are the left and right flux vectors considered in a local Riemann problem; $\mathbf{f}_{*L}$ and $\mathbf{f}_{*R}$ are the left and right parts of the middle region flux vectors considered in a local Riemann problem which can evaluated as follows:

$$\mathbf{f}_{*L} = \begin{bmatrix} \mathbf{f}_{1*} \\ \mathbf{f}_{2*} \\ \mathbf{f}_{1*} \cdot v_{L} \end{bmatrix}, \mathbf{f}_{*R} = \begin{bmatrix} \mathbf{f}_{1*} \\ \mathbf{f}_{2*} \\ \mathbf{f}_{1*} \cdot v_{R} \end{bmatrix} \quad \textbf{(3-10)}$$

in which v_L and v_R are the left and right parts of the tangential velocity component in a local Riemann problem; $\mathbf{f}_{1*}$ and $\mathbf{f}_{2*}$ are the first and second components of the flux vector $\mathbf{f}$ in the middle region, which can be evaluated by (Harten *et al.*, 1983).

$$\mathbf{f}_* = \frac{S_R \mathbf{f}_L - S_L \mathbf{f}_R + S_L S_R (\mathbf{u}_R - \mathbf{u}_L)}{S_R - S_L} \qquad \textbf{(3-11)}$$

In equation (3-13), S_L, S_M and S_R are the speeds of the left, middle and right waves, which are expressed by the following formulas (Fraccarollo and Toro, 1995).

$$S_L = \begin{cases} u_R - 2\sqrt{gh_R} & if \quad h_L = 0 \\ \min\left(u_L - \sqrt{gh_L}, u_* - \sqrt{gh_*}\right) & if \quad h_L > 0 \end{cases} \qquad \textbf{(3-12)}$$

$$S_R = \begin{cases} u_L + 2\sqrt{gh_L} & if \quad h_R = 0 \\ \max\left(u_R + \sqrt{gh_R}, u_* + \sqrt{gh_*}\right) & if \quad h_R > 0 \end{cases} \qquad \textbf{(3-13)}$$

$$S_M = \frac{S_L h_R (u_R - S_R) - S_R h_L (u_L - S_L)}{h_R (u_R - S_R) - h_L (u_L - S_L)} \qquad \textbf{(3-14)}$$

$$u_* = \frac{1}{2}(u_L + u_R) + \sqrt{gh_L} - \sqrt{gh_R} \qquad \textbf{(3-15)}$$

$$h_* = \frac{1}{g}\left[\frac{1}{2}\left(\sqrt{gh_L} + \sqrt{gh_R}\right) + \frac{1}{4}(u_L - u_R)\right]^2 \qquad \textbf{(3-16)}$$

The full–shallow 2D model has been used and applied in a number of investigations regarding flooding which includes flood waves, rapidly-varying dam breaks and slow-evolving inundations and coastal applications. The numerical results are found to agree well with analytical solutions, as well as real practical data obtained such as laboratory measurements and field data (Wang, 2011).

3.4 Human response modelling

3.4.1 Human factors in the risk analysis

Human factors now attract more and more concern because of human action's large contribution to the probability of system failure. Hirschberg (1990) reported that the contribution of human actions to Probabilistic Safety Assessments (PSA) can be as high as 88% in manmade systems such as nuclear or chemical plants in transport operation research field, it suggest that any meaningful PSA needs to examine human performance (U.S. Department of Transportation, 2003).

Human reliability analysis

Human Reliability Analysis (HRA) is a straightforward extension of PSA for assessing human reliability. Evaluating Human Error Probability is traditionally the main task of HRA (Parker *et al.*, 2007a). Human error refers to humans' contribution to system error (Thorpe, 2012). Typical HRA includes several phases: 1) Identification of human errors, 2) Modelling of important actions, 3) Assessment of probabilities of human actions.

The human factor models for HRA can be classified as first generation and second generation models. The first generation HRA methods such as THERP (Technique for Human Error Rate Prediction) (Hollnagel, 1998) focus on the skill and rule base level of human action. They treat human actions the same as other physical systems. Human error is influenced by performance shaping factors (PSF). The PSF include: Available time, stress and stressors, complexity, experience and training, procedures (including job aids), ergonomics and human-machine interface, fitness for duty and work processes (Idaho National Laboratory, 2005). Though the first generation HRA methods are useful and regularly used for quantitative risk assessments, they are often criticised for not considering the impact of context, organisational factors and errors of commission (Bell and Holroyd, 2009). The second generation models such as CREAM (Cognitive Reliability and Error Analysis Method) (Xie and Sun, 2007) are enhanced by allowing the consideration of context and errors of commission in human error prediction. They emphasize more of the cognitive mechanisms of human activities. However, most of the second generation methods are still under development and need to be empirically validated (Bell and Holroyd, 2009).

Task analysis is the first step of the HRA where the system is deconstructed, dividing human actions into sub-actions, such as detection, diagnosis and manual actions and PSF are analysed. As a result, a human error event tree is developed to indicate the sequence of actions and the possible failure in each task step that leads to human error.

HRA assumes that time is a key issue that affects human behaviour, so probability distributions for diagnostic time called TRC distribution (time reliability correlation) should be considered. TRC models are best suited for actions after an initiating event, especially when the available time is short.

Human reliability analysis provides a complete way of integrating the contribution of human factors to a risk event into the probabilistic risk analysis approach. HRA outlines a basic but practical approach for how to analyse human factors in the system. This can be used for setting up the framework for analysing human factors in the flood event management. However, human reliability analysis is more suitable for the system, which can be described as a linear sequenced event, in which human error can be clearly identified. Unfortunately, flood risk management is not such a simple system, as human actions cannot be easily identified as right or wrong actions. Comparatively, human actions in the flood event are more likely to be trade-off actions according to their behaviour rules in the context of an open and complex system.

Resilience engineering

In recent years, the core concept "Human Error" has been questioned, especially when the HRA is used in more complex systems. It is increasingly recognised that accidents were not the conclusion of a sequence of humans' incorrect actions but emerged from the complexity of people's activities in an organizational and technical context (Dekker *et al.*, 2008). Therefore, the variability of human performance and how to manage the variability should be the focus of this approach, which is called Resilience Engineering.

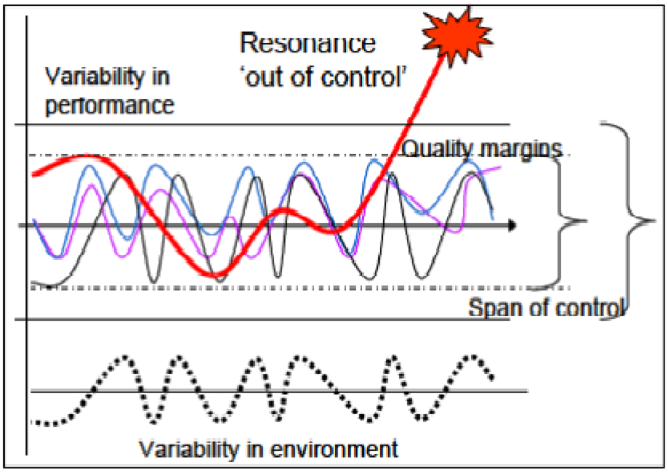


Figure 3-3 Functional resonance accident model (Hollnagel *et al.*, 2006)

Resilience Engineering uses the principle of resonance to represent how the variability of normal performance can combine dynamically in ways that may lead to disproportionate (non-linear) effects. This is shown in Figure 3-3.

This model describes how the functions of (sub) systems may, under unfavourable conditions, resonate and create situations that are running out of control and hence are unwanted. The consequence of using this model is the search for function (process) variations and conditions that influence each other and then may resonate in the case of risk analysis, or have resonated in the case of accident analysis.

The performance is never stable in an open system. There is internal variability due to the adaptations required by resource constraints, and external variability due to changes in the environment is normal. System variability is also desired since it allows learning from high and low-performance events (Hollnagel *et al.*, 2006). Human performance may vary due to psychological (e.g. affecting perception and vigilance), organizational (e.g. organizational goals, stretching resources), social (e.g. social expectations), contextual (e.g. severe working conditions) factors or other unexpected factors (Eurocontrol, 2009). In order to describe the characteristic variability of the system, observable, valid and sensitive performance indicators are required.

Resilience engineering inherited the basic process of analysing the human factor contribution to the system from the HRA. However, it places more emphasis on safety management in a complex system such as flood risk management, in which the entities in the system have non-linear interactions between each other and the emergence is the characteristic of the system failure (Dekker, 2001). However, as it is in the early stages of conceptual development, Resilience Engineering is qualitative and difficult to apply operationally. It is difficult to identify effective and quantitative performance indicators.

In this research, there is an attempt for common measurements of flood risks such as loss of life and flood economic damage to be taken as performance indicators in order to apply the Resilience Engineering concept to the practical flood event management system.

3.4.2 Human behaviour in flood disasters

Human factors have been more widely accepted as a variable that significantly impacts on flood emergency management. A better understanding of both individual and organisational human behaviour during a flood would obviously lead to more efficient emergency management. Some fruitful research studies on human behaviour in a disaster have been studied by sociologists to form a new branch of disaster sociology. In this part, the main sociological research on human behaviour in disasters as well as flood survey results will be summarised in order to outline the basic human behaviour rules for a human response simulation model.

Disaster Sociology demystifies some myths about human behaviour in disasters. Empirical studies show that human behaviour in disasters is rational instead of panic-stricken (Quarantelli, 1988). Human behaviour in disasters is a convergence of individuals (Fritz and Marks, 1954). The chaos of the disaster is an emergent phenomenon of the collective behaviour of individuals. Disaster victims react actively, not passively in a disaster. They do not wait for offers of aid from organizations (Quarantelli and Dynes, 1977). Although fear is present, they behave in a reasonable manner and are often very adaptable. They react immediately, attending to their well-being and helping those nearby.

Another significant contribution of disaster sociology is to outline the timeline and the structure of human behaviour in disasters. In the 1960s, the famous disaster lifecycle (response, recovery, preparedness and mitigation) was summarised (Mileti *et al.*, 1975). Drabek invented the concept of the human system response, which covers responses of different levels According to the increased complexity in structures, the structural dimension includes six categories: individual, group, organisational, community, society and international response systems. The temporal dimension is disaster phases, which is fourfold: preparedness, response, recover and mitigation, and each of these phases were then subdivided into 2 subtopics (Figure 3-4) (Drabek, 1986).

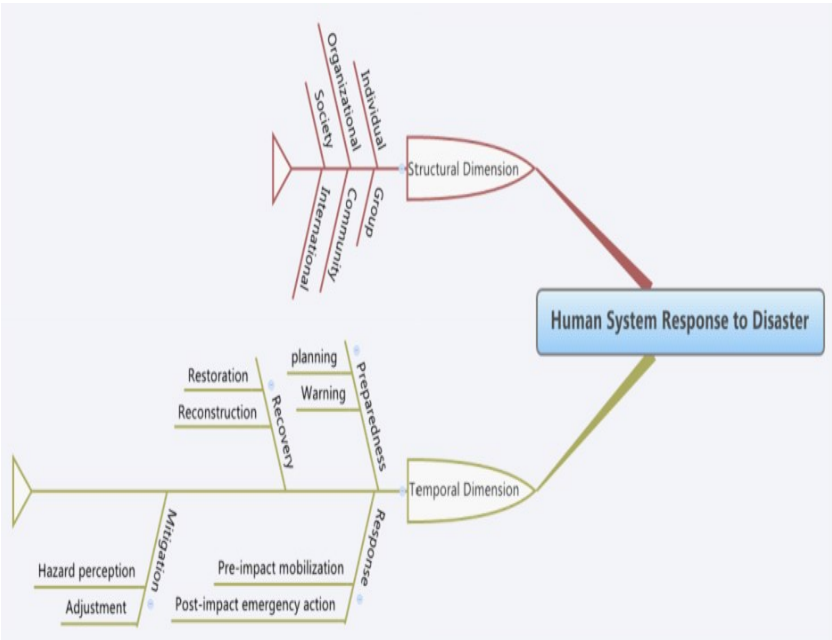


Figure 3-4 Time dimension and structural dimension of human response to disaster adapted from (Drabek, 1986)

The timeline and the structural framework are helpful for deconstructing the human behaviour in the flood event into parts for risk analysis. The research focuses on the human behaviour in a flood event for flood incident management, where the first two phases, preparedness and response, are emphasised. Only human behaviour research on preparedness and response in a temporal dimension are of interest. In the structural dimension, Towyn, a coastal town in North Wales is taken as the case study area, and the larger structural scales such as society and international level human behaviour are excluded. Group level and community level are also omitted because there is ambiguity surrounding their definitions as well as very little practical data. For example, a family is categorized as a group but a household is categorised as an individual. As a result, only human responses at individual and organisational levels are considered in my research.

Liu outlined human response to a flood disaster into two phases, as shown in Figure 3-5, in which both flood warning and evacuation order are included in the warning phase.

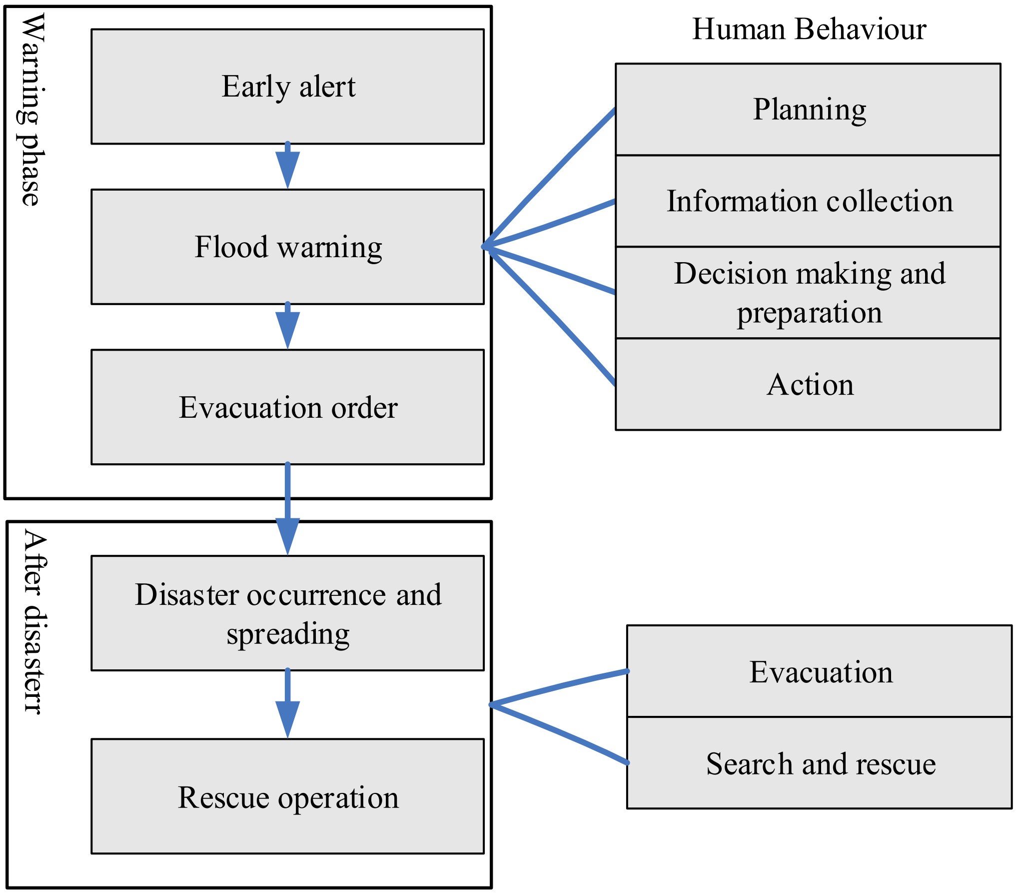


Figure 3-5 Human behaviour in the flood disaster process (adapted from (Liu *et al.*, 2005))

At pre-flood phase, possible emergency actions corresponding to the flood warning are listed (Fielding *et al.*, 2007) in Table 3-3. The initial reaction to a warning is disbelief, and people try to deny that they might be in danger. Then they want to confirm the message (Drabek, 2007). Upon receiving a disaster warning, people engage in the confirmation-seeking behaviour. The context rather than the content of the message is more important in influencing the response. Individuals intend to assess the validity of the information. During the flood, human responses include evacuation, search and rescue and flood fighting. When warned adequately of an approaching natural disaster, over half of the threatened population will evacuate upon receipt of official advice (Perry *et al.*, 1982). 84% of families left in their cars. Vertical evacuation is more frequently considered than horizontal evacuation.

Table 3-3 Potential actions corresponding to the flood warning

List of potential actions	Categories
Do nothing	Do nothing
Watch water levels	Form own assessment of flood risk
Listen/watch out for warnings	
Listen to local/national radio/TV stations for further information	
Check the Environment Agency website	
Contact friends and family for help and advice	Seek advice and/or information
Contact Emergency Services (Police/Local Council)	
Contact the Environment Agency for further information (i.e. Floodline)	
Block doorways/airbricks with sandbags etc	Take steps to minimise water entry to property
Put flood boards or flood gates in place	
Block toilet	
Move valuable/personal belongings upstairs or to a safe place	Protect personal property
Move property out of reach of the flood (e.g. put furniture/appliances on bricks or empty bottom shelves)	
Move cars to a safe place	
Warn your neighbours	Help others
Help neighbourhood/community prepare for flood	
Prepare or move pets/livestock to a safe place	Prepare to evacuate/prepare and muster people/pets to safety
Keep track of family members and pets	
Take warm clothing and/or food/water/medication to a safe place	
Move yourself or others in the household to a safe place	
Be prepared to be evacuated	
Switch off gas and/or electricity	
Be prepared for a loss of power (e.g. take a torch)	
Lock/secure home	

There are many factors that influence human behaviour during a flood event. Individuals' decision-making is influenced by demographic and social economic status (SES) such as variables like gender, age, race, education level and work status (Cutter *et al.*, 2003) (Grothmann and Reusswig, 2006). Both low and highly educated people disregard warnings while middle SES are more likely to accept a formal warning. Women are more likely to interpret a signal as being valid than men are. The elderly are more reluctant to believe a warning (Mileti *et al.*, 1975). In the UK, flood experience, length of time at present address, age and class all appeared to have an important effect on flood warning awareness (Burningham *et al.*, 2008). People with flood experience were quicker to accept warnings. However, the "cry wolf " syndrome may emerge (Irish and Falconer, 1979; Smith and Tobin, 1979). In the UK, warnings are very often ignored until the flood damage has become inevitable (Thrush *et al.*, 2005).

Recently, surveys on flood perceptions and institutional reactions to a flood event have appeared (Raaijmakers *et al.*, 2008; Hopkins, 2012; Kellens *et al.*, 2013). Hopkins (2012) conducted a survey on residents' flood responses in Ryedale, North Yorkshire to the flood perception changes after the 2005 flash flood there. This provides a better understanding of how the experiences have impacted on residents' awareness of floods. However, the whole map of the residents' timeline of action in the flood event and how their changing behaviours impact on the flood risk are still not clear.

The quality of the warning message is also an important factor (Fielding *et al.*, 2007). Message quality is related to three factors: 1) content, 2) source and 3) number (Mileti *et al.*, 1975). If the information is vague and not specific, by adding their original denial attitude, people tend to define the risk as low (Perry *et al.*, 1980). A flood warning should be regarded as significant in order to deliver the information successfully (Handmer and Parker, 1989).

In the area of organisational behaviour, the research is mainly focused on the organisations involved in the warning process and the most typical responses. It is quite common that warnings sent from the media are general and not specific enough. It is also noted that organisational effectiveness is not only decided by the inter-organisational structure, but also by the interdependency between the multi-organisational systems. The co-ordination is multi-organisational, and communication is a key factor for a better post-impact response. For example, when a disaster takes place, organisations might confront various voluntary organisations that are willing to help, but are not easily integrated into the organisational structure. It is said that the more centralized the authority structure of an established organization is, the more routine the disaster response is, but the less adaptive the organization is in providing non-routine solutions (Krep and Bosworth, 1993). Therefore, the effectiveness of an organisation's rescuing activity may depend on the flexibility of its structure and its ability to adapt its procedures to the ongoing activity (Wenger, 1977).

By reviewing key sociological research findings related to human behaviour during disasters, it is noted that a structural and conceptual foundation for the framework of the human behaviour model can be established. However, many of these research studies are qualitative rather than quantitative. They are inefficient for developing a numerical social simulation model. It is expected that statistical survey data on human behaviour in a flood event could supplement a human behaviour simulation model.

The data from the post-flood warning is very useful for modelling the individual human responses to a flood event. It can be adopted to parameterise an FIM simulation model. However, it is only limited to the individual level and just for flood warning reactions. Data for validating the model is still limited, and therefore uncertainty about the model is inevitable. Therefore, uncertainty analysis is necessary for the research. In the section 3.6 methods for controlling model uncertainties will be discussed in detail.

3.4.3 Human behaviour modelling

Flood exercises

As it has been realized that a positive response can reduce flood risks, flood exercises are carried out all over the world to enhance better flood responses. For example, in the Netherlands, flood exercises are regularly conducted. In the UK, there is a national flood exercise – Watermark (DEFRA, 2011a). The flood exercises do give both the residents and organizations involved a good practice, however, it is not only costly but also inconvenient. Furthermore, only one flood scenario can be tested, even if the flood planning is done according to experiences from flood exercises. Thus there is still great uncertainty for the next flood hazard.

Social simulations

With the development of artificial intelligence, computer science has made it possible to simulate human intelligence using computers. Since 1996, artificial intelligence has been applied to simulate social behaviour (Epstein and Axtell, 1996) and social simulation has become a field that attracts a wide range of research interest. In the social simulation, computers support human reasoning activities in order to simulate the scenarios of a complex non-linear society system, which are difficult to study with classical mathematical equation-based models.

There are two levels of social simulation: macro simulation and micro-simulation. Macro simulation tries to simulate the social system at the whole system level. For example, when trying to simulate traffic flows, pedestrians are taken as a non-turbulent, Newtonian fluid (Helbing *et al.*, 2000). Very few simulations simulate human response in the context of a flood event. MASSVAC is computer software that simulates population evacuation under the threat of flooding as a result of dam failure. It looks at the evacuation process on the network by focusing on major road arteries at the macro level (Alsnih and Stopher, 2004). It performed well for small rural community evacuation under the threat of dam failure flooding. The research demonstrates that computer simulation would significantly enhance the potential for flood emergency management. However, the simulation represented a unique type of flood – a dam failure and only represented a limited part of the transportation system. Simonovic and Ahmad (2005) implemented a computer-based dynamic simulation model for flood evacuation emergency planning. The model simulated the procedure of Red River Valley citizens' flood evacuation behaviour in Canada. People's decision processes and flood responses were simulated. In the study, the practical survey data was combined with systems dynamic simulation model, although the model only captures the gross number of people evacuated, due to its macro dynamic modelling limitation. Human behaviour's emergent character and their spatial features in flood events are not shown in the model. For example, it is unable to identify roads that are likely to be congested as a result of the flood event evacuation, or even roads that will be cut off during a flood.

Agent-based model

Micro simulations that are represented by agent-based model simulation are now taken as a mainstream social simulation due to their strong ability to simulate the emergent phenomena, as well as the interactions between social agents in the system.

1) The definition of the agent-based model

An agent-based model (ABM) is a bottom-up simulation approach that consists of agents and their environment (see Figure 3-6). Agents are entities that have the intelligence of being self-driven and are self-organizing, thus able to make decisions according to some predetermined behaviour rules. Although each agent behaves individually, they interact with other agents and the environment. An ABM can display agents' collective behaviour patterns and has often been used to demonstrate the dynamics of a system. The emergent behaviours that are not easy to capture can be observed through ABM. In the recent developments of ABMs, agents have the ability to self-learn and adapt (Bonabeau *et al.*, 1999).

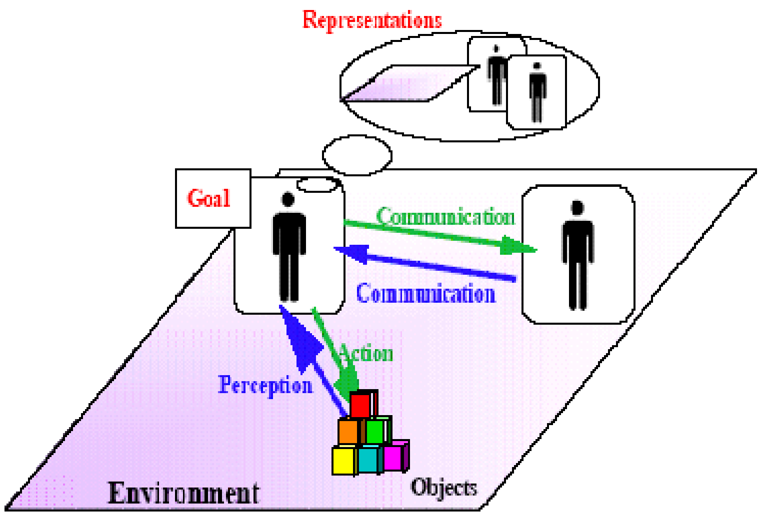


Figure 3-6 ABM system general organisation and principles (Ferber, 1999)

2) The benefits of the agent-based model

The advantages of ABM compared with other modelling methods are:

- ABM describes a system in a natural way

ABM models a complex system in the most natural way by identifying the set of behaviour rules of agents. There are no restrictions on the style of the agents' rules: both mathematical equations and simple action commands identified can be accepted by ABM. Therefore, ABM makes it possible to describe some complex systems, especially social systems such as traffic jams and the stock market that has interrelationships that are too complicated to be summarized by mathematical equations, and thus mathematical analysis is very limited and intractable.

- ABM captures emergent phenomena

ABM's bottom-up microscopic simulation examining individual behaviour naturally captures emergent phenomena in the process (Bonabeau, 2002). Usually the emergent phenomena are difficult to trace and predict, and the features are different and even contradictory to the features of the single systems constituting the unit. Due to its ability to describe the interactions between agents and the environment, ABM is capable of displaying the appearance of novel patterns and properties during the evolution of a system. For example, Craig Reynolds (1987) formulated 3 simple rules for each agent (bird) in the model Boid to simulate collective behaviours of a flock of birds, which is an emergent phenomenon, was obtained. Boid model proves that collective behaviour can be deduced from simple agent rules, and small changes in an agent's rules can have a striking impact on the group's behaviour. ABM seems to be the most appropriate method to use to simulate the system in which emergent novel results are important for the system.

3) ABM applications for disaster management

ABM has been widely used in studies both on the environment and socioeconomic systems. It is also used to support disaster management such as fire evacuation, helping to identify the benefits of fire prevention measures, potential problems (e.g. overcrowded evacuation routes) by analysing simulation outputs. Some reliable and efficient computer models have been successfully applied to simulate disaster evacuation such as Egress, which was developed by the UK Atomic Energy Authority in 2002, GridFlow developed by the Fire Research Service (FRS) and EXODUS developed by Greenwich University (Johnson, 2005). However, these models have focused on small areas such as an airport, ship or building.

4) Potential for FRM

In general, ABM seems to be the most suitable simulation model for simulating human behaviour in a flood event. However, there are some challenges in applying ABM to simulate human response in the context of flood events.

First of all, spatially, the scale of a flood emergency simulation is far larger than other types of disaster simulation such as a fire or shipwreck. Also, the simulation scales are very limited. Few models can simulate a mass evacuation movement in a large spatial area such as a town. Because of flood emergency simulation, the scales range from a town to a city or a catchment. ABM has to be integrated with a Geographic Information System (GIS), which includes all the methods and techniques for processing and analysing spatial data, in order to simulate a large-scale disaster such as flood events.

Secondly, there is a need for accurate representation of the flood. The existing model cannot meet the temporal requirement in the field (Cutter *et al.*, 2003). For the environmental context of the human response simulation, the hydro-dynamics of a flood have to be simulated.

Thirdly, human behaviour in a flood event has its unique features. Compared with human behaviour in a fire, people in a fire make decisions in a panic but in a flood event, people's decision-making is often more rational (Fielding *et al.*, 2007). It is only when their stress exceeds their psychological strength (e.g. perhaps in a flash flood) that panic is more likely. Therefore, a new social simulation model that can describe human behaviour during a flood event is required.

The Life Safety Model (LSM) is apparently one of the complete models that combine the hydrodynamic model, GIS and the human behaviour model. With LSM, the dynamics of the flood as well as human evacuation behaviour in a large area can be simulated (Tagg *et al.*, 2013). This model has been successfully used for preparing flood evacuation planning. However, human behaviour in a flood event does not include flood evacuation, therefore, how to improve people's response to flood warnings should also be investigated. This needs a more complex human behaviour model.

Furthermore, a series of risk-based performance indicators for interpreting simulation results need to be established. The aim of human response simulation in flood events is to help emergency planners to evaluate the impact of non-structural measures to flood risk. Simulation serves as an appraisal of flood risk mitigation measures. Existing simulation models are more focused on the details of how to simulate human behaviour instead of the appraisal of the performance of the system. Therefore, in this research, a risk analysis model is designed to fulfil this function.

This research takes a risk-based ABM model integrated with GIS to simulate not only the hydrodynamics of a flood but also the unique features of human response in a flood event, for the benefit of appraising emergency decision-making in terms of flood risk

3.5 Flood impacts and vulnerability

In the risk analysis theory, one of the most important concepts is the quantification of risks, and the kind of measurement we use to evaluate the risks is the foundation of this flood risk analysis approach.

It is suggested that the potential harmful consequences considered in assessing risk include:

(a) Human health

(b) The social and economic welfare of individuals and communities

(c) Building and infrastructures

(d) The environment (including cultural heritage)

With the development of flood risk analysis, some practical risk measurements have been widely used such as flood damage or mortality. Here, we will review some of the main flood risk measurements such as loss of life and flood damage. Furthermore, the measurement for evaluating flood risk to vehicles is discussed.

3.5.1 Loss of life

Floods are cited as being the most lethal of all natural disasters (Alexander, 1993). Floods cause the loss of thousands of lives every year all over the world. In the process of flood risk analysis, loss of life (flood death or flood fatality) is always an important type of consequence of flood incidents (Jonkman, 2007). In this part, the definitions of flood fatality and the methods of estimating flood fatality will be provided.

Flood fatality definition

Flood fatality, also called “loss of life in floods”, “flood mortality” and “killed by flooding” refers to a fatality that would not have occurred without a specific flood event (Jonkman and Kelman, 2005). However, it is an ambiguous concept because it can be explained in different ways under different circumstances.

Flood death toll is the most common reported figure for flood fatality. Flood tolls are often carried out during or soon after a flood event and show the number of deaths due to the flood event. The flood fatalities counted in the flood toll are caused by the physical aspects of the flood water such as drowning.

Another kind of flood fatality statistics is mainly from health and epidemic research, which assess the immediate deaths but also some delayed deaths due to psychological effects or disease. It is observed that the socioeconomic and health conditions of the community are a significant factor that determines the flood death and injuries (Ohl and Tapsell, 2000). Bennet (1970) observed a higher mortality rate in the flooded area compared with the non-flooded area after investigating the longer-term effects of floods on mortality after the 1968 floods in Bristol, United Kingdom. Strong evidence shows the correlation between psychological health effects and mortality in flood disasters. However, quantitative assessments are difficult due to the challenges of long-term data collection and definitively attributing a specific death to a particular cause long after an event (Jonkman and Kelman, 2005).

As this research is for flood emergency management, only half of the disaster cycle - the preparation and response phases, are emphasised. Further, the flood planners are more concerned about the risk to people due to the floods. The flood death definition used by the flood toll is more suitable for this research. Specifically, the flood death mentioned here is a direct flood death due to the physical upload of flood water.

Estimation of flood death

In order to assess the flood risks and to identify the mitigation strategies, many methods of estimating loss of life due to floods have been developed, based on the main factors that influence the loss of life in flood events. Jonkman notes that flood risk to people can be considered at individual or societal scale. Individual risk refers to the probability of an individual being exposed to the flood and being in danger, while societal risk refers to the probability of a flood incident with a large number of fatalities (Jonkman *et al.*, 2011).

1) Societal risk

One metric of societal risk is the flood mortality function. Flood mortality is defined as the fraction of the inhabitants of the flooded area that have lost their lives in the flood (Jonkman, 2003):

$$M = N_f / N_T \quad \textbf{(3-17)}$$

Where:

M: Mortality
N_f: Number of fatalities
N_T: Total number of affected persons

The rule of thumb has been widely used in the practical flood risk assessment process and assumed that the loss of life due to the flood is about 1% of the exposed population (Sebastian Nicolas Jonkman, 2007). This rule agrees with the overall number of fatalities for some historical flood events such as the 1953 flood in the Netherlands and the flooding of New Orleans in 2005.

According to the observed practical flood death data, many mortality functions were deduced for different types of floods in different locations in the world (Tsuchiya and Kawata, 1981; Boyd, 2005; IPET, 2006; Jonkman, 2007), and these models attempt to determine the relationships between the flood mortality and water depth. Besides, the variations in flood warning, evacuation and shelters for different flood events at different locations are not taken into account.

In England, a method of assessing the flood risk to people was developed by Flood Hazard Research Centre (FHRC) (Penning-Rowsell *et al.*, 2005). The method of calculating risk to people is expressed as follows:

$$E = f(F, L, P) \quad \textbf{(3-18)}$$

Where:

E = Nature/extent of effects (on those exposed)

F = Flood hazard characteristics (depth, velocity, etc.)

L = Location characteristics/area vulnerability (inside/outside, nature of housing)

P = Population characteristics/people vulnerability (age, health, etc.)

Flood hazard describes the flood conditions in which people are likely to be swept over in a flood with the possibility of drowning, and is a combination of flood depth, velocity and the presence of debris.

Area vulnerability describes the characteristics of an area of the floodplain that affect the chance of being exposed to the flood hazard. The variables used to calculate area vulnerability are:

- Flood warning: Including % of at-risk properties covered by the flood warning system; % of warnings meeting the two-hour target; and % of people taking effective action (score).
- The speed of onset of a flood: (Score).
- Nature of area: Multi-storey apartments; typical residential/commercial /industrial properties; bungalows, mobile homes, campsites, schools, etc. (score).

People vulnerability describes the characteristics of the people affected by flooding and their ability to respond to ensure their own safety and that of their dependants during a flood. The variables used to calculate People vulnerability are the percentage of residents aged 75 years or over and the percentage of residents suffering from long-term illness. People Vulnerability is the combination of these two factors. The method is applied to three case studies covering past river floods in the UK, and the obtained results agree with the observed historical data.

FHRC's risk to people model considers the flood mortality from different determinants of flood, location and population characteristics, which gives a detailed description of the driver of flood mortality. However, the model is based on the macro level. It is not suitable for the ABM micro-simulation.

2) Risk to individuals

In the process of modelling mortality function, the importance of flood risks to individuals emerged. Several research studies focus on the flood impact on individuals. In terms of individual level, the loss of human stability and consequent drowning is the highest personal risk (Jonkman and Kelman, 2005). Human instability in flowing water has been investigated and shows that the product of water depth and velocity would cause a person's instability (Jonkman and Penning-Rowsell, 2008).

Abt et al. (1989) derived an equation from the resulting empirical data to estimate the critical product hV_c at which a human subject becomes unstable as a function of the subject's height and mass (equation 3-19). Based on the test of a person's height and mass (Karvonen *et al.*, 2000) it was found that the critical depth velocity products are between 0.64 m2/s and 1.29 m2/s. Suetsugi (1996) reports that these results indicate that people will experience difficulties in walking through water when the depth–velocity product exceeds 0.5 m2/s.

$$hV_c = 0.0929(e^{0.001906Lm+1.09})^2 \quad \textbf{(3-19)}$$

Through laboratory experiments, it has been proved that the often-used depth-velocity (hv) product has a physical relationship with moment instability (Jonkman and Penning-Rowsell, 2008). Penning-Rowsell et al. (2005) proposed an equation to relate the flood hazard to people to the depth and velocity of the water as well as the amount of debris that is in the water. The flood hazard rating is calculated using the following equation:

$$HR = d \times (v + 0.5) + DF \quad \textbf{(3-20)}$$

Where,
HR = (Flood) hazard rating
d = Depth of flooding (m);
v = Velocity of floodwaters (m/sec);
DF = Debris factor

The flood hazard can be estimated and then categorized as 'low,' 'moderate,' 'significant' or 'extreme' as shown in Figure 3-7.

d * (v+0.5) + DF

Velocity \ Depth	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.00	0.13	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13	1.25
0.50	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
1.00	0.38	0.75	1.13	1.50	1.88	2.25	2.63	3.00	3.38	3.75
1.50	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00
2.00	0.63	1.25	1.88	2.50	3.13	3.75	4.38	5.00	5.63	6.25
2.50	0.75	1.50	2.25	3.00	3.75	4.50	5.25	6.00	6.75	7.50
3.00	0.88	1.75	2.63	3.50	4.38	5.25	6.13	7.00	7.88	8.75
3.50	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
4.00	1.13	2.25	3.38	4.50	5.63	6.75	7.88	9.00	10.13	11.25
4.50	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25	12.50
5.00	1.38	2.75	4.13	5.50	6.88	8.25	9.63	11.00	12.38	13.75

Categories of flood hazard:

	From	To	
Class 1	0.75	1.50	Danger for some
Class 2	1.50	2.50	Danger for most
Class 3	2.50	20.00	Danger for all

Note: The table gives values of flood hazard (= d·(v+0.5) +DF)

Figure 3-7 Flood hazard index by FHRC (Penning-Rowsell *et al.*, 2005) (the level of hazard to people can be estimated and then categorized as 'low' (yellow)', 'moderate' (orange) and 'significant' (red)).

Compared with societal risk analysis, individual instability research is more significant to this research that is mainly based on the individual behaviour simulation. Therefore, the individual instability research can be directly used for individual behaviour modelling.

3.5.2 Flood damage

In terms of the consequences of flooding, the flood damage has been one of the most important risk measurements used. Here the estimation methods of flood damage as well as the human behaviour's impact on the flood damage are reviewed, so that a suitable way for calculating the human impact on the flood damage can be developed.

Flood damage definition

Flood damage refers to the economic cost caused by a flood disaster. There is a wide range of research on flood damage, in which the definition of flood damage varies. A classification of various types of flood damage is listed in Table 3-4, where the flood damage is categorized as direct damage inside the flooded area and indirect damage that occurs outside the flooded area. Tangible damages are damages that can be priced, and intangible damages are those for which no market prices exist (Jonkman *et al.*, 2008).

Table 3-4 Different dimensions of flood damages (Jonkman *et al.*, 2008)

	Tangible and priced	Intangible and unpriced
Direct	• Residences • Capital assets and inventory • Business interruption (inside the flooded area) • Vehicles • Agricultural land and cattle • Roads, utility and communication infrastructure • Evacuation and rescue operations • Reconstruction of flood defences • Clean up costs	• Fatalities • Injuries • Inconvenience and moral damages • Utilities and communication • Historical and cultural losses • Environmental Losses
Indirect	• Damage to companies outside the flooded area • Adjustments in production and consumption patterns outside the flooded area • Temporary housing of evacuees	• Societal disruption • Psychological traumas • Undermined trust in public authorities

Considering this research interest is the FEM and for the convenience of quantitative analysis, only direct tangible flood damage is considered here.

Flood damage function

Direct damages are estimated by flood damage function, which are related to flood characteristics (mainly flood depth) and the extent of economic damage. Here is an example of a flood damage function (Figure 3-8). This figure shows that when the water depth exceeds 4.5m, the flood damage is about 100%. Similar damage functions are deducted according to the practical data in different countries for different flood types.

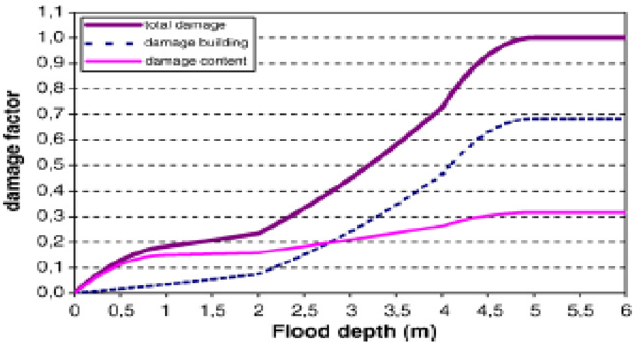


Figure 3-8 Examples of the damage function. (It is assumed that the flood damage is related to flood depth. Flood damage can be total damage, or damage to buildings and contents damage).

The process of estimating direct tangible damage is as shown in Figure 3-9. Firstly the inundation depth is calculated to get the flood characteristics. Secondly, land use data is obtained to decide about the buildings exposed to the flood. Thirdly, the damage functions are applied to the area so that the flood damage map can be obtained.

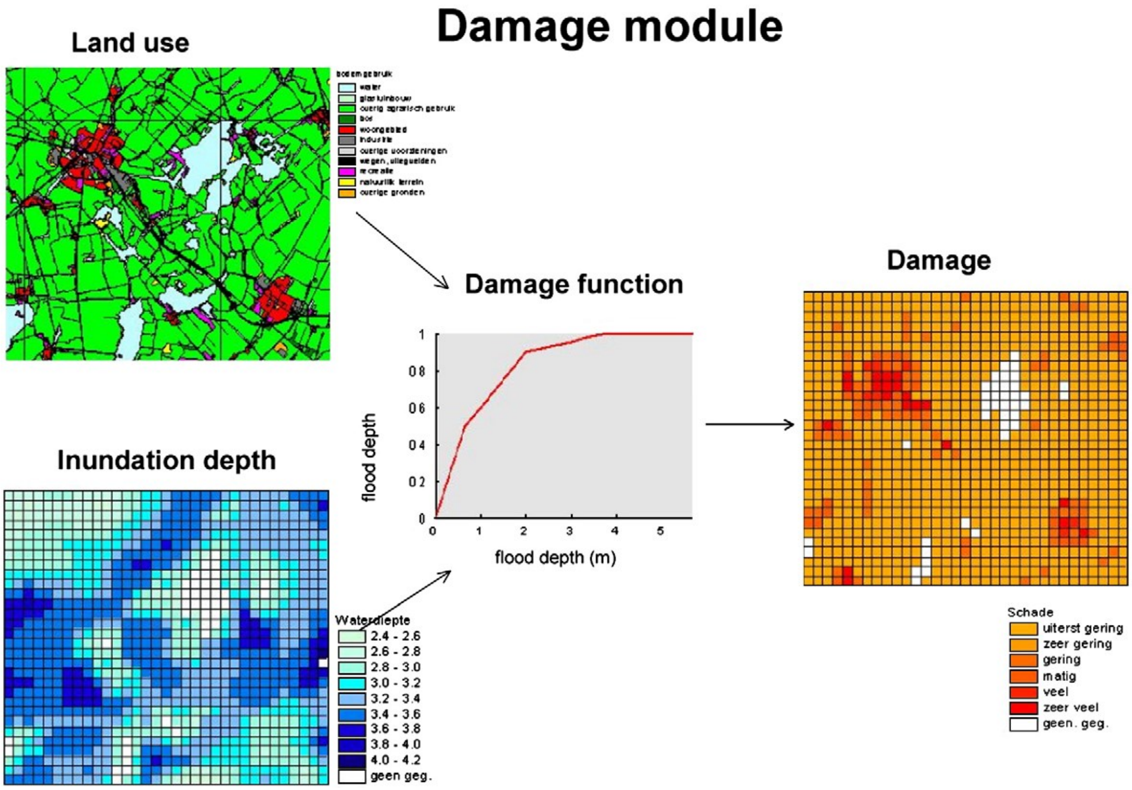


Figure 3-9 Schematization of the assessment of direct physical damages due to catastrophe flooding (Jonkman *et al.*, 2008)

In the UK, the flood damage estimation methods for the UK by FHRC (Penning-Rowsell *et al.*, 2010) bring together information on the impacts of flooding and coastal erosion to provide guidance on appraising flood hazards in the UK. The guidance aims to calculate annual average damages, and nearly all types of flood damage (direct, indirect, tangible and intangible flood damage) are considered. In terms of direct tangible flood damage, the relationships between flood damage and the flood depth are for two types of properties: residential and non-residential. The building fabric depth/damage matrices provide convincing data for evaluating the flood damage during a flood event. This is the main guidance this research used to calculate economic flood damage.

Evaluating human responses impact to flood damage

FHRC had a convincing research on the benefits of flood warning (Parker *et al.*, 2007a; Parker *et al.*, 2007b). The FHRC model emphasises direct, tangible flood damage impacts on individual households. The FHRC's calculation equation for the flood warning impact is given as follows:

$$FDA = PFA \times R^1 \times PRA \times PHR \times PHE \qquad \textbf{(3-21)}$$

Where:

PFA is the maximum potential flood damage avoided

R^1 is the warning system's effectiveness

PRA is the % household available to respond to a warning

PHR is % of response capability

PHE is % response effectiveness

However, the FHRC's flood warning benefit research mainly considers flood warning as one single factor, but how the factors that affect the effectiveness of the flood warning such as the flood warning acceptance ratio, flood warning lead time and the human response to the flood warning were not explored in detail. Carsell (2004) investigated the relationships between the residential contents protected and the length of warning lead time and noted the significance of warning lead time when quantifying the benefits of a flood warning system. It is also noted that in England and Wales, a wide range of key organizations are involved in the flood emergency management and clear and targeted communication is necessary for an effective flood warning (McCarthy *et al.*, 2007). Parker and Priest (2012) identified the process that affects the effectiveness of a flood warning (Figure 3-10).

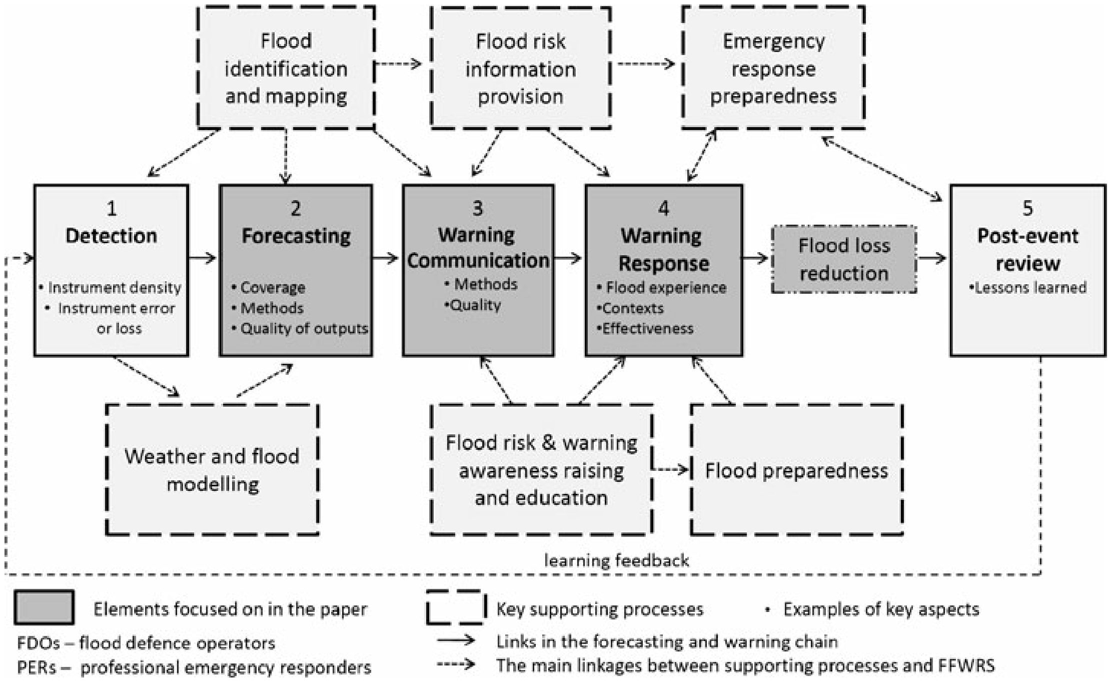


Figure 3-10 The chains that affect the effectiveness of a flood warning (Parker and Priest, 2012)

As human behaviour and response has been recognized as a key issue that impacts on the flood risk reduction, an approach that combines the human behaviour model with the flood damage curve was set up for the problem of flood warning effectiveness (Carsell *et al.*, 2004) in the form of an event tree. The human behaviour model is utilized to identify weak links of the flood warning chain (Molinari and Handmer, 2011). The agent-based model has been utilized to simulate the unofficial channels of flood warning dissemination (Nagarajan *et al.*, 2012). By developing an ABM of evacuee households, the effect of the unofficial channel for warning dissemination is quantitatively analysed. The result shows that even a low proportion of the behaviour of sending warning messages to a neighbour would have a significant impact on the warning effectiveness. However, in Nagarajan's research, human behaviour and responses impact on the flood warning effectiveness is not presented in terms of economic damage.

Research on the impact of human behaviour and responses to floods mainly assesses the benefits of flood warnings. However, the related research has not been integrated into the whole framework of the quantitative flood risk analysis. Therefore, in this research, based on FHRC's flood damage assessment method, a human behaviour simulation model will be integrated into the flood risk analysis framework in order to quantify the non-structural measures' impact on flood risk.

3.5.3 Vehicle instability

In a flood event, when a flood is coming, it threatens not only the residents inside buildings but also those in vehicles. Therefore, the flood risk to vehicles also needs to be calculated.

The research on flood risk to vehicles is limited. Xia (2011) created a formula to predict the incipient velocity of flooded vehicles based on the mechanical condition of a sliding equilibrium, which has been supported by a series of flume experiments using three types of scaled die-cast model vehicles.

In Xia's paper (2011), the instability of vehicles is related to the intensity of the flood, vehicle type (weight, volume) and some other factors such as car density. A formula that represents the relationship between the instability of vehicles and those factors is as follows:

$$U_c = \alpha \times (\frac{h}{h_c})^{\beta} \times \sqrt{2g(\frac{\rho c - \rho f}{\rho f})h_c} \quad \textbf{(3-22)}$$

Where: U_c is the incipient velocity of a vehicle that has been exposed to the flood hazard; ρc ρ_c and ρf ρ_f are the densities of the vehicle and water; h_c h_c is the vehicle height; h is the incoming water depth; α and β parameters are related to the shape of the vehicle, the type of tyres and the road surface, which are determined by flume measurements. In Figure 3-11 the incipient velocity curves for commonly used vehicles parking on flooded roads or streets are given.

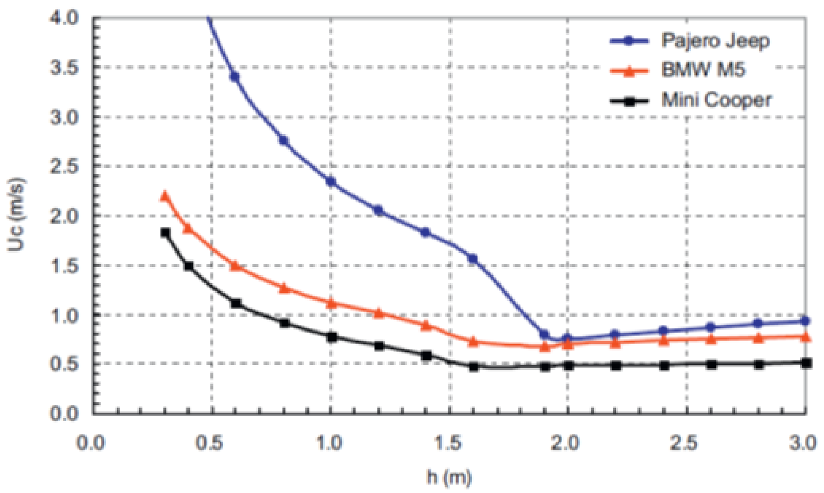


Figure 3-11Relationships between incoming water depths and incipient velocities for three prototype vehicles (Xia *et al.*, 2011)

Xia's method is not only derived based on hydrodynamic water equations, but is also very practical for operating risk assessment. This will be used in the research to evaluate flood risks to the vehicles for traffic planning.

3.5.4 Traffic congestions

For evacuation plan, shelter selection and identifying evacuation route are key issues. These tasks are all closely related with traffic control. Ideally, route capacity can be increased, travel demand resulting from evacuation can be limited and fluent traffic flow can be maintained by better coordination (Alsnih and Stopher, 2004) .

Methods are developed for evaluating shelters according to the shelter selection standard. For example, a location–allocation model was set up to select a set of candidate shelters from among the potential shelters to minimize the total evacuation time (Sherali *et al.*, 1991). Some models simulate both evacuee and the authorities behaviour of setting shelter and routing (Kongsomasaksakul *et al.*, 2005).It is mentioned that for selecting shelters, multi objectives should be considered such as to minimize the travel distances, to minimize the risk faced when travelling, to minimize the risks at the shelters and to minimize the total time used (Coutinho-Rodrigues *et al.*, 2012). As to the evacuation route study, the focus is on the analysis of optimizing the transportation network (Church and Cova, 2000), of which clearing time is the key measurement for the model.

According to the Highway Capacity Manual (HCM 2000), both capacity and quality of a road network are important. The capacity of a facility is the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given period under prevailing roadway, traffic, and control conditions.

The quality measure characterizes operational conditions within a traffic stream. Level of service (LOS) is one such quality measure describing operational conditions within a traffic stream, generally in terms of such service measures as speed and travel time, freedom to manoeuvre, traffic interruption and comfort and convenience. Six LOS are defined for each type of facility from A to F, with A representing the best operating conditions and F the worst (Table3-5). A defined method for assessing capacity and level of service for measuring performances is provided.

The character of urban street flow can be expressed with the variables of free-flow speed (FFS) and travel speed v. FFS is the average speed of the traffic stream when traffic volume are sufficiently low that drivers are not influenced by the presence of other vehicles and when intersection traffic control is not present or is sufficiently distant as to have no effect on speed choice.

Table 3-5 Average travel speed at different operating level of service (Transport Research Board, 2000)

Level of LOS	Operation Description	Average Travel Speed (% of FFS)
A	Primarily free-flow operations at average travel speeds	90
B	Reasonably unimpeded operations at average travel speeds	70
C	Stable operations	50
D	Borders on a range in which small increases in flow may cause substantial increases in delay and decreases in travel speed	40
E	Significant delay	33
F	Urban street flow at extremely low speeds	25

The Equation for calculating average travel speed is as follows:

$$v = FFS \times \frac{1}{1 + \alpha \times (\frac{q}{C})^{\beta}} \quad \textbf{(3-23)}$$

Where:
v : Average travel speed km/h
q: Flow rate cu/ hour
C: Capacity of the road cu /hour
α: The observation parameter usually is 0.15
β : The observation parameter usually is 4.

3.6 Uncertainties and sensitivity analysis

3.6.1 Uncertainties of models

When the flood risk analysis is expanded to the whole flood risk management system, uncertainties are inevitable (Hall and Solomatine, 2010). The flood event management system involves many different agents who have interactions with each other. Therefore, understanding and reducing the uncertainty to a certain extent is a necessity for the research.

Uncertainties can be categorized as aleatory and epistemic uncertainty (Woodward, 2012). Aleatory uncertainty refers to the variable nature of the system, for example, there are some random variables in the system. Epistemic uncertainty stems from a lack of knowledge about the system.

This research model is an agent-based model for simulating a non-linear complex system, with a large number of parameters in the model. In order to calibrate the parameters, a huge amount of data is needed but may not be accessible or obtained (Ouyang, 2014). The validation is very limited. Therefore, understanding the uncertainties of the model is necessary.

3.6.2 Global sensitivity analysis

For the aleatory uncertainty, the Monte Carlo method is available for quantifying the uncertainty. The Monte Carlo simulation is a key step of the probabilistic risk analysis approach, which fits the probability distributions to the sets of simulation results of different scenarios (Rubinstein and Kroese, 2008). As a flood is a natural phenomenon with great uncertainty, the Monte Carlo method needs to be utilized in this research.

Based on the Monte Carlo simulations, recent global sensitivity analysis (GSA) provides a way to understand the uncertainty of a complex system model.

Sensitivity analysis (SA)/uncertainty analysis (UA) is a process of measuring the given input's effect on a model output (Rabitz, 1989), as shown in Figure 3-12. In real practice, if the focus is on the variance of the output, the process is called uncertainty analysis (UA).

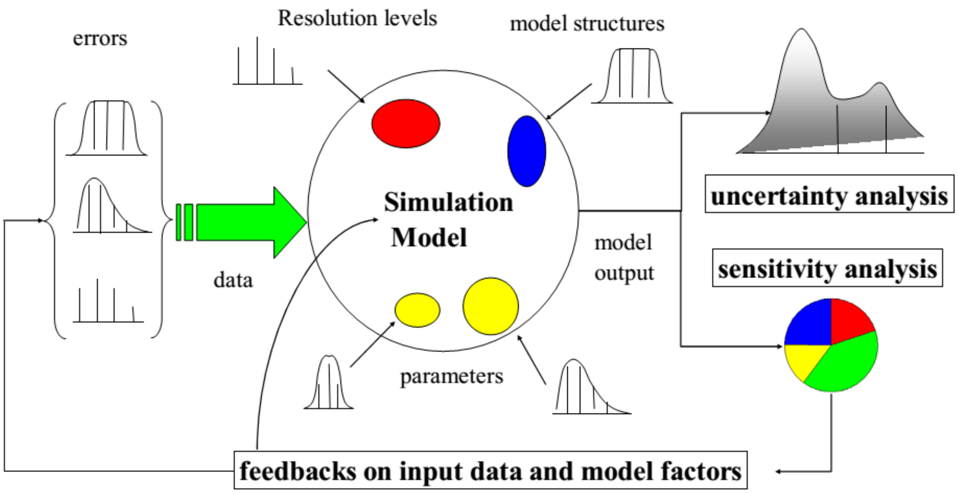


Figure 3-12 An overview of SA/UA process (Tarantola, 2010)

Different from the local or one-at-a-time (OAT) sensitivity analysis, which analyses the variance of one input parameter at a time, GSA decomposes the output uncertainty to the uncertainties of different inputs of in the model (Saltelli *et al.*, 2004).

Variance-based sensitivity analysis is a form of GSA in which uncertainties are measured in terms of variances. The variance of the model output is decomposed by the following equation:

$$V(Y) = \sum_{i} V_i + \sum_{i<j} V_{ij} + \sum_{i<j<m} V_{ijm} + \cdots \_V_{12\ldots k} \quad \textbf{(3-24)}$$

Where:

$V(Y)$: The total variance of the model output Y
V_i: Output variance fraction due to input factor x_i
V_{ij}: Fraction of variance due to interactions between factors x_i and x_j
V_{ijm}: Fraction of variance due to the interactions among the factors $x_{i,}$ x_j and x_m
k: Input factor numbers

Such defined variance can be used to calculate the first order (S_i) and total-effect (ST_i) indices of every input factor x_i ($i = 1,2 \ldots k$):

$$S_i = \frac{V_i}{V(Y)} = \frac{V_{X_i}[E_{X_{-i}}(Y|X_i)]}{V(Y)} \quad \textbf{(3-25)}$$

Where:
X_{-i}: The set of all variables except X_i
$E_{X_{-i}}(Y|X_i)$: The conditional expectation of Y when the particular factor X_i is fixed.
The first order index is the expected variance reduction when Xi is fixed.

$$ST_i = \frac{V(Y) - V_{X_{-i}}[E_{X_i}(Y|X_{-i})]}{V(Y)} = S_i + S_{ij} + S_{im} + S_{ijm} + \cdots + S_{ij\ldots k} \quad \textbf{(3-26)}$$

Where $E_{X_i}(Y|X_{-i})$ is the conditional expectation of Y when all the other factors except X_i are fixed. The total-effect index is the expected variance reduction if all factors except X_i are fixed.

Sobol (1993) provides a GSA technique which is a straightforward Monte Carlo simulation-based method for calculating first order (S_i) and total-effect (ST_i) indices. Sobol's method has been widely used for sensitivity analysis on the critical input parameters of many environment related models (Glen and Isaacs, 2012). The method can work well for complicated models with large numbers of random variables. In this research, Sobol's method will be employed to sensitivity analysis on flood factors and detect source of uncertainty.

There are several advantages of the GSA. First of all the GSA makes it possible to analyse the impact of each input on the output of the model on a global scale, and therefore produces the sensitivities of each input variable and the importance of the variables can be compared. Secondly, it can be applied to non-linear functions. Furthermore, the impact of interactions between the input factors can be measured. As the human behaviour model is a non-linear and complex model with lots of parameters, GSA is utilized in this study to analyse the uncertainty of the model.

3.7 Summary

In this chapter, the methods that are relevant to the modelling flood risk analysis in the flood event process are discussed.

Reviewing flood risk analysis methods has provided a framework for this research. Advances in the appraisal of flood event management approaches will require new and innovative methods to improve upon existing approaches. Following a review of options, a simulation based risk analysis framework is proposed that couples hydrodynamic simulation with human behaviour modelling. A study of the literature in these areas recommends coupling the Newchan shallow 2D model with an agent-based model to capture the dynamics and processes of floodwater and human behaviour. The model will be supported by the research results of disaster sociology as well as post –flood survey data that have been explored in Chapters 2 and 3.

Finally, the flood risks will be measured in terms of loss of life, flood damage and the risk to vehicles and some other spatial risk indicators such as road congestions and traffic flows. The next chapter describes in detail how the model has been implemented.

Chapter 4. Methodology

4.1 Introduction

The previous two chapters reviewed the challenges and possible technical approaches to developing an appropriate FEM risk analysis method. This method should be able to quantify the benefit of non-structural measures, the effectiveness of which is mediated by human factors. Therefore, it is necessary to model human responses during a flood event and thus to estimate their impact on flood risks. The agent-based models (ABMs), which have been used for simulating human behaviour in other safety related fields, have been shown to be one of the most promising approaches to satisfy these requirements.

This chapter describes the risk analysis methodology developed for the flood event management, which is one of the major original works accomplished in this research. Furthermore, the software tool developed on the ABM platform Netlogo is also introduced. The case study described in Chapter 5 and the research results described in Chapter 6 are all based on the methodology and software tool introduced in this chapter.

The chapter first provides an overview of the general model structure before describing individual components such as the flood simulation module, the human behaviour simulation module and the risk analysis module in detail. Then the simulation scenario setting in this research is described.

4.2 NetLogo platform

In recent years, more and more ABM platforms have been developed for the increasing demand of ABM simulations in a wide range of research fields. According to the previous study about the ABM platform and the features of the flood risk management study, the following criteria are identified for selecting the ABM platform.

The first criterion is the ABM platform’s capability of modelling the system. This includes the ability to model agents’ complex behaviour, to visualise the spatial environment (3D, GIS connection) and to display related parameters.

The second criterion is the ABM platform’s software development capability, such as the ABM platform’s type of licences, programming language, resources, GUI and IDE, batch mode and execution speed and so on.

The third criterion is the ABM platform's connection to other software or other models, for example, the connection between statistical analysis software, connection to the database and connection to the flood simulation model.

Considering that the large-scale spatial–temporal feature of flood event human behaviour is the focus of the research, the ABM platform's connections to GIS and connections to the flood simulation model and database are the most important criteria that should be considered.

Railsback et al. reviewed the most widely used ABM platform (MASON, Netlogo, Repast, Java Swarm and Object-C Swarm) by implementing a benchmark model (Stupid Model) on each platform. From the perspective of the scientist lacking software development expertise but wishing to use ABMs for research, the platforms are compared in terms of programming experience, execution speed and model development issues (Railsback *et al.*, 2006). NetLogo is a stable, well-maintained and supported ABM platform that provides a customised programming language and graphical interface to support the development of ABM models. The NetLogo environment also provides an interface for visualising the model in operation. The recent version of NetLogo (NetLogo 5.0) has proved to be an efficient and powerful ABM platform that is widely used.

NetLogo (Wilensky, 1999) is chosen as the ABM platform for this research for several reasons. First of all NetLogo has been successfully applied in human behaviour simulations, which is one of the important aspects of this research. Secondly, NetLogo has a GIS extension for importing spatial data into the ABM platform. As flood event management involves a larger spatial area compared with other disasters such as shipwrecks or explosions, having a good connection with GIS is also very important. Last but not least, Netlogo is open-source software, which not only provides a free license for using the software but also provides all the source code to the developers. To set up a FEM risk analysis tool, one of the major research tasks is the secondary software development on the ABM platform, therefore, Netlogo's developer-friendly interface and documents are a vital reason for the ABM platform option.

In the following part of the chapter, how a FEM risk analysis tool is built up on the NetLogo platform is described.

4.3 General architecture of the simulation model

4.3.1 ABM Procedure

In order to set up the risk analysis approach for flood event management, flood event management related information was collated for the representation of flood and human responses within ABM. Then the flood risks, which are expressed in the widely accepted flood risk currencies, were calculated according to different flood event scenarios simulated, in which non-structural measures and human responses are embodied. Thus, the effectiveness of non-structural measures and the impact of human factors on the flood risk can be evaluated. The generic model framework is designed as shown in Figure 4-1.

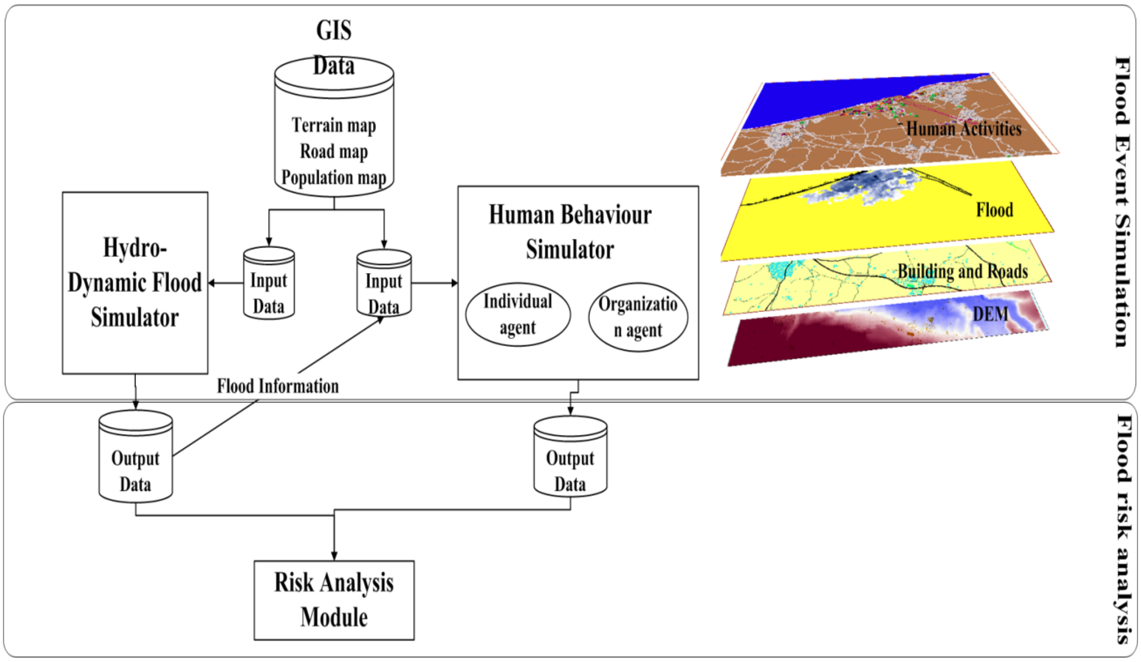


Figure 4-1 System architecture and data flow under agent-based model framework

The model consists of three main components: Hydrodynamic simulator, human behaviour simulator and risk analysis module.

Firstly, GIS data such as elevation, roads is imported to set up a natural and building environment, as well as the transport system. Methods for modelling the building environment and the road network are described in section 4.4.

The hydrodynamic simulator (HDS) simulates the dynamics of the flood wave throughout a flood event. The output of this module together with GIS data formed the (virtual) environment that individuals and organisations interact within. The HDS is described in depth in section 4.5.

The human behaviour simulator (HBS) described in section 4.6 simulate both individuals' and organizational behaviour in a flood event.

The risk analysis module (RAM) described in Section 4.7 quantifies the flood risk based on the flood and human behaviour scenarios simulated. The flood risks are described in terms of the expected loss of life, flood damage and vehicles in danger. Spatial flood risks related to the flood evacuation planning are also analysed.

4.3.2 Agents in the model

In ABM, one fundamental concept is to describe the system with entities (agent) and their behaviour rules, the behaviour rules describe how they interact with each other and their environment. In this model, three classes of entities are required: physical agents, individual agents and organizational agents. The agents in the model are shown in Table 4-1.

Table 4-1 List of agents in the model

Agent Type	Examples
Physical	Land patches, road network, flood defences, shelters
Individual	Civilians, the Police, ambulance workers, EA staff, flood wardens
Organizational	Environment Agency (EA), Police Authority (PA), local authority (LA), fire & ambulance, multi-agency control group (MACG)

- Physical agents are immobile agents that represent different objects in the physical environment. Land patches and road networks represent land grids and the transport system of the area. Flood is the agent representing the flooded water when a flood defence (represented by a defence agent) is breached. Shelters are the places where people escape to in an evacuation.
- Individual agents that represent individual persons can move around the model domain. Civilians represent the civilians living in the flooded area. The Police, ambulance workers, EA staff and flood wardens represent organizational staff that carry out specific tasks allocated by the organization they belong to.
- Organizational agents are immobile agents that represent administrative authorities. For example, the EA, PA and LA represent the Environment Agency,

the Police authority and the local authority. MACG corresponds to the control room.

Agents interact with other agents. Some key relationships are shown in Figure 4-2. Detailed descriptions of these interactions are provided along with an introduction to each agent. Specifically, the physical agents are described in sections 4.4 and 4.5. Individual agents and organizational agents are introduced in section 4.6. In this research, all the agents listed in the Table 4-1 and their interactions shown in Figure 4-2 are all implemented in the ABM model developed.

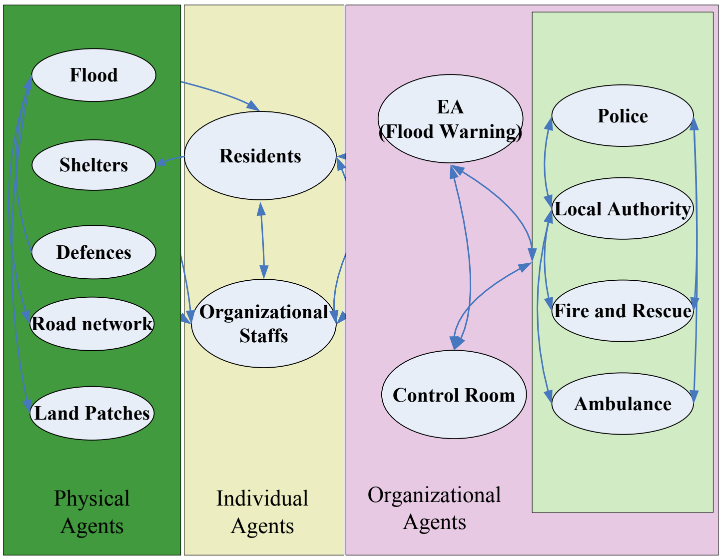


Figure 4-2 Interactions between physical agents, individual agents and organizational agents

4.3.3 Model structure

An ABM has two major tasks: model initialization, which is to set up the initial status of the model; and model scheduling, which is to set the agent's behaviour rules for each time step. The FEM model is described in the following sections in terms of the different sub-functions in the computer code shown in Figure 4-3.

In this model, ***Model-Setup*** for model initialization and ***Model-Step*** for model scheduling are two main functions (the function names in the model are bold-italicised in the thesis). All other functions are clustered around and serve these two central functions as shown in Figure 4-3. All the agent initialization related functions are identified in the module the agents belong to, for example, ***Water-Setup*** is defined in the hydraulic module, ***Individual Behaviour-Setup*** and ***Organization Behaviour-Setup*** are defined in the human behaviour module. However, all the initialization related functions are executed when ***Model-Setup*** is run. Similarly, all the functions, which are related to the modelling agents' behaviour at each time step, are identified in the modules the agents belong to. The functions are triggered and executed when the function of ***Model-step*** is executed. Functions in each module are explained in detail in Appendix I.

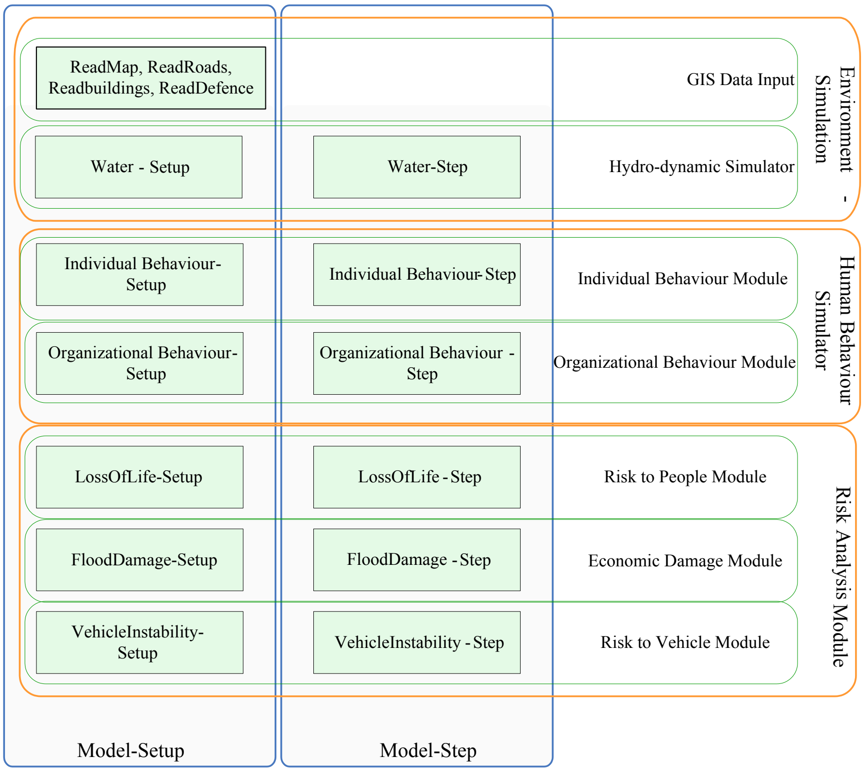


Figure 4-3 Structure of the model functions

4.4 GIS data input

GIS data is imported Netlogo to set up the geographic (spatial) context of the simulation. The area is represented by a rectangular grid of square cells. Each cell is regarded as a land patch (agent). Based on the land patches, a road network is also set up to simulate the transport system.

4.4.1 Land patches

Land patches are the spatial environment where other agents in the model are located. Land patches are also the place and media where different agents interact with each other. Apart from geographical coordinates, a land patch has a set of attributes that are relevant to the flood and human behaviour simulation. DEM and flood defence data are imported for the HDS and land use data, and in particular building type data is imported for the HBS because all civilian agents choose their trip destinations according to the building type attributes (how civilians choose their destination is introduced in section 4.6.3). In Chapter 5, the data sources used for the case study will be described in detail. Land patch also has attributes for recording the simulation result such as *h* for water depth at this land patch, *v* for water velocity, which are obtained from the HDS and the number of people in danger, the number of vehicles stranded or flood damage value for this land patch which are obtained from the RAM.

4.4.2 Road network

In order to simulate human travel behaviour during a flood event, road network data is imported into the model, in which three objects (agents) are used to simulate the transport system, ***road***, ***rlink*** and ***node***. The ***road*** agents correspond to real roads on the map. Once the road is created, the road records the land patches it covers; meanwhile two ***node*** agents and two ***rlink*** agents are produced. One node agent represents the start point node, and the other node agent represents the end point node of the road. The two ***rlink*** agents represent the two directions of the road; one is from the start point node to the end point node, and the other is from the end point node to the start point node. The relationships between ***road***, ***node*** and ***rlink*** agents can be interpreted by Figure 4-4. For one road, it has a start node Node0 and an end node Node1; it also has rlink0 from node0 to node1 and rlink1 from node1 to node0 which enables one- and two-way roads to be modelled, with the potential to switch on a contraflow during extreme conditions as part of an evacuation strategy. Indeed, residents and vehicles travel along the rlink instead of moving from cell to cell (how they travel along the road is introduced in section 4.6.5). The setting of nodes and rlinks makes it possible to differentiate between the travels directions of individual travellers, and the travel flow of the road can be calculated.

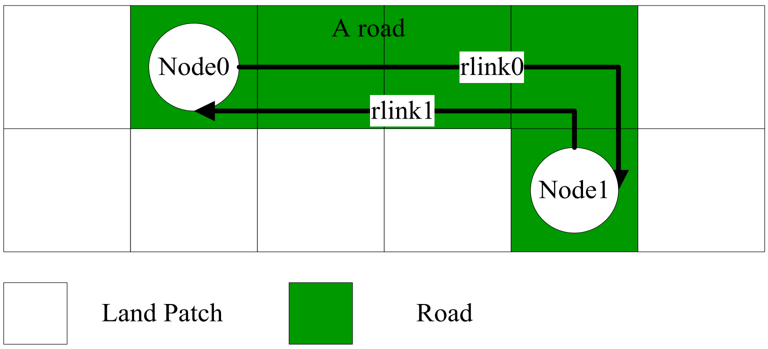


Figure 4-4 Road network representation in the simulation model

4.5 Hydrodynamic simulator

The HDS is used to calculate the land patches' hydraulic attributes including the water velocity (*u*, *v*) and the water depth (*h*). On reviewing the numerical models of flood simulation, it shows that CFD provides methods for simulating flood extent accurately. A full-shallow 2D model that obeys the conservation of mass and the conservation of momentum principles has a better simulation result for flood velocity than 2D model diffusion models that only obey the law of mass conservation, therefore it is more suitable for use in flood simulation for flood emergency management, where time prediction is vital to the decision-making.

Here the implementation of a finite-volume Godunov-type scheme solving the full 2D shallow water equations on the ABM platform is explained.

The initialization of the HDS module involves importing DEM data, identifying the source water flux and the flood defence breach information, in addition to setting the initial values of water velocity (u, v) and the water depth (h) at zero.

Model scheduling, which is mainly implemented in the ***Water-Step*** function in the model, is used to set the flood water behaviour rules for every time step. The land patches' water velocity and depth are changed according to a finite-volume Godunov-type scheme numerical solution. The flood water behaviour rules are as shown in Figure 4-5.

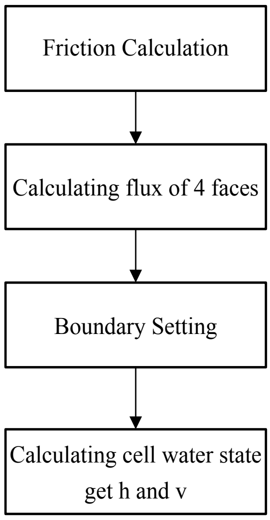


Figure 4-5 Flow chart for HDS schedule (h and v are the water depth and velocity)

4.5.1 Friction calculating

The friction calculating step is to solve the friction terms using an implicit solver; meanwhile wet/dry cells are categorised. In a practical situation, bed friction significantly influences the flow dynamics. Calculating the friction is an important step in flood modelling. A splitting point-implicit scheme is used to calculate the friction component (Fiedler and Ramirez, 2000). In the calculation, Manning's coefficient (n), which represents surface roughness, is the only parameter that needs to be calibrated. In this study, the coastal area is identified as a developed, medium density area. So the Manning coefficient is set at 0.018 (USDA, 1986).

4.5.2 Calculating fluxes through the four cell interfaces

The calculation of the numerical fluxes across the four interfaces of each cell involves the flow variables from the previous time step at the cell under consideration and its four neighbours, as shown in Figure 4-6.

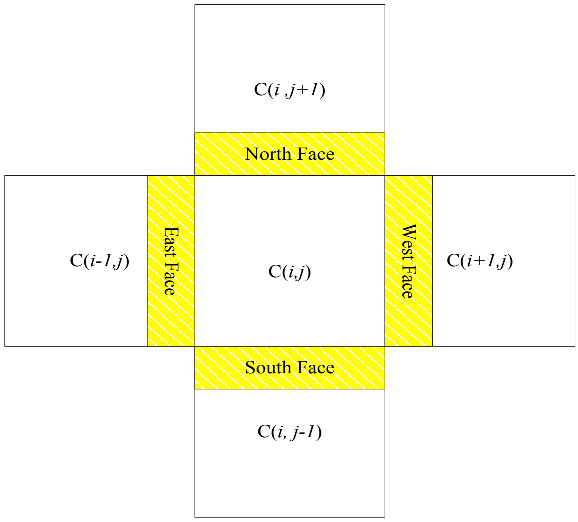


Figure 4-6 Neighbour cells involved in calculating fluxes through the four interfaces of the patch C (*i, j*)

4.5.3 Boundary setting:

Boundary conditions are necessary when the flux calculation involves the boundary patches that lack neighbouring cells. As shown in Figure 4-7, a virtual neighbour is allocated to each of the boundary cells, so that interface fluxes can be calculated. The flow states in the virtual neighbour cells are set to be the same as those in the corresponding boundary cells for open/transmissive domain boundaries.

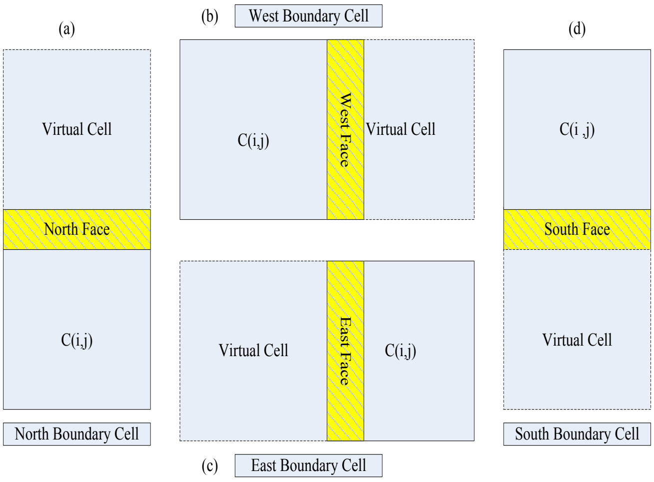


Figure 4-7 Rules for boundary cell setting a) North boundary cell setting, b) boundary cell setting, c) East boundary setting, d) South boundary setting for each virtual cell, h (virtual cell) = h(c(i,j)),v(virtual cell) = v_(c(i,j))

4.5.4 Updating water states

Finally, the water flow attributes at each patch (h, v) are updated using the finite volume time marching formula according to the four interface fluxes.

4.6 Human behaviour simulator

4.6.1 Introduction

The human behaviour simulator (HBS) simulates the responses of individuals and organizations involved in the flood events. This behaviour interacts with the outputs of the HDS to provide simulations of human responses to a flood event so that it can be used by the risk analysis tool to appraise the effect of non-structural measures to the flood risk.

Within the HBS, individuals or organizations are considered as agents. Each agent behaves according to its rules and has interactions with the environment and other agents. This section introduces the general framework for agent behaviour before providing a detailed description of the agent behaviour rules and how they are implemented within the NetLogo platform. The outline of this section is as shown in

Figure 4-8.

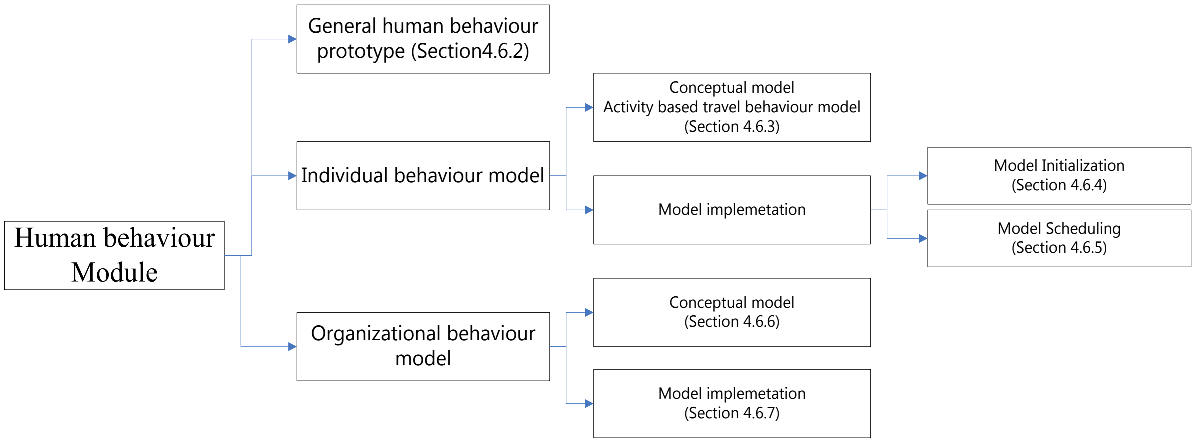


Figure 4-8 Outline of Section 4.6 - human behaviour simulator introduction

4.6.2 General prototype of human behavior

Input-decision-action cycle

An agent's behaviour is modelled using a human decision-making model with an input-decision-action cycle (Kanno *et al.*, 2006). As shown in Figure 4-9, agents first get information or resources from the environment or other agents before processing the information and then make a judgment on the situation and the potential risks. Then the agents generate a decision (set of goals and tasks) based on their knowledge. Finally, the agents send out information, resources or actions to change the attributes of the environment to other agents or itself.

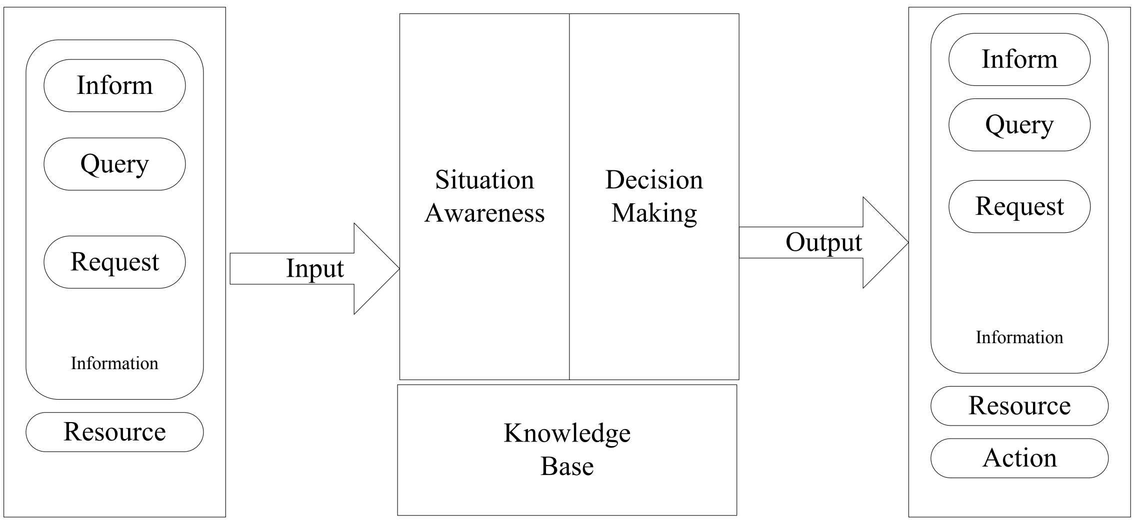


Figure 4-9 Agent behaviour normal form based on input-decision-action cycle (adapted from Kanno, Morimoto et al., 2006)

Message Format

The process by which information is communicated and perceived is a vital element for triggering an agent's behaviour. The FIPA (Foundation for Intelligent Physical Agents) and ACL (Agent Communication Language) message format (Foundation for Intelligent Physical Agents, 2001) is adopted to formalize this process within the model. This has three basic types: 1) Inform, 2) Query and 3) Request (Table 4-2). *Inform information* is a one-way message from the sender. *Query information* is a two-way message sent from the sender, and the receiver has to give feedback information to the sender. *Request information* is the message from a sender that asks the receiver to implement at least one task. The output of an agent includes information, resources and actions. *Resources* are the materials and manpower sent out or received. An *action* is a movement that results in a mixture of sending out a piece of information, using some resources or changing some attributes of itself, other agents or the environment. Agents get information or resources from the environment or other agents, decide the appropriate tasks based on the rules with reference to the knowledge base and its judgment about the situation, and then execute the actions, and/or send out information or resources.

Table 4-2 Agent's response to different type of information

Message Type	Response	Example
Inform	One-way message: The receiver adds the information to its own knowledge base.	Flood Warden sends a one-way inform message to EA. Receiver EA only adds the information to its own knowledge database.
Query	Two-way message: The receiver has to retrieve information from its own knowledge base and send an answer message to the sender.	Police may send a query message to EA asking for the current flood situation. Once this query has been received, EA has to give an informed message back to the police.
Request	One way or two-way message: The receiver has to formulate at least one	When the Council receives a request from a household asking for sandbags, the council has to formulate the task of sending a sandbag. The action of this

	task. Sometimes the receiver needs to give an answer message to the sender.	task includes: sending manpower to the civilian's location (a change in the council staff's location attribute), adding to the number of sandbags (civilian's attribute) and changing the inventory record of the Council (council's attribute).

The behaviour rules for each type of agent were derived from the analysis of disaster sociology research as well as data from a post-flood survey (BMRB International, 2001), the flood emergency plans of a range of organizations such as London Resilience Team (2007), Northumberland County Council (2009), and some empirical data from interviewing stakeholders and attending multi-agency flood exercises held at Conway Council, North Wales. These behaviour rules are described in the following sections.

4.6.3 Individual behaviour conceptual model

Individuals in HBS include civilians and organizational staff such as flood wardens, the police, EA staff, etc. Here civilians' responses are mainly discussed. Organizational staff's behaviour rules are introduced in the organizational behaviour section (section 4.6.6).

Active and static civilians

As shown in Figure 4-10Figure 4-10, civilians are either *Static civilians* who stay in place and are not involved in a trip or *Active civilians* who are on a trip at a time step. Once a civilian is activated it first moves to the road network from the building and then the agent chooses a transport mode - walking or by car. If it chooses a car, the agent turns into a *Vehicle*, otherwise they are a *Walker*. When the trip is finished, it changes back to a S*tatic civilian*.

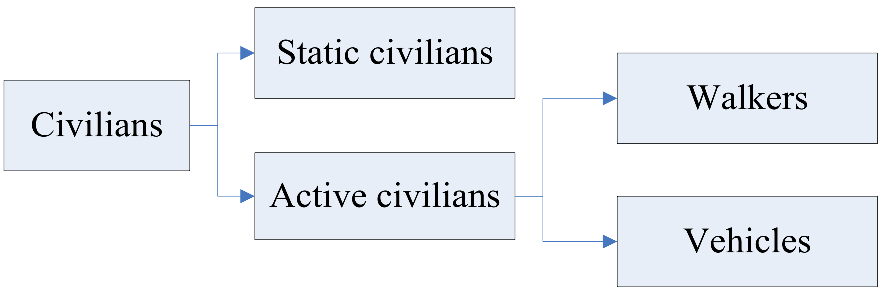


Figure 4-10 Civilian types in HBS

Activity-based travel behaviour model

An activity-based travel behaviour model is developed to model active agents' travel behaviour. Activity-based travel demand modelling is a travel behaviour simulation method that has become of increased interest for its ability to model household activity scheduling, which is one of the most important issues in travel behaviour (Axhausen and Gärling, 1992).

The concept of activity-based travel simulation is a segmentation of a daily activity/travel pattern according to practical activity/travel behaviour data. The activity /travel pattern can be classified by various aspects such as activity types, duration, location or mode choices. In the activity-based travel simulation, each member (household) is assigned with a 24-hour activity pattern. The members will perform the travel behaviour according to their travel activity pattern, and the duration, location and choices are based on the observed data until this activity is finished (XU *et al.*, 2003). In this thesis, an activity-based travel behaviour model is set up based on national travel survey data.

Nine activity types are set up for modelling travel behaviour (see Table 4-3). The first eight activity types are identified according to national travel survey data and Welsh travel survey data. They describe civilian agents' normal travel behaviour, (details of the activity type identification can be found in the Appendix II). The last one, which is 'evacuation type', is to simulate agents' emergency behaviour to the flood situation.

Table 4-3 Civilian agents' activity types and their travel routes

Behaviour Type	Activity Type	Travel route
Normal travel behaviour	Commuting	Home-workplace Workplace-home
	Business	Workplace-workplace
	Education	Home-school School-home
	Escort education	Home-school-home
	Shopping	Home-shopping centre-home Education-shopping centre-home Work-shopping centre-home Other purpose-shopping centre-home

	Other escort /personal business	Home-doctors/bank/betting/library/church-home
	Visiting friends	Home-home/leisure centre
	Leisure and just walking	Home-interesting places Camp site/hotel-interesting places
Emergency behaviour	Evacuation	Any place - evacuation shelters

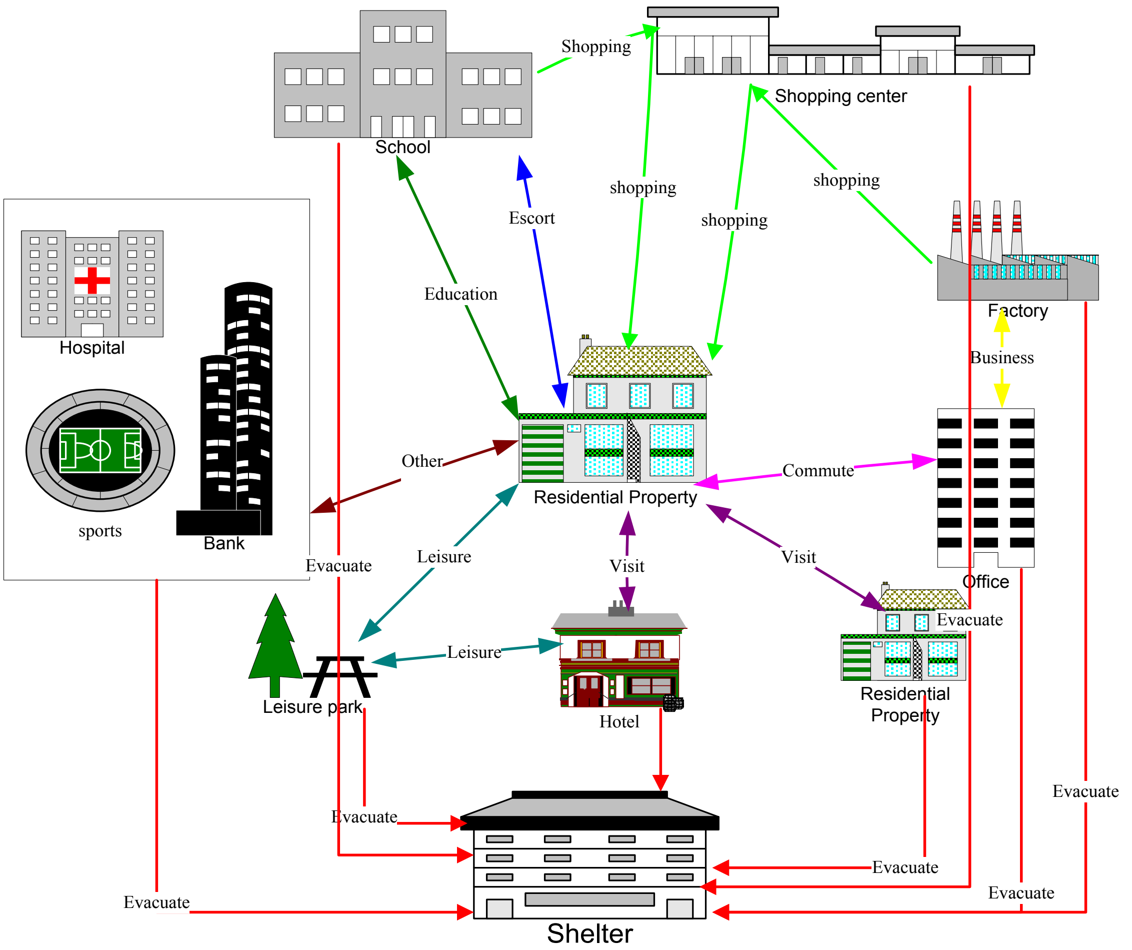


Figure 4-11 Demonstration of nine activity types in the model

Figure 4-11 demonstrates the activity types and their travel routes in the HBS simulator. Details of how an agent is produced and the identification of its specific destination are introduced in sections 4.6.4 and 4.6.5. The agent type can change according to the environmental condition of the simulation. For example, static agents change to active agents and start an evacuation travel trip once they receive the evacuation command from the EA. An active agent turns into a static agent once their normal travel trip is finished, and normal travel activity can be changed to evacuation activity during the trip. The trigger of these changes will be discussed in section 4.6.5.

4.6.4 Individual behaviour module initialization

It is assumed that the civilians are in their everyday normal status and not affected by the flood water initially. The normal status might be staying at home (as static agents) or on their normal travel trips (active agents) such as commuting, working, shopping or going to school or other personal activities. Individual agents' normal travel behaviour is simulated according to census data (Office for National Statistics, 2011) and national travel behaviour survey data (Department for Transport, 2011). The model aims to catch the time sequence of each activity type trip on one weekday in order to simulate the travel behaviour dynamics. The numbers of active agents and static agents are identified hourly. The initialization is to produce agents and to allocate each agent an activity type and the original location.

Initialization of active agent

The initialization of active agents includes four main components, as shown in Figure 4-12.

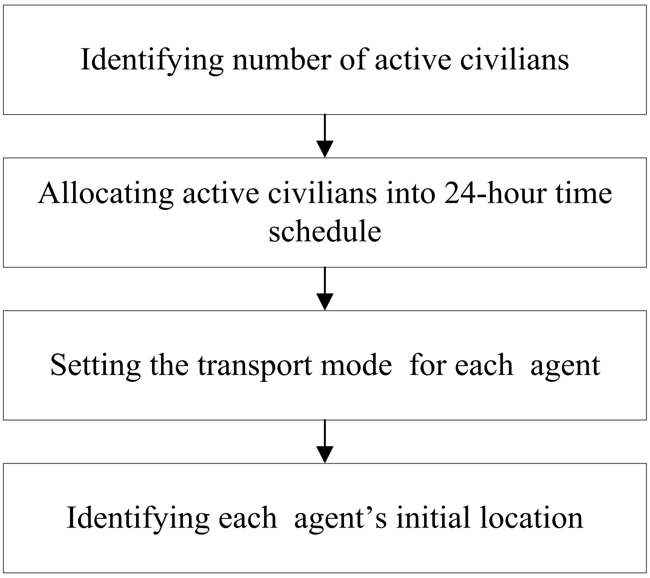


Figure 4-12 Components of active agent initialization

1. Identify number of active civilians

The total number of active agents is calculated using the following equation:

$$TR_T = P \times TR_D \qquad \textbf{(4-1)}$$

where:

TR_T: Total trips in one day
P: Population
TR_D: Average trips per person per weekday
The population can easily be obtained from census data (Office for National Statistics, 2011). For example, the daytime population of Towyn is 2,239. According to the Welsh Government's personal travel statistics (2012), the average trips per person per weekday is calculated as 2.9 trips (details for this calculation can be found in Appendix II). For Towyn ward, the total trips in one weekday, therefore, can be estimated as 6,493 trips.

According to the statistics, on average, trips by day of the week and purpose, the percentage of each normal activity pattern in the total number of one day total trips can also be deduced and then, for one day, the number of trips of each normal travel activity type can be obtained (Table 4-4).

Table 4-4 Towyn one day trips divided by activity types

Activity Types	Percent of the total one-day trips	One day trips for the activity type
Commuting	0.14	909
Business	0.03	195
Education	0.06	390
Escort education	0.04	260
Shopping	0.21	1,363
Other escort /personal business	0.20	1298
Visiting friends	0.17	1,104
Leisure and just walking	0.15	974
Total	1	6,493

2. Allocating active civilians into 24-hour time schedule

Once the number of trips of each activity type is identified, this number of agents needs to be allocated to 24-hour time slots. In the National Travel Survey data, the time sequences of each trip type are clearly listed (see Appendix II). Based on this the time sequence of one-day trips of each activity type for initializing the number of active civilian agents is obtained, as shown in Table 4-5.

Table 4-5 Towyn sequence of one-day trips by activity type

Towyn time sequence of one day trips by activity types								
Start time	Commuting	Business	Education	Escort education	Shopping	Other personal business and escort	Visiting friends/ entertainment/ sport	Holiday/ Day trip/ Other
0000 - 0059	0	2	0	0	0	0	0	0
0100 - 0159	0	2	0	0	0	0	0	0
0200 - 0259	0	0	0	0	0	0	0	0
0300 - 0359	0	0	0	0	0	0	0	0
0400 - 0459	9	0	0	0	0	0	0	0
0500 - 0559	27	2	0	0	0	0	0	10
0600 - 0659	55	6	0	0	0	13	0	10
0700 - 0759	145	14	26	5	14	52	11	39
0800 - 0859	136	20	160	94	41	104	22	49
0900 - 0959	36	16	8	21	109	117	44	68
1000 - 1159	18	14	4	3	164	104	55	88
1100 - 1159	18	14	4	5	177	104	66	68
1200 - 1259	27	14	8	5	150	104	66	58
1300 - 1359	36	14	8	3	123	91	66	68
1400 - 1459	27	14	12	20	123	91	66	78
1500 - 1559	27	16	125	86	123	104	77	87
1600 - 1659	91	18	19	10	95	116	89	88
1700 - 1759	136	14	8	5	81	104	100	68
1800 - 1859	55	8	4	3	67	77	111	68
1900 - 1959	18	4	4	0	55	52	111	49
2000 - 2059	18	1	0	0	27	26	77	39
2100 - 2159	10	1	0	0	14	26	66	19
2200 - 2259	10	1	0	0	0	13	44	10
2300 - 2359	10	1	0	0	0	0	33	10
All day	909	196	390	260	1363	1298	1104	974

3. Setting the transport mode

The one-day trips by activity type include all travel modes such as walking, car/van, bus, train, local bus and other. In order to analyse the car traffic, trips by car/van mode need to be extracted from the total one-day trips by activity type. This is done based on the National Travel Survey, and the percentage of each travel mode is obtained, as shown in Table 4-6

Table 4-6 Percentage of each travel mode by activity type

Percentage of each travel mode by activity types						
Purpose	Walk	Car/van[1]	Local bus	Rail[2]	Other[3]	All modes
Commuting/business	0.105748	0.698549	0.077071	0.064286	0.054346	1
Education/escort education	0.414768	0.415856	0.096741	0.017785	0.05485	1
Shopping	0.238487	0.635009	0.094174	0.007607	0.024723	1
Other escort	0.122	0.840544	0.023334	0.003826	0.010296	1
Personal business	0.238571	0.64644	0.072369	0.011677	0.030943	1
Leisure[4]	0.176215	0.696408	0.052716	0.021479	0.053182	1
Other including just walk	0.989029	0.01057	0.000401	0	0	1

4. Initial location of active civilians

The active civilians' initial locations are determined by the travel routes of their activity types according to Table 4-3. Civilians are randomly allocated to a land patch that contains the properties in accordance with the route start point types. For example, a commuter will be randomly allocated to a land patch that contains residential properties or office buildings; a civilian on a business trip is initially allocated to a land patch that contains office buildings or factory properties.

Initialization of static agent

Apart from the active civilians, the rest of the population are identified as static agents; they are randomly allocated to a land patch that contains residential properties. As long as the agent keeps its static status, the agents location is not changed.

4.6.5 Individual behaviour scheduling

Individual behaviour scheduling is used to set rules for civilians' behaviour in every time step. Civilian behaviour rules can be summarized as five steps, as shown in Figure 4-13.

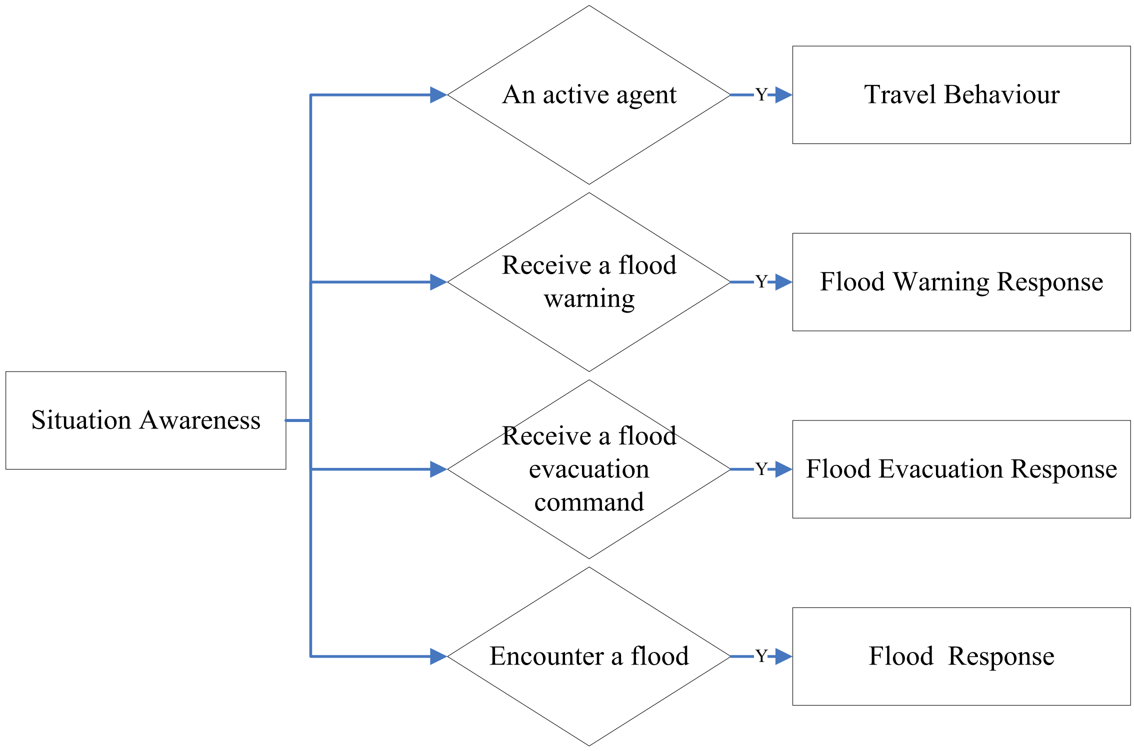


Figure 4-13 Flow chart of civilian agents' behaviour rules for each time step

Situation awareness

Civilian agents first sense the environment condition and the situation of itself. It includes 1) spatial location awareness, 2) agent's status awareness, 3) flood awareness and 4) information awareness. Status awareness is the agents checking their status, such as whether they are on a trip, whether they have a target destination, whether the route has been identified or whether they have finished their journey. Flood awareness is to sense whether there is a flood within a certain distance. The agent will report he is in danger if the places they stay have reached the threshold of death (for static agents and walkers) according to the mortality function (Jonkman and Penning-Rowsell, 2008) or the threshold of instability (for vehicles) according to the vehicle instability function (Xia *et al.*, 2011). Information sensing is to see whether there is some information given by other organizational agents such as the EA's flood warning or flood evacuation commands. Situation awareness provides agents with the conditions of the environment and themselves so that different actions can be taken according to the various conditions.

Travel behaviour

Travel behaviour only applies to active agents. Once a decision to take a trip has been made, active civilian agents have 4 common steps at each time step, which are: 1) Setting destination, 2) Finding a route, 3) Moving to destination and 4) Off road, as shown in Figure 4-14 .

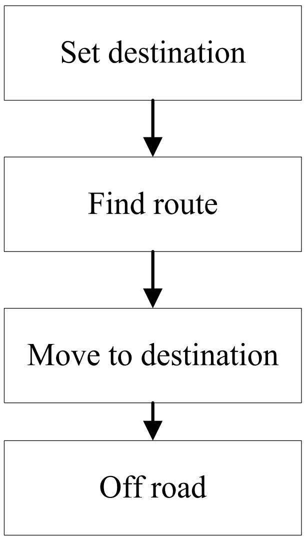


Figure 4-14 Four common steps of travel behaviour

- Set destination

For every time step, an active agent first needs to make sure a destination is identified according to its activity type. For normal travel activities, a trip of each activity type is decomposed into several steps, and the probability of each step is identified according to the National Travel Survey data for the purpose of the next trip. After normalizing the trip numbers into percentages, the general travel chain behaviour feature can be listed as follows (see Table 4-7):

Table 4-7 Purpose of next trip: Great Britain, 2009 (Adapted from National Travel Survey)

	Previous Trips			
Next trip purpose	**All purposes**	**Work or business**	**Escort education**	**Shopping**
Work or business	11	10	8	3.02
Education	3	0	2	0.26
Escort education	3	1	3	0.32
Shopping	11	6	4	6.50
Other escort	6	3	4	1.48
Personal business	5	2	2	1.50
Visit friends[1]	9	3	3	4.98
Other leisure[2]	9	2	1	2.49
Home	43	74	73	79.46
	100	100	100	100.00

Trips in Table 4-7 can be divided into two categories: direct trips and second order trips. Direct trips are trips where the next trip purpose is "Home". If the next trip purpose is not home, the trip can be called a second order trip. The percentage of direct trips and second order trips by purpose can be used as the probability of each activity step. In the next part, each activity type will be decomposed into a combination of direct trips and chain trips. For commuting and education trip types, due to the lack of practical data, the probabilities for the agent choosing the starting point are based on estimation. Full descriptions of all activity type trips can be found in the Appendix II. Here commuting type is taken as an example (Figure 4-15).

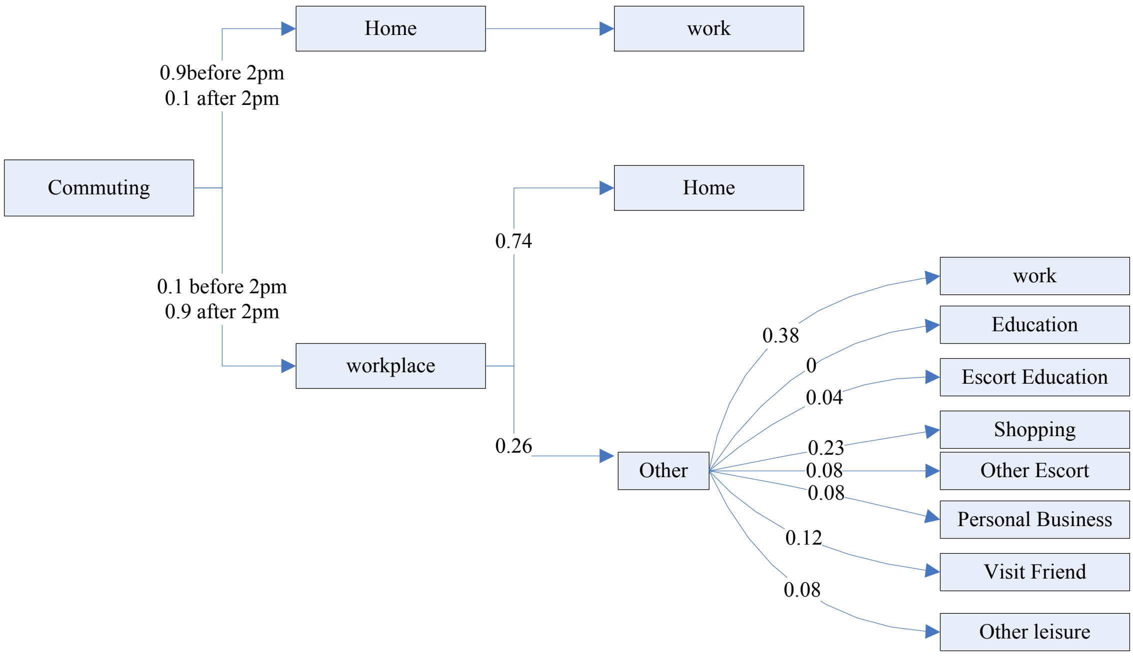


Figure 4-15 Travel behaviour of commuting trips

For evacuation type, it is a description of people's evacuation behaviour. It is triggered by the flood danger encountered or due to receiving a flood warning or an evacuation command. The evacuation trips can be started from any place, but the destinations are all shelters (Figure 4-16).

Figure 4-16 Travel behaviour of evacuation type

- Find route

Once a destination is set, the agent tries to find the shortest route. Agents travel along the road network, and the route is a set of road links. A* algorithm (Zeng and Church, 2009) is successfully implemented in the model for agents' behaviour in finding a route.

- Move to destination

Moving to the destination is the step of agents changing their positions along the route (road network) selected. Walkers and vehicles have different speeds when they move along the road. A walker's speed is set according to the HCM2000 (Highway Capacity Manual) standard 1.2m/s, while vehicles' speed changes according to the number of cars driving on the road, Car speed is related to car numbers on the road and the free speed of a road (Transport Research Board, 2000), car speed setting will be described in section 4.7.4.

- Off road

Once a traveller arrives at the destination, the agent will be off the road, relocated to a land cell and will change their status to a static civilian again.

Apart from the travel behaviour, civilian agents have responses to the flood, and information received such as flood warning and flood evacuation. Next, how HBS simulates civilians' responses to the flood warning, flood evacuation and the flood itself is described.

Flood warning response

Flood warning response refers to civilians' receiving and processing the flood warning information and taking actions against it. The simulation of flood warning responses can be divided into three steps: receiving flood warning, warning reaction and action against the flood warning, as shown in Figure 4-17.

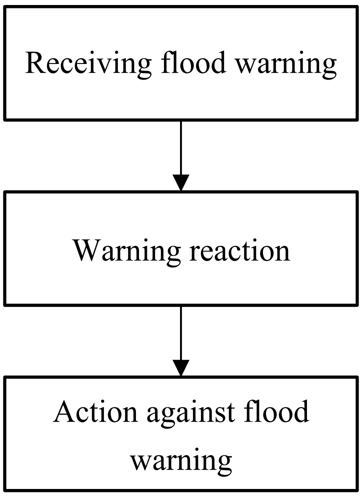


Figure 4-17 Civilian's behaviour of flood warning response

- Receiving flood warning

Civilians receive flood warning messages from the EA. A flood warning is assigned as an inform message in FIPA ACL format. It is the condition that triggers civilians' responses to the flood warning.

- Flood warning reaction

Flood warning reaction is the civilians' reaction to the flood warning before taking real actions. Not all civilians take actions when receiving a flood warning (Boyd, 2005). Disaster sociologists claim that message quality, receivers' flood awareness and receivers' flood preparedness are the three main factors that influence whether or not civilians take action following a flood warning (Drabek, 1986). Therefore, civilians' flood warning reactions can be modelled as an event tree.

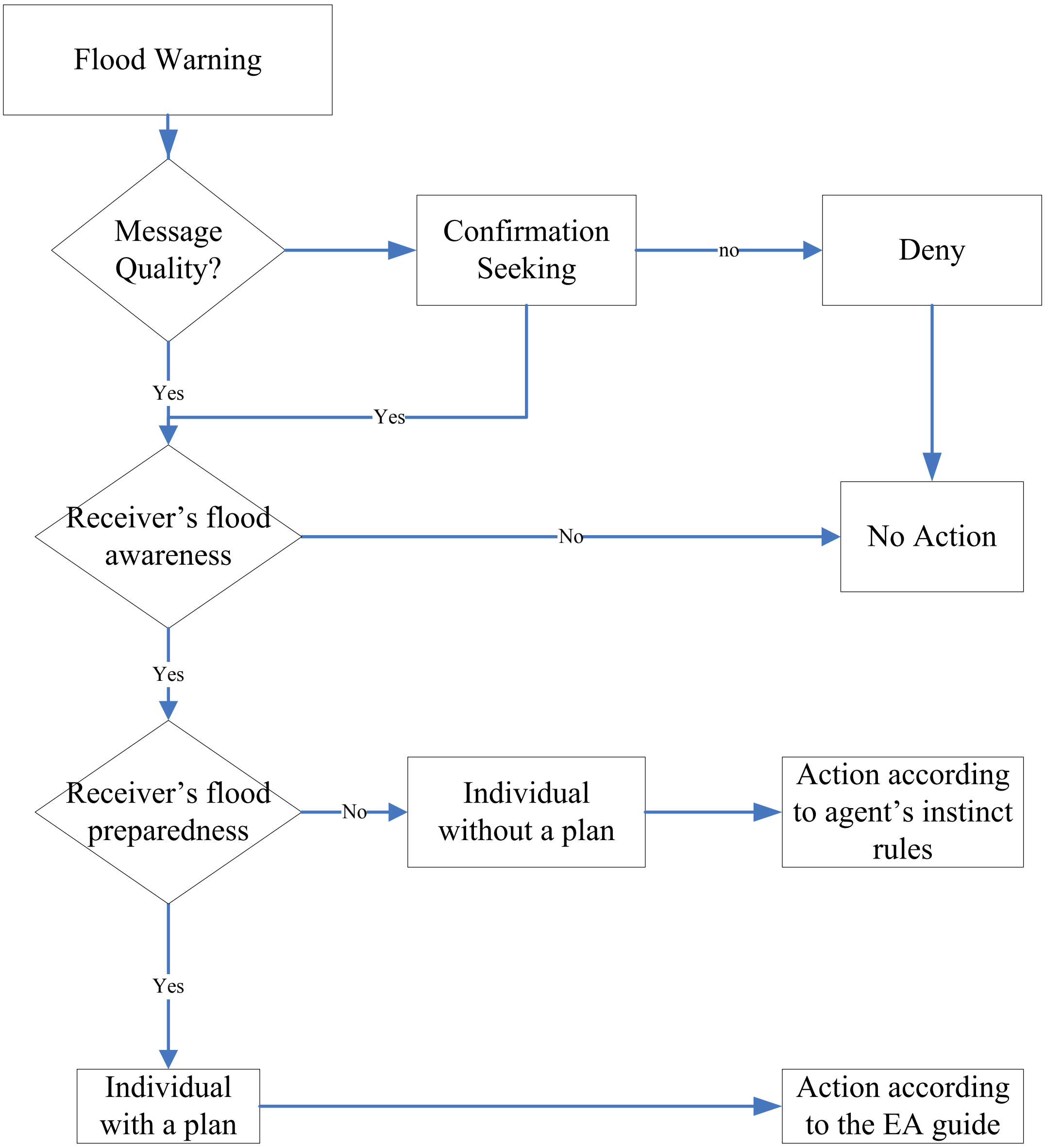


Figure 4-18 The event tree of a typical civilian's reactions to a flood warning

As shown in Figure 4-18, when a flood warning is received, it first goes to a filter named *Message Quality,* which is determined by the flood warning message content, message source and message numbers. Some agents confirm and accept the warning once they receive a warning, however, if the message quality is not good enough, some agents deny the warning, whilst others take an action of *Confirmation Seeking* in order to get more information to confirm the flood warning.

The second filter that makes individuals have different behaviour is the receivers' flood awareness, which refers to civilians' ability to judge the dangerous flooding situation in the right way so that necessary actions can be taken

The third filter is the receivers' flood preparedness. This is the percentage of people that will make a flood plan in advance and prepare for being exposed to the flood. Though every individual resident might have their preparation, it is assumed in this research that those who accept the flood warning and have a flood plan in advance, will act according to the EA Guide (Fielding *et al.*, 2007). The remainder will act according to their rules, of which several items of preparation listed in the EA guide are neglected.

- Actions against flood warning

When the civilians confirm the flood warning and want to take action, their actions are still varied depending on their experience and preparedness. Their actions can be categorized as prepared or unprepared actions, as shown in Figure 4-19.

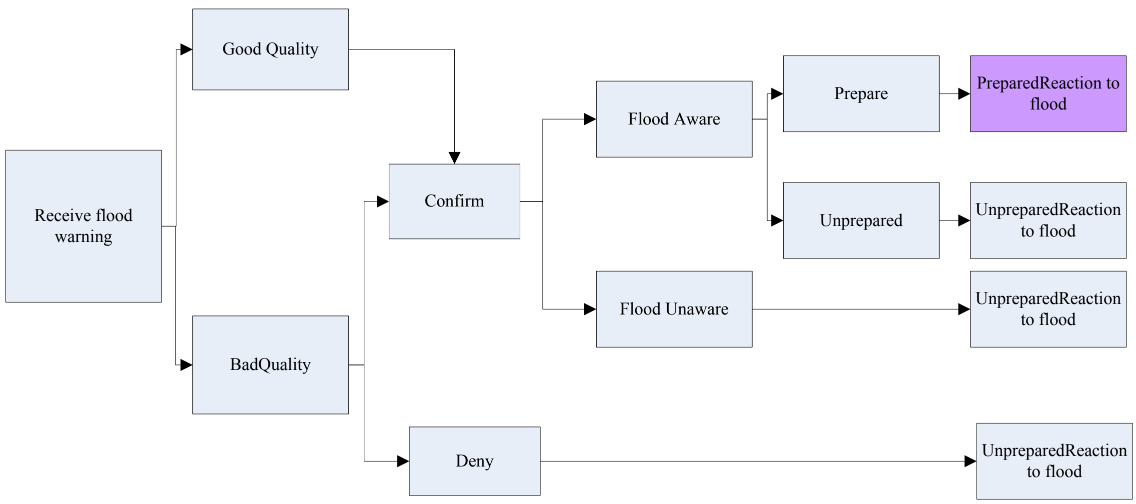


Figure 4-19 Event tree showing how the quality of reaction to a flood warning is determined according to the message quality and individual awareness

It is assumed that agents with prepared actions will follow what the EA has advised, and make good preparations for the coming flood risk (Environment Agency, 2007c; Environment Agency, 2007b; Environment Agency, 2007a). The unprepared type of reaction to the flood will not follow what the EA has advised and will act according to the agent's rules. In this research, the prepared and unprepared actions taken by the civilians are listed in Table 4-8.

Table 4-8 Actions taken by civilians, following receipt of a flood warning, who are prepared or unprepared for a flood

Actions		Prepared	Unprepared
Pre-flooding	Check insurance	●	○
	Know how to turn off utilities	●	○
	Prepare flood kit/contact number	●	○
	Move things to safe place	●	○
	Prepare sandbags, flood boards	●	○
During flood event	Gather essential items together upstairs	●	●
	Using sandbags to help stop water entering	●	●
	Fill jugs and saucepans with clean water	●	○
	Move family and pets upstairs or to a higher place with a means of escape	●	●
	Turn off gas, electricity and water supplies when flood water is about to enter	●	○
	Keep listening to local radio for updates or call Floodline	●	●
	If in danger call 999 immediately	●	●

All these actions are successfully implemented in the simulation model. The functions for implementing these actions are listed in Appendix I.

Flood evacuation response

Civilians' responses significantly impact on the efficiency of flood evacuation. Not all civilians will follow the evacuation requirements when they are asked to. For example, during the Hurricane Katrina flood disaster in the United States in 2005, despite mandatory evacuation orders, many people did not leave New Orleans. Even after the city was flooded and uninhabitable, some people still refused to leave their homes (Adeola, 2009). Here the civilians' behaviour rules to the flood evacuation command based on disaster sociology research are summarized (Figure 4-20):

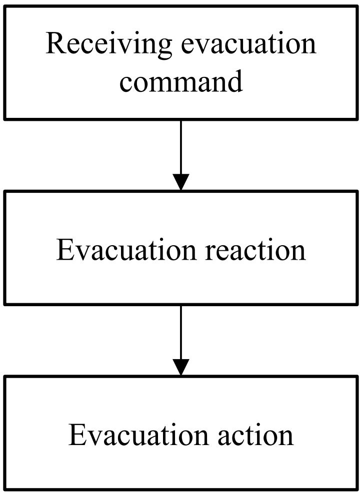


Figure 4-20 Civilians' behaviour of flood evacuation response

- From receiving the evacuation command to making the decision to take action

Similar to the process of flood warning, when an evacuation message is sent to an agent, the message quality and receivers' quality are the two main factors that influence the evacuation rate.

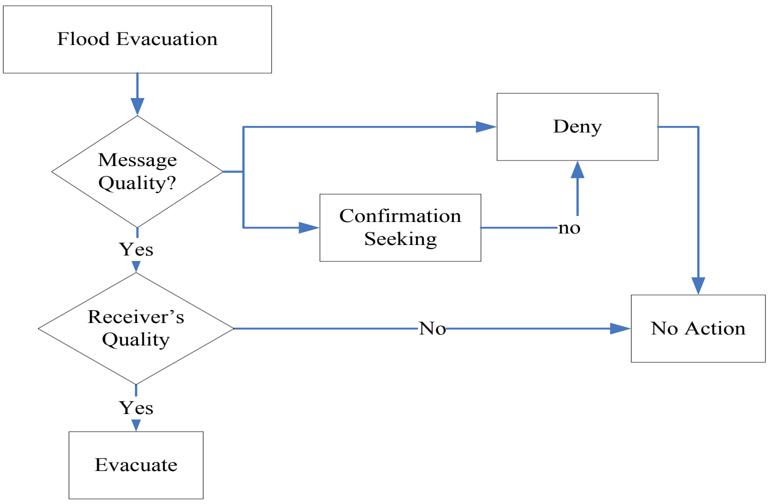


Figure 4-21 The event tree of civilians' reaction to a flood evacuation

As shown in Figure 4-21, when a flood evacuation command is sent out, it first goes to a filter named Message Quality which is determined by the flood evacuation message content, the message source and the message numbers. Some agents confirm and accept the evacuation order once they receive the message, however, if the message quality is not good enough, some agents deny the evacuation order, whilst others take an action of Confirmation Seeking in order to get more information to confirm the evacuation order.

The second filter that makes individuals have different behaviour is Receiver's Quality, which refers to civilians' ability to judge the dangerous flooding situation in the right way so that the action of evacuation can be taken. Receiver's Quality is an instance that is influenced not only by personal characteristics such as age, gender, education and social-economic status or flood experiences, but also some physical conditions in which the civilians are situated. The physical conditions that might influence the receiver's evacuation behaviour are the age of the house, the elevation of the house and the type of house. Not all the relationships between these factors and their influence on the evacuation behaviour have been fully explored, however, major physical conditions such as house type and elevation, as well as the occurrence time are taken into account in this research.

- Evacuation actions

Civilians' evacuation action is simple. Once they decide to evacuate, they follow the evacuation instructions given by the local authority and start a trip to the pre-defined shelters. However, the efficiency of their evacuation is influenced by their socio-economic or demographic characteristics, flood experiences and the transportation conditions during the evacuation.

Flood response

Flood response refers to the individual's reactions when a flood occurs. Individual reactions are mainly for flood fighting and damage avoidance or life-saving. In this research, it was assumed that individuals' responses to the flood are a spontaneous, unprepared reaction. Therefore, the unprepared actions described in flood warning action also apply to any civilians who needs to respond to the flood.

For active civilians, on the way to their destination, once the road chosen is affected by a flood, the civilians will modify their route to avoid the flood. If there is no way through, the civilians will be stranded.

4.6.6 Organizational behaviour conceptual model

The organizational behaviour conceptual model is based on analysing the interactions between the organizations involved in the flood event management of the Morfa Rhuddlan West Multi-agency Tidal Flooding Response Plan (Conwy County Borough Council, 2009).

This section starts with a description of a generic prototype of organizational behaviour, followed by an overview of the relationships between organizations in a flood incident and the analysis of key organizations' tasks, to see how these tasks can be implemented in the simulation model and finally shows the results of a simulation in a simple case.

Three dimensions of organizational behaviour

Organizational behaviour in a flood event can be described in three dimensions.

1. Time dimension

The time (or flood phase) can affect the organizational behaviour during a flood event. In terms of flood phases, organizational behaviour can be categorized as follows:

- Preparedness: Planning, warning
- Response: Pre-event mobilization, post-event response (emergency actions)
- Recovery: Restoration, reconstruction
- Mitigation: Hazard perception, adjustment

2. Task dimension

Organizations are to implement flood reduction tasks. According to their objectives, three types are categorized:

- Environment-centred tasks (water centred)

The environment centred tasks mainly focus on sensing and forecasting the environmental trends or changes. E.g. EA flood wardens are observing the level of flood water or the Met Office forecasting the extreme weather that might cause a flood.

- Human-centred tasks

The human-centred tasks mainly aim to protect human beings from floods. For example, the EA sends flood warnings to households; the government has flood exercises in order to raise awareness of a flood and fire rescuers help old people to evacuate from flooded areas.

- Resource-centred tasks

The resource-centred tasks take public properties or critical infrastructures as its objects. For example, EAs maintain the flood defence, water companies maintain the drainage system for the flood, or the government prepares sandbags for residents to defend against the flood.

3. Administrative dimension

The administrative dimension is the administrative structure for organizational behaviour. The administrative structure defines an organization’s role as well as their internal and external communications. The differences and changes in the administrative structure might lead to a very different performance of the flood management.

In general, every organization's behaviour can be described precisely in these three dimensions.

General prototype of organizational behaviour

In order to establish the basic agent behaviour model, the model of organizational behaviour tasks can be described, as shown in Figure 4-22.

For any organization, a trigger condition is needed to start implementing a task. The trigger conditions can be any of the following factors:

- Time
- Information from other agent, e.g., the evacuation order that the police received from the central command control group
- Critical attributes which the organization itself or other agents will reach, including flood depth, the number of individuals trapped in the flood and so on

Similarly, the implementing tasks can be terminated according to certain conditions.

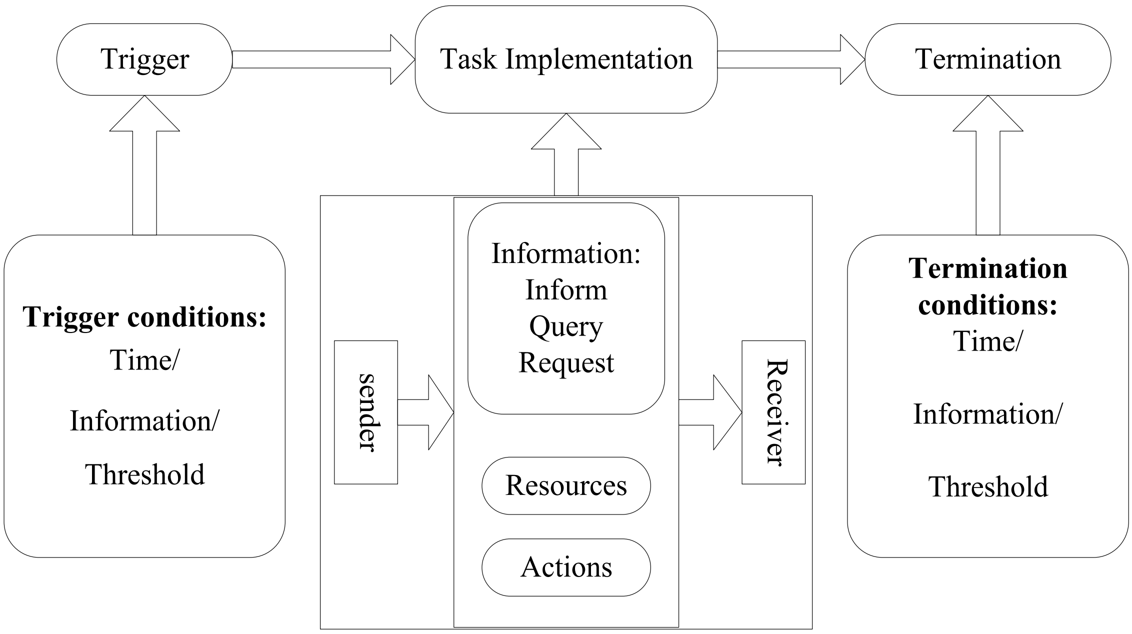


Figure 4-22 Conceptual overview of organizational behaviour

The task output can be defined by the form of receiving and sending information or resources or actions that change the attributes of the agent itself or other agents. It has to be mentioned that the sender and receiver in the model are organizations that might include organization members. For example, the organization of the police not only refers to the local police station but also to the policemen that are sent out to implement related tasks. The local police station is an organizational agent while a policeman is an instance (breed) of this organizational agent.

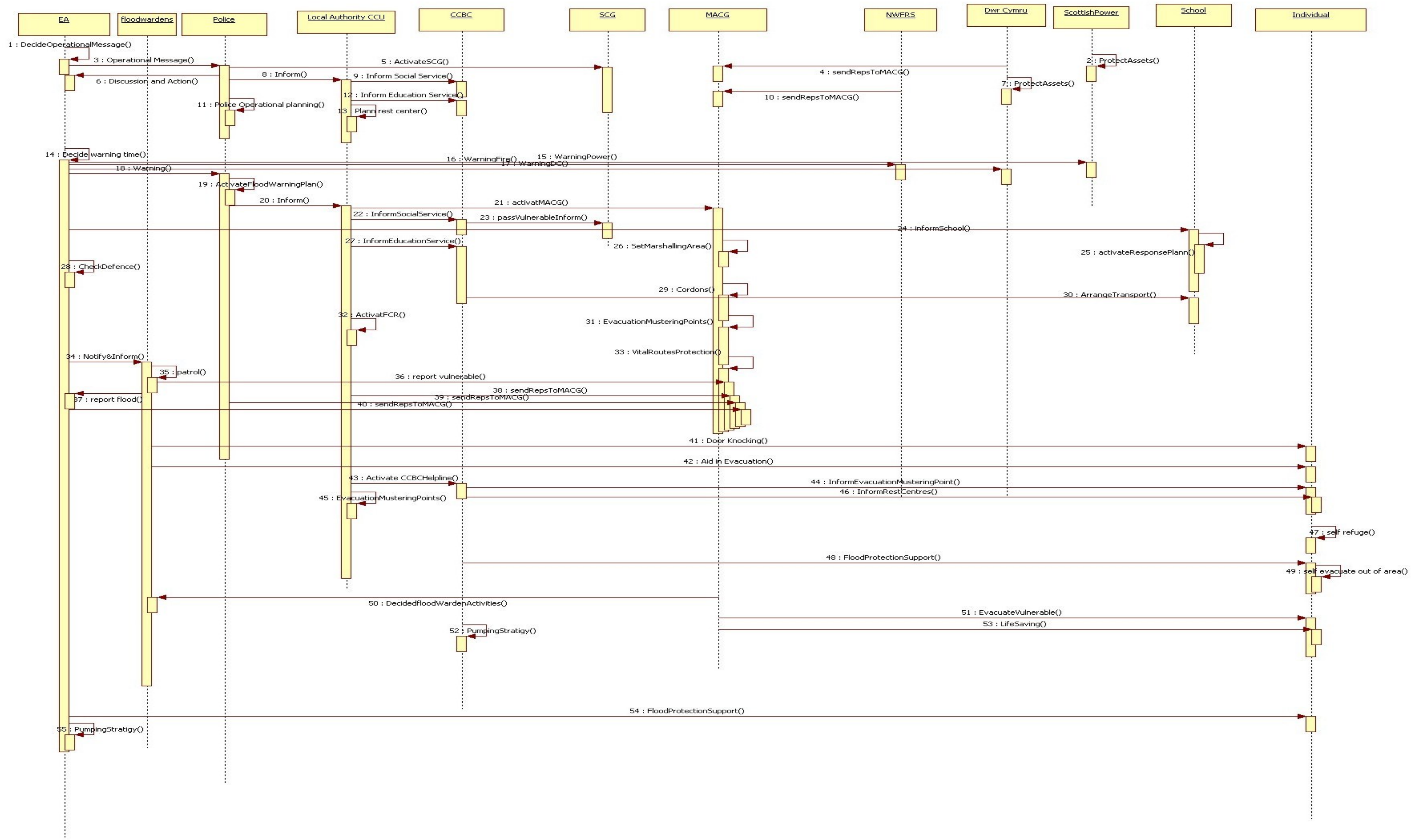
Overview of the relationships between organizations in a flood event

In a flood event, organizational behaviour is complex due to the interdependence of the organizations involved in flood event management. It is quite common that an organization's responses to the flood event are triggered by the information or commands from another organization; meanwhile one organization's emergency action might affect another organization's decision-making. Therefore, it is necessary to have an overview of the interrelationships between key organizations in the flood event management. Based on the approaches to flood event management as applied in Conway, North Wales (Conwy County Borough Council, 2009), the relationships between the key organizations involved can be summarised by the UML chart (Figure 4-23)

A UML sequence diagram is usually used for visualizing the logic flow within the system for dynamic modelling, which emphasises the identification of the behaviour in the system, from which the logic of a complex operation or procedure is easily visualized (Larman, 2004).

In a sequence UML chart, the organization names are in the boxes at the top, and under each name box there is a sequence line, where the logic of one organization is shown via the sequential response actions (horizontal arrows). The first action is at the top, then the next one is just below that one. The arrows pointing to other agents mean the object of the action is the other agent, self-pointing arrows means the actions' object is the agent itself.

Figure 4-23 Overview of organizational interrelationships in a flood event (adapted from (Conwy County Borough Council, 2009))



With the help of a sequence UML chart, a brief insight into the logic of the approach to the flood emergency management is offered. The main organizations mentioned in the multi-agency flood plan of Morfa Rhuddlan West are the Environment Agency (EA), flood wardens, the Police, local authority CCU (Civil Contingencies Unit), CCBC (Conwy County Borough Council), SCG (Strategic Co-ordinating Group), MACG (Multi-Agency Control Group), NWFS (North Wales Fire Service), Welsh Water, Wales Ambulance and the coastguard. Because some organizations' responses are for schools and individual civilians, schools and individuals were listed as an organization at the end in order to describe the scenario. The significant responses of all key organizations within the flood event management system are identified. From the chart, it is clear that the EA, the Police, the local authority and the MACG are the core organizations in terms of communication.

4.6.7 Organizational behaviour simulation implementation

The organizational behaviour described here includes both organizational agents' behaviour and the behaviour of the individual staff in the organization. To shape the model to be as simple as possible while realistic enough to be useful for simulating the scenario, those organizations that have similar functions are merged as one agent. For example, Wales Fire and the coastguard are all the organizations for rescuing vulnerable, so only one agent, named FA (Fire Authority), is set to represent both Wales Fire and the coastguard. Similarly, water and power companies are merged as a utility agent. Civil Contingencies Unit (CCU) and Conwy County Borough Council (CCBC) has been merged into a local authority (LA) agent, while Strategic Co-ordinating Group (SCG) is merged into a Police Authority (PA) agent. As a result, in the model, the organizational agents include the EA (Environmental Agency), PA, LA, MACG and FA. The individual staff agents include EA staff, flood wardens and ambulance men. Here EA and EA staff are taken as an example of organizational behaviour modelling.

EA and EA staff

EA plays the most important role in implementing government policy on flood risk. The EA's flood responses flow chart (Figure 4-24) shows that during a flood event, EA is responsible for producing flood risk maps and issuing flood warnings as well as maintaining flood defences and giving flood support to civilians as required.

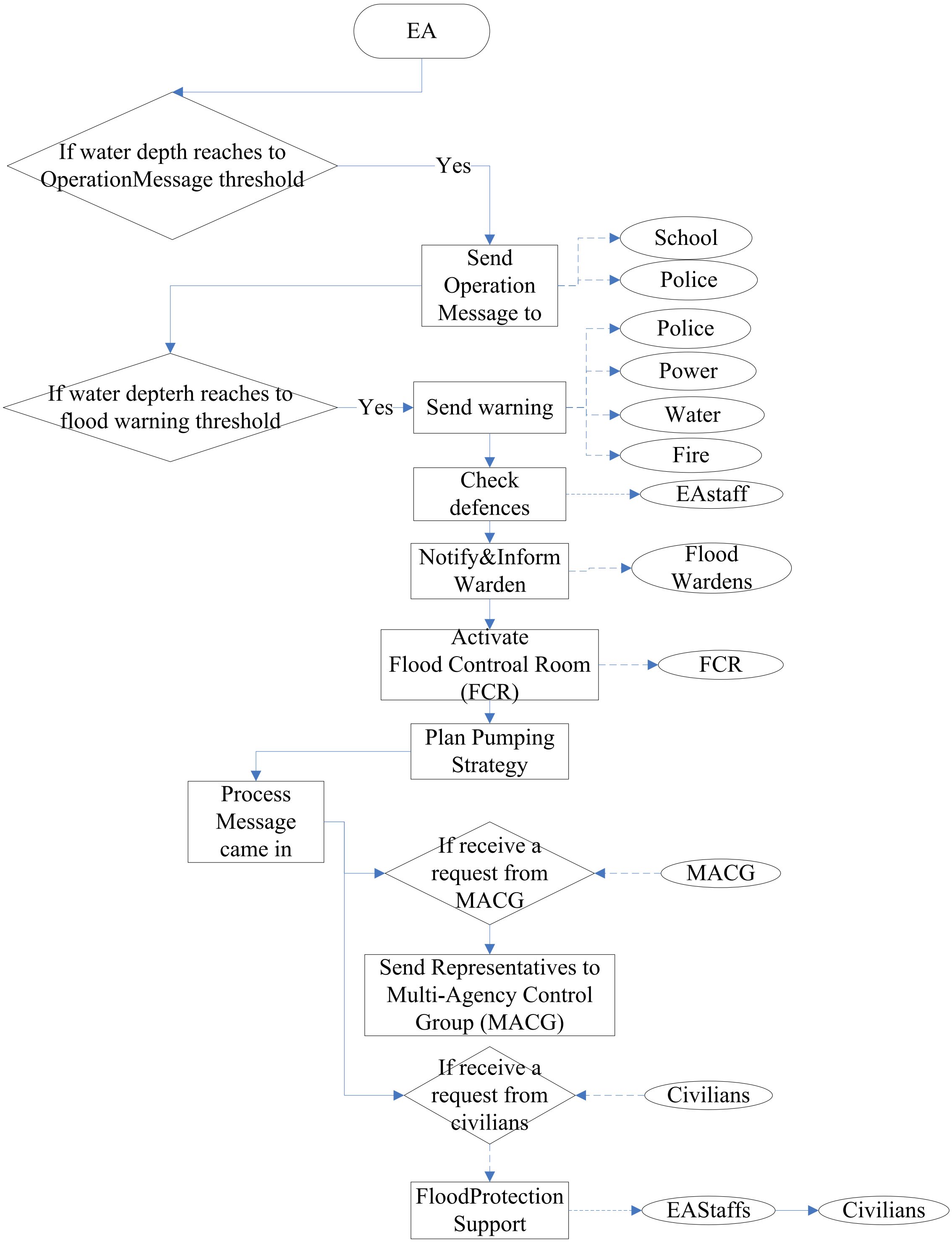


Figure 4-24 Flood responses flow diagram for the EA (Names in the oval box are organizations or individuals that the EA interact with)

The trigger for EA's response actions are: 1) flood water depth, 2) other organization's command or request, 3) civilian/individual request. Messages sent out include: operational messages and flood warnings. The operational message and flood warning issuing is according to whether the flood water depth of some gauges has reached a threshold. Operation messages are sent to schools and the police. Flood warning messages are sent to the police, the utility companies, fire and rescue organizations. Flood warning messages are also broadcast to all flood wardens. The form of any message in this model includes six parts as follows:

["inform" "sender:34" "receiver:38" "content:" "FloodWarning" "senderType:EA" "receiverType:Utility"]

The first part notes the message type, such as inform, request, query, the second part identifies the sender's ID (each agent in the model has one unique ID number once the model is initiated), the third part is the receiver's ID, the fourth part is the content of the message, and the fifth and sixth parts are the types of sender and receiver such as EA, PA, LA, FA, EA staff, flood wardens, utilities, etc.

Besides sending out messages, EA also receives messages from other organizations such as from MACG and individuals asking for flood support. Functions set up enable EA agents to activate related actions according to the different types of messages. For example, if EA receives a flood support request from a civilian, EA staff would be sent out to give flood support such as sending sandbags to civilians.

The action functions refer to functions that change the attributes of the agent itself or other agents. The activating flood control room (FCR), which sends representatives to MACG, and the planning pumping strategy are action functions in which the EA changes the attributes of itself or others. Checking flood defences and flood protection support are two actions that allocate a specific action to EA staff. Flood protection support is activated once EA receives a flood support request from an individual. Once the action has been activated, EA staff agents are sent to the individual's location and give the sandbags to the related individuals. Checking the flood defences is activated by the flood warning issuing. Once activated, an EA staff agent is sent near flood defences and is responsible for checking and maintaining flood defences. If there is a breach of the defences, the EA staff will take the time to fix it or call for help from the EA if the situation is beyond his abilities.

The flood responses of other organizations, including PA and the police, LA, MACG, FA, flood wardens and ambulance workers are all implemented in the simulation model in the same way. Full descriptions of the modelling of all organizations' responses to a flood event can be found in the Appendix I.

4.7 Risk analysis tool

4.7.1 Introduction

This part of the thesis describes the development of a risk analysis tool, the last but core layer of the simulation model, which focuses on the measurement and evaluation of flood risks. A feature of this flood risk analysis tool is that human responses are taken into account. By using a risk analysis tool, flood risks under certain conditions can be estimated.

As this research is focused on human responses, the economic flood damage (residential and non-residential), the loss of life and the instability of vehicles are the three indicators of flood risks. As the non-structure measures are mainly considered in the research, the appraisal focuses on the effect of flood warnings and flood evacuation.

Therefore, the Risk Analysis Tool consists of four components to calculate:

1. Economic flood damage in a flood event.
2. Flood impact to human life in a flood event.
3. Vehicle instability in a flood event.
4. Spatial dynamics of the flood evacuation, e.g. in terms of road congestion

Each of these components draws from different disciplinary backgrounds, requiring different approaches.

4.7.2 Method to calculate economic flood damage

Introduction

As an ABM is a micro simulation model, the flood damage calculation from the summation of the flood damage in each land cell. The flood damage in the area is the sum of flood damage of land cells.

As reviewed in Chapter 3, the flood damage estimations are mainly for macro scale, but some of them can be adapted for micro-simulation such as damage function. Because the FHRC model is based on the UK flood data, it is very suitable for an application in the case study site of Towyn, North Wales (introduced in Chapter 5). However necessary adjustment is taken to adapt the grid-based simulation.

Flood damage calculation process

1. Overview

Steps to calculate the flood damage in the flood event are designed as shown in Figure 4-25.

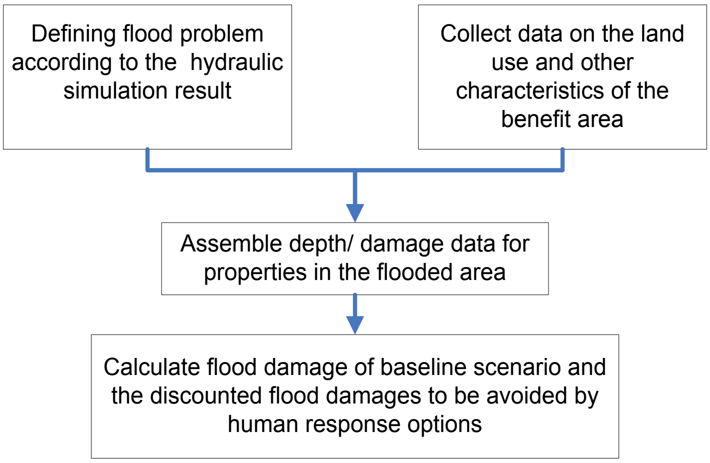


Figure 4-25 Steps to calculate flood damage during a flood event

The process starts from two aspects, one is to identify the flooded area and the other is to collect land use information about the flooded area. By applying damage functions that combine the flood depth with the damage data for different types of properties, the flood damage of each spatial cell can be calculated.

2. Define flooded area

In a flood event, the flood situation changes every minute. The HDS is each grid's values of water depth and velocity. Whether a grid is flooded or not depends on whether its water depth is greater than zero. For flood damage calculation, the damage function is related to the water depth that is above the upper surface of the ground floor that is 0.38m (Penning-Rowsell *et al.*, 2010).

3. Land use data

Building points with three digit building codes that show the land use type from the master map are imported into the simulation model. In order to calculate the flood damage, buildings are first divided into two classes: residential and non-residential buildings. As for the non-residential buildings, flood damage has a large variance, and it is divided into ten sub-sets in accordance with MCM categories (Penning-Rowsell *et al.*, 2010), as shown in Table 4-9.

Table 4-9 Land use types for flood damage calculation

Type Name	Type
RP	Residential property
NRP	Non-residential property
NRP_21	Shop/store
NRP_22	Vehicle services
NRP_23	Retail services
NRP_3	Office
NRP_4	Distribution/logistics
NRP_51	Leisure
NRP_52	Sports
NRP_6	Public building
NRP_8	Industry
NRP_9	Miscellaneous

For each cell, there are variables for counting different types of buildings. When there is a flood on the grid, the flood damage can be counted according to the flood damage function.

4. Damage function

It is assumed that the flood event is a short duration flood event (Penning-Rowsell *et al.*, 2010).The damage functions adapted from the MCM are listed here.

- Residential house damage function

Residential properties' flood damage is calculated based on property units. For each single residential property, the average flood damage curve is shown as follows:

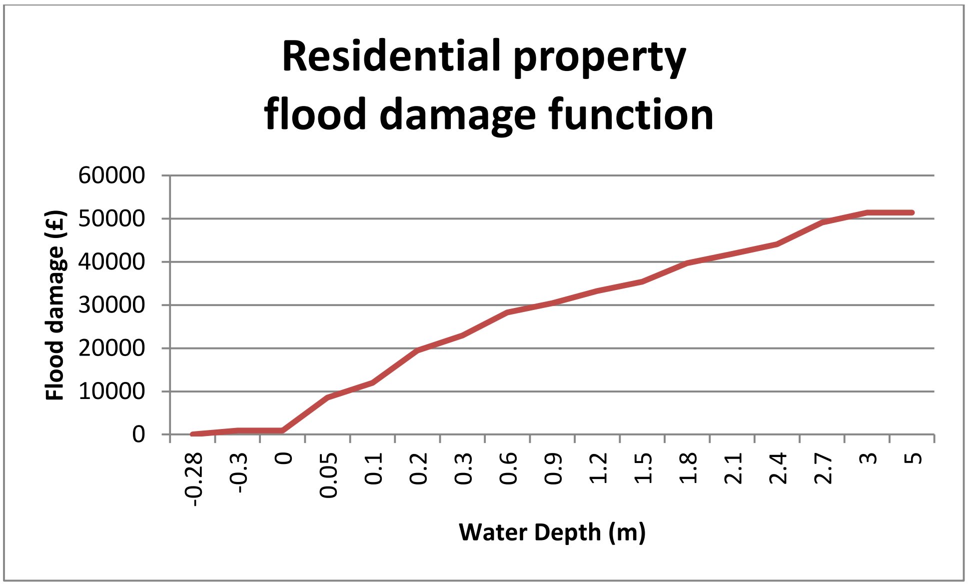


Figure 4-26 Residential property damage function (adapted from (Penning-Rowsell *et al.*, 2010))

For each grid, if it is flooded, the residential flood damage is calculated by the following equation:

$$GR_{RP_T} = N_{RP} \times DM_{RP}(fd) \quad \textbf{(4-2)}$$

where:

GD_{RP} : Each grid's residential property flood damage

fd : Floor depth, water depth above the upper surface of the ground floor which is 0.38m

N_{RP} N: Number of residential properties in the grid

$DM_{RP}(fd)$: Average residential property flood damage at floor depth fd

- Content damage

Sometimes content damage instead of the total damage is used in the process of calculating the benefit of flood risk reducing measures. Therefore, here the content damage is also calculated according to the content damage listed in the directory of household inventory damage in MCM (Penning-Rowsell *et al.*, 2010). The content damage curve is shown as follows:

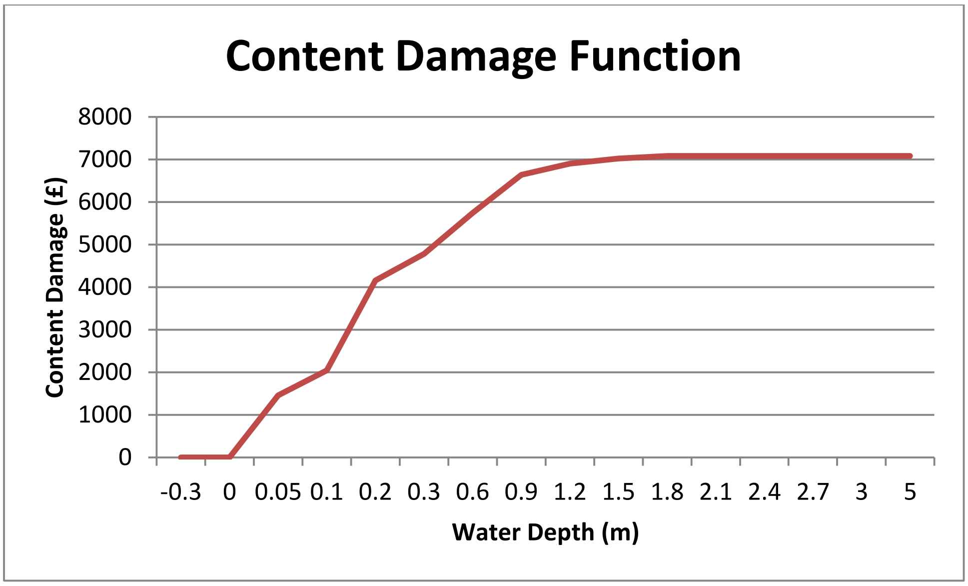


Figure 4-27 Content damage function for a residential property (adapted from (Penning-Rowsell *et al.*, 2010)

$$GD_C = N_{RP} \times DM_C(fd) \tag{4-3}$$

Where:

GD_C : Each grid's residential property flood damage

$DM_C(fd)$: Average content damage at floor depth fd

- Non-residential house damage function

The non-residential property flood damage function is given in different bulk classes, as shown in Figure 4-28.

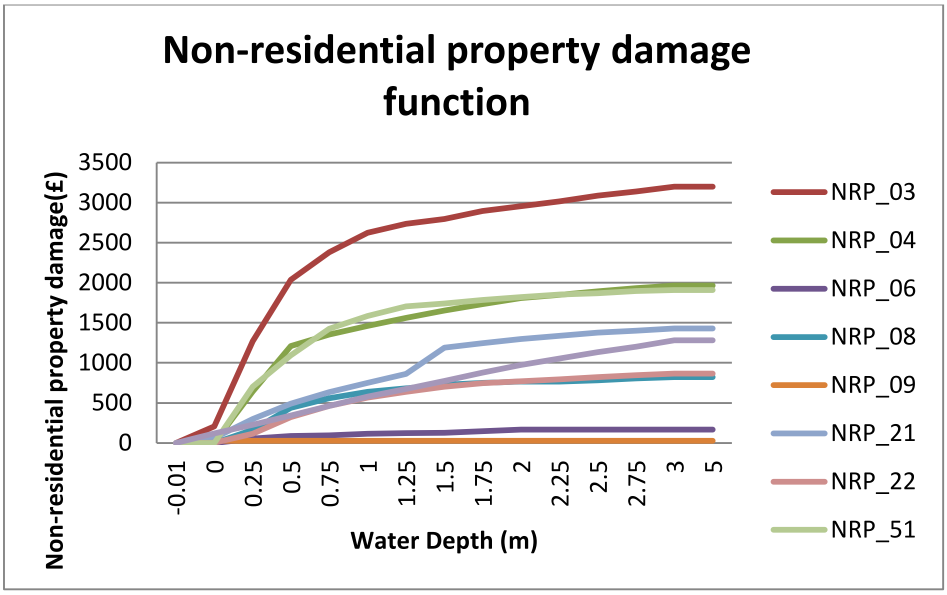


Figure 4-28 Non-residential damage function (adapted from (Penning-Rowsell *et al.*, 2010)

The non-residential property flood damage function is calculated in terms of square meters. Therefore, the mean floor area of each different type of non-residential property has to be obtained in the calculation. The mean floor area for bulk classes is listed in Table 4-10.

Table 4-10 Mean floor area for bulk classes (from MCM, 2010)

Bulk class	Mean floor area (m^2)
Retail	198
Warehouse	755
Office	307
Factory	865
All bulk	442

For each grid, the non-residential properties' flood damage can be calculated with these equations:

$$GD_{NRP} = \sum_{i} GD_{NRP\_i} \tag{4-4}$$

$$GD_{NRP\_i} = N_{NRP\_i} \times DM_{NRP\_i}(fd) \tag{4-5}$$

Where:

GD_{NRP}: Each grid's non-residential property flood damage

GD_{NRP_i}: Each grid's flood damage of type NRP_i non-residential property

N_{NRP_i}: Each grid's number of type NRP_i non-residential property

$DM_{NRP\_i}(fd)$: Average type NRP_i non-residential property flood damage at floor depth fd

Calculating human behaviour impacts on the flood damage

Very few practical research study results can be found for quantifying the impact of human behaviour on the flood risk. This made it difficult to calculate the flood damage discounted by human behaviour in the model. A key problem in the HBS module is that many types of human behaviour can be simulated, however, its impact on the flood risk cannot be estimated due to the lack of practical survey data support. One approach that combines the human behaviour model with the flood damage curve for calculating the benefit of flood warning lead time has been developed (Carsell *et al.*, 2004). In the research, warning lead time impacts on the flood risk are clearly expressed, as shown in Table 4-11.

Table 4-11 Residential content protected with warning (From Carsell et al., 2004)

1/2-h warning	2-h warning	4-h warning	>4-h warning
Color television (console)	Carpet sweeper	Largest appliances, such as dryer and refrigerator	Appliances such as dishwasher, oven, freezer, and washer
Color television (portable)	Larger appliances, such as microwaves, blenders, toaster ovens	Bookcases	Kitchen utensils
Stereo equipment	Items in cupboards	Dining table and chairs and other furniture	Central heating system
Smallest electric appliances	Expensive clothing	Food	Piano
Vacuum cleaner	Curtains and drapery	Some carpet	Dressers
Personal effects	Vehicles	Additional clothing and personal effects	Beds
	Additional personal effects		Linoleum/tiles

With this data, combined with the MCM economic value for the related content, flood warning lead time damage function estimates for residential structures are created.

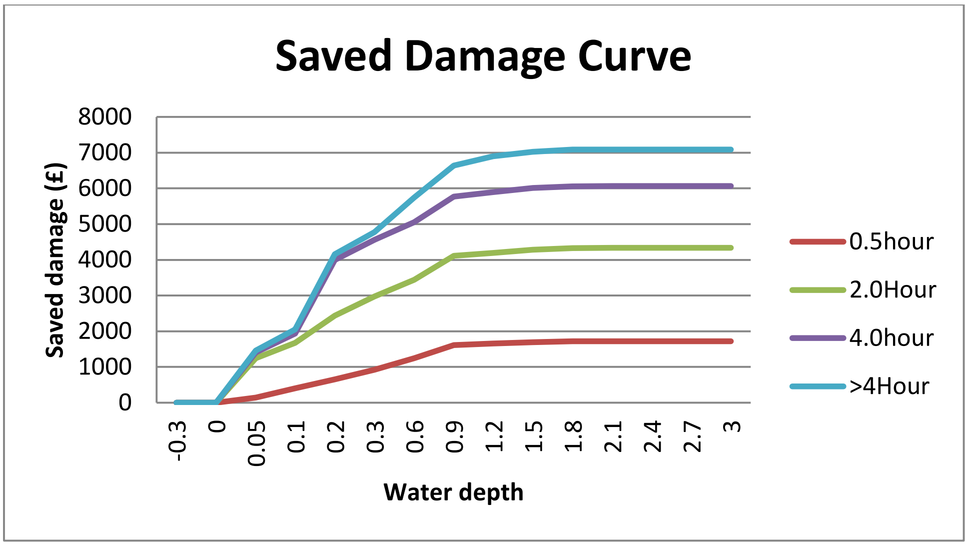


Figure 4-29 Saved content damage function estimates for residential structures for different flood warning lead times

For each cell, if there are residential properties and civilians in the building carrying out some mitigation actions such as moving things upstairs, then the flood damage reduction can be calculated.

4.7.3 Method for loss of life calculation

As reviewed in Chapter 3, the individual risk analysis makes it possible to calculate the evolution of risks during the flood event according to the flood dynamics. Penning-Rowsell's research (2005) has been validated by UK flood data; it has been the most reliable model for modelling human behaviour and response in this research. Considering the purpose of the research, loss of life is identified as a direct human death due to the physical water uploading during the flood events.

The method used to calculate the risk to life is adapted from the method prompted by Penning-Rowsell (2005) in Defra's Risk to People project. As introduced in section 3.5.1, it is based on the following three concepts: 'Flood Hazard', 'Area Vulnerability' and 'People Vulnerability'. The process estimates the possible annual average individual or societal risk of fatality due to flooding. As with economic damage, loss of life is the summation of losses in each model cell. The concepts of flood hazard, area vulnerability and people vulnerability are adopted in the simulation model, but the variables used have to be adjusted to judge whether an individual agent is in danger.

Flood hazard

The flood condition is expressed as a flood hazard rating, which is calculated by the following equation:

$$HR = wh \times (wv + 0.5) + DF \quad \textbf{(4-6)}$$

Where:

HR is a (flood) hazard rating:
wh is the depth of flooding (m)
wv is the velocity of floodwaters (m/sec)
DF is the debris factor.

Based on each land cell's flood depth and flood velocity value, the HR value can be calculated. The flood condition can be rated as dangerous to some, dangerous to most and dangerous to all according to Figure 3-7. This provides the environment condition for the civilians to respond to the flood.

Area vulnerability

In this model, the concept of area vulnerability describes the risks caused by the characteristics of an area of the flood plain that affects the chance of being exposed to the flood hazard. However, the speed of the onset factor in the original method is thought to overlap with the flood hazard rating because the speed of the onset is directly decided by the water depth and water speed. Furthermore, a flood warning is taken as a main non-structure measure to be evaluated in this research, therefore only the nature of the area is considered, as the characteristics that influence the probability of civilians being exposed to a flood hazard. The property type is chosen to represent the nature of the area. Properties are divided into two classes: high-risk class and low-risk class. High-risk class refers to the properties that have high risks of the flood such as bungalows, mobile homes, busy roads, parks, single storey schools and campsites, etc. Low-risk class includes multi-storey apartments or 2- storey homes, commercial and industrial properties. Building height data is used to identify the property type of each cell. Properties with heights lower than 4.5 metres are identified as high-risk properties (Forest of Dean District Council, 2010; Great Britain, 2010). Civilian agents can have different reactions to a flood based on the different area characteristics.

People vulnerability

People vulnerability in Defra's method is expressed as the percentage of civilians who suffer from long-term illness or are aged over 75 (Office for National Statistics, 2011). In this simulation, vulnerability is reflected in the mobility of civilian agents. A civilian agent's mobility can be classified into 3 levels (Table 4-12):

Table 4-12 Classifications of civilian agents' mobility

Mobility Value	Meaning	Mobility condition
1	No mobility	Mobility award claimants
2	Weak mobility	Elderly people over 70
3	Good mobility	Others

Age and disability are two factors that impact a resident agent's mobility value. For the factor of disability, using the percentage of civilians suffering from a long-term illness is not accurate if a walking disability is mainly concerned. For example, there might be a person who suffers from asthma, which is a long-term illness while this long-term illness would not have any negative effect on his ability to escape from a flood. It is noticed that the Mobility Component of Disability Living Allowance by UK government is only given to people who have walking disabilities. Therefore, the number of Disability Living Allowance claimants who receive a mobility award is considered to be the substitute for indicating vulnerable people with a walking disability.

For the factor of age, there is no evidence to show why the age of 75 is set as the division for old people's mobility. In the simulation model, to better connect the disability data from the Disability Living Allowance claimants' dataset, the age of 70 is set as the age division for old people's mobility.

Rules for calculating loss of life

Resident agents' reaction to flood hazard is based on the nature of one area and their mobility. With the setting up of HR, property type and resident agent's mobility, the three main considerations of risk to people in a flood event can be simulated. Figure 4-30 summaries the relationship between HR, flood depth and the vulnerability category of the agent.

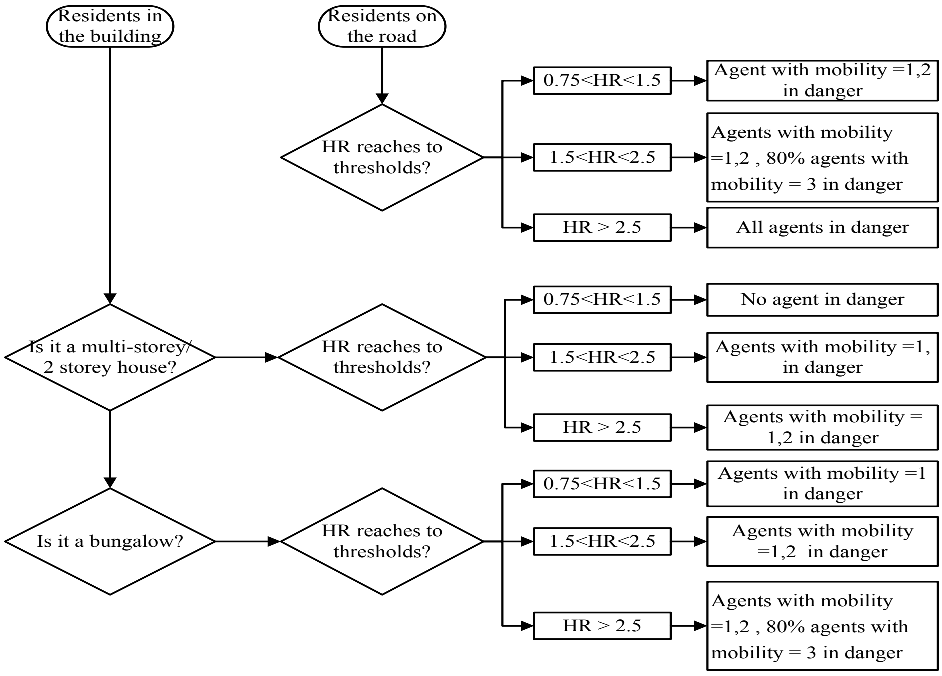


Figure 4-30 Rules of calculation of loss of life in the simulation model

The civilian agents are divided into two classes: active agent and static agent. Active agents are civilians on the road network, and are outside of buildings and, therefore, are exposed directly to flood water. Static civilians are civilians who are protected by the building when a flood comes. Therefore, their vulnerability to a flood is different. The flow chart above shows the different reactions to a flood from active civilians and static civilians.

For the civilians on trips, they are on the road network regardless of whether they are walking or in vehicles. When a flood comes, civilians are directly exposed to the flood water; therefore their reaction to the flood depends on the intensity of the flood hazard, which is measured by the variable of HR, and their mobility according to the Risk to People report.

When the HR is between 0.75 and 1.50, it is dangerous for some people, when HR is 1.5 - 2.5, it is dangerous for most people, and if HR is greater than 2.5 it is dangerous for all. However, the exact proportions for “some” and “most” are not specified. In this simulation, “some” is translated as the civilians whose mobility values are 1 or 2. “Most” is translated as 80% of the whole population.

For static civilians, the buildings can be protection when flood water comes. Therefore, the property type will influence the flood risk to the civilians. The static civilians’ reactions to the flood are different depending on their property types. It is assumed that even the worst condition of buildings, such as bungalows and mobile homes, have a better chance of protecting civilians from being exposed to flood water. The better the property type, the higher the HR threshold is set, and the less flood risk is anticipated.

The counting of civilians who are in a dangerous status is represented by the variable *DangerCount* in the simulation model.

4.7.4 Method to calculate the risk to vehicles

Based on Xia's (2011) formula for predicting the incipient velocity of flooded vehicles the method to calculate the risk to vehicles is developed.

Because there is no supporting practical data about the residents' car sizes, for each civilian agent who chooses a vehicle as their travel mode, the vehicle is randomly set as a large, medium or small size car.

Calculating incipient velocity (U_c)

As introduced in section 3.5.3, the instability of vehicles is related to the intensity of flood, vehicle type (weight, volume) and some other factors such as car density.

In equation (3-22), assuming M= $\sqrt{2g\left(\frac{\rho_c-\rho_f}{\rho_f}\right)h_c}$, for a certain type of vehicle, M is a constant. The formula can be rewritten as:

$$Uc = \alpha \times \left(\frac{h}{h_c}\right)^{\beta} \times M \quad \textbf{(4-7)}$$

Therefore,

$$M = \frac{Uc}{\alpha \times \left(\frac{h}{h_c}\right)^{\beta}} \quad \textbf{(4-8)}$$

Combining the h and Uc data given by Figure 3-11 with the α and β data given by Xia (2011), M can be calculated. Thus, all the constants used in the equation (3-23) can be obtained, which is shown in Table 4-13, and for a certain type of vehicle at a certain water depth, the incipient velocity Uc can be derived.

Table 4-13 All the parameter values in the formula

Flood degree	Partially submerged		Fully submerged			
Parameters	α	β	α	β	M	Hc
Pajero Jeep	1.492	-0.731	0.737	0.532	1.02	1.806

BMW M5	1.116	-0.558	0.816	0.264	0.759	1.634
Mini Cooper	1.225	-0.708	0.932	0.121	0.534	1.376

Situation judgement.

For a vehicle in a flooded area, if the flood velocity (v) of the land patch is greater than the incipient velocity of the vehicle (Uc), the vehicle is counted as a vehicle in danger. Risk to vehicles is represented by the variable called *DangerCarCount* in the simulation model, which is the number of vehicles in danger in the flood event at a time step.

4.7.5 Measures for evaluating flood evacuation plan

A flood evacuation plan is one of the most important non-structural measures for mitigating the loss of life due to a flood event. Usually, in a flood evacuation plan, shelter selection, and effective evacuation routes, namely transit response, are the key issues. When an evacuation command is released, the whole population of an area may need to be evacuated to one or several shelters within a very short period. The high volume of transport flow might cause significant congestion that would hinder the effect of evacuation. Therefore, in this report the transport capacity theory is used to explore what kind of transport indicators can be selected to represent the performance of a flood evacuation plan in the simulation model.

As reviewed in section 3.5.4, congestion is one of the most important indicators for evaluating the traffic performance. Therefore, calculating congestion is included in the simulation model for flood evacuation planning.

As HCM's congestion measurement method is a widely accepted, it is adopted in the research for spatial risk analysis for flood event management.

$$\mathrm{v} = \mathrm{FFS} \times \frac{1}{1 + \alpha \times \left(\frac{q}{C}\right)^{\beta}} \tag{4-9}$$

Where:

v : Average travel speed km/h
q: Flow rate cu/hour
C: Capacity of the road cu/hour. Here it is set as 1409 according to the road grade.
α: The observation parameter is usually 0.15
β : The observation parameter is usually 4

If the car speed is less than 50% of FFS, the road is counted as a congested road. It is also possible that congestion could be defined as level D, slight congestion, level E, medium congestion and level F, heavy congestion in a further study.

4.8 Simulation scenario setting

4.8.1 Simulation model interface

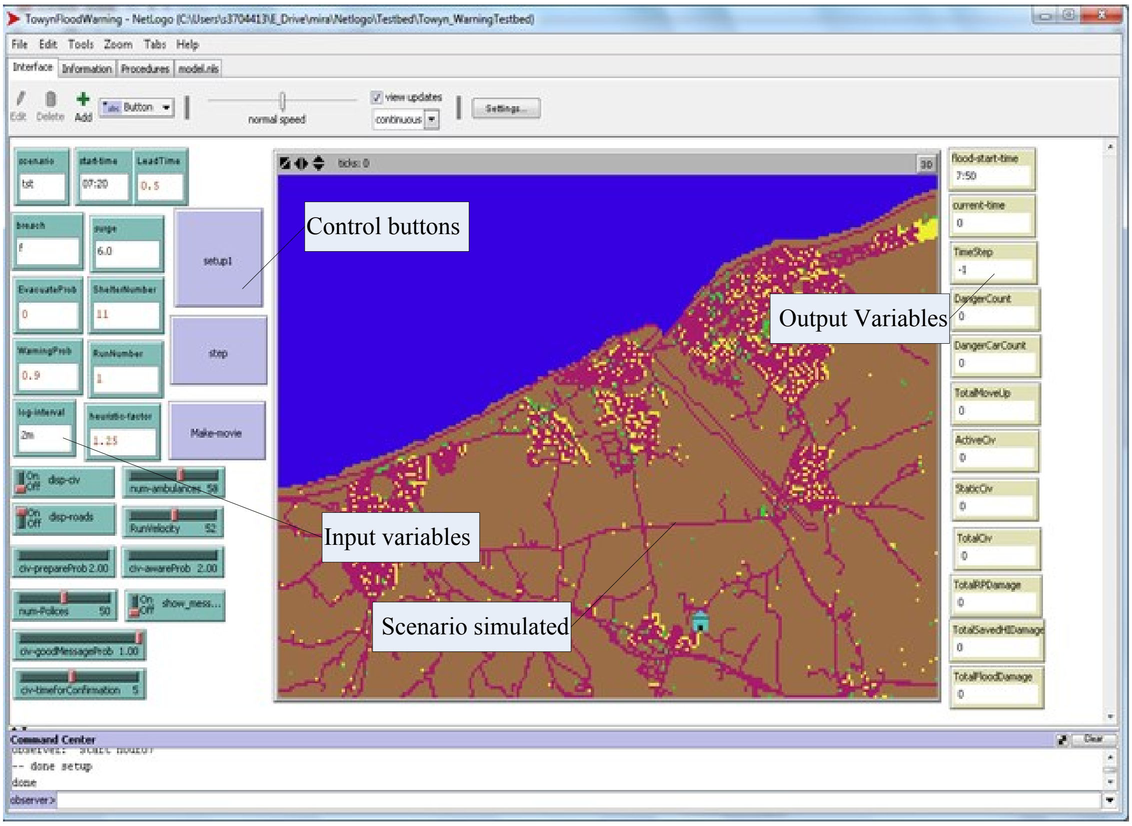


Figure 4-31 Simulation model user interface

Figure 4-31 shows the simulation model user interface. The middle area is the window for showing the scenario simulated while on the left are the input variables within green labels and the control buttons within purple labels such as setup, step or make a movie. On the right-hand side are the output variables such as total flood damage, total residential property flood damage, number of people who are in danger and number of vehicles that are in danger.

4.8.2 Scenario setting

In this research, three simulation scenarios are tested: a baseline scenario, a flood evacuation scenario and a flood warning scenario. The research began by simulating a baseline scenario, in which no non-structural measures are involved, and then calculating the flood risk under this baseline scenario. Then, the evacuation scenario, which assumes that an evacuation command is sent out, was simulated. Finally, some human factors affecting flood warning such as flood warning lead time, flood warning accept rate and evacuation rate were added to produce the flood scenarios taking individual responses into account, and then the flood risks under these scenarios were calculated. Finally, the impact of non-structural factors and structural measures of the flood risk were compared. Table 4-14 provides an overview of the three simulation scenarios.

Table 4-14 Overview of the three simulation scenarios

	Baseline scenario	**Evacuation scenario**	**Flood warning scenario**
Lead time	Not included	Not included	Included
Flood simulation	Included	Included	Included
Individual behaviour	Normal travel behaviour. Individual's spontaneous flood reactions.	Only evacuation behaviour.	All the individual behaviour described in the model.
Organizational behaviour	None	EA sending evacuation command in the beginning.	EA sending flood warning according to the lead time.

The flood scenarios simulated are a simplified flood event instead of the real flood situation due to several reasons. Firstly, real coastal flood events are caused by a combination of several conditions: high tide, overtopping from the river, and flood defence breach. As not all hydraulic data for simulating all the conditions can be obtained and for the purpose of simplifying the simulation, the flood simulation is only limited to the flooding situation caused by defence breaching.

Secondly, flood defence is considered as one variable that influences the sensitivity of flood risks, and not only one flood defence breaching but also other flood defence breaches that potentially threaten an area are simulated.

Thirdly, ABM simulation is time-consuming, and the simulation running time is directly related to the degree of the model's complexity and the time steps simulated. For the flood warning scenario simulation when all the human responses to the flood event are included, a scenario of a 10 hour flood event simulation needs 4 hours running time for a PC with duo cores and 4G RAM. Besides, the GSA requires the running of over ten thousand simulations, as explained in chapter 6.

4.9 Summary

This chapter describes the method and techniques used in this research.

The short-term flood risk analysis model is implemented on the ABM platform Netlogo. The general structure is composed of three main layers. The flood simulator is the fundamental layer providing the environment, and the human behaviour simulator is the core module that makes it possible to visualise the human factor impact. The flood risk analysis tool calculates the flood risks in flood risk common currencies.

The geographic environment information that includes both land patches and the road network are first imported into the ABM model.

Full-shallow 2D models that obey the conservation of mass and the conservation of momentum principles have a better simulation result for flood velocity than other 2D models. Therefore, a finite-volume Godunov-type scheme that solves the full 2D shallow water equations is implemented in the ABM platform to simulate flood behaviour.

The human behaviour simulator (HBS) simulates the responses of the individuals and organisations involved in the flood events. Within the HBS, individuals or organisations are considered as agents. Each agent behaves according to their rules and interacts with the environment and other agents. A general prototype of human behaviour is set up first, and then an activity-based travel behaviour model is developed to model active agents' travel behaviour. A conceptual, organisational behaviour model is also built to simulate organisational flood responses in a flood event. Finally, all the conceptual human behaviour models are successfully implemented as flood event human behaviour simulation software on the NetLogo platform.

The flood risk analysis tool in the simulation model focuses on the measurement and evaluation of flood risks. By using the risk analysis tool, flood risks can be estimated under certain conditions. In this tool the economic flood damage (residential and non-residential), the loss of life and the instability of vehicles are the three indicators of flood risks.

The appraisal focuses on the effect of flood warnings and flood evacuation. Flood simulation is a simplified flood event that only considers flood defence breechings rather than a real flood event. Three scenarios are set, which are the baseline scenario, the flood warning scenario and the flood evacuation scenario.

In the next chapter, the established simulation model will be applied in a case study area to determine practical flood management solutions.

Chapter 5. Case Study

5.1 Introduction

The flood event management simulation, and flood risk analysis, is applied in a real study area in Towyn, North Wales, to explore the possibilities of using the model to solve some practical flood event management problems. This chapter provides an introduction to the model application before more detailed consideration of model behaviour and uncertainties in Chapter 6. In this chapter, the basic information about the case study area, data collected from the case study area, model validation and testing and the scenario settings in the case study area are described.

5.2 Case study area

Towyn is a seaside resort located between Rhyl and Abergale in the county borough of Conwy, North Wales (Figure 5-1). Towyn has a population of 2,239 (Office for National Statistics, 2011).

As a typical coastal flood area, most of the flood events in Towyn are caused by extreme sea levels coupled with high wave conditions (HR Wallingford, 2008). In 1990, Towyn was inundated when 450m of the seawall was breached by a 1 in 500-year event. This occurred when a 1.3m storm surge coincided with high tide and 4.5m high waves (Dawson *et al.*, 2003). Four square miles of land was flooded, affecting 2,800 properties, over 5,000 people were evacuated, and the flood damage was estimated to be in excess of £50 million (HR Wallingford, 2008).

In the last 20 years, EA and the local government paid for a massive flood risk mitigation effort in the Conway area, including structural measures such as constructing rear flood walls, improving the sea wall across the Kinmel Bay frontage as well as non-structural measures such as adjusting the residential development plan, the flood plan and recently the multi-agency flood plan. Towyn has been a case study area for many coastal flood studies in the UK ((Bates *et al.*, 2005; Lany *et al.*, 2009; Dawson *et al.*, 2011a)), and therefore plentiful practical data has been accumulated for my research.

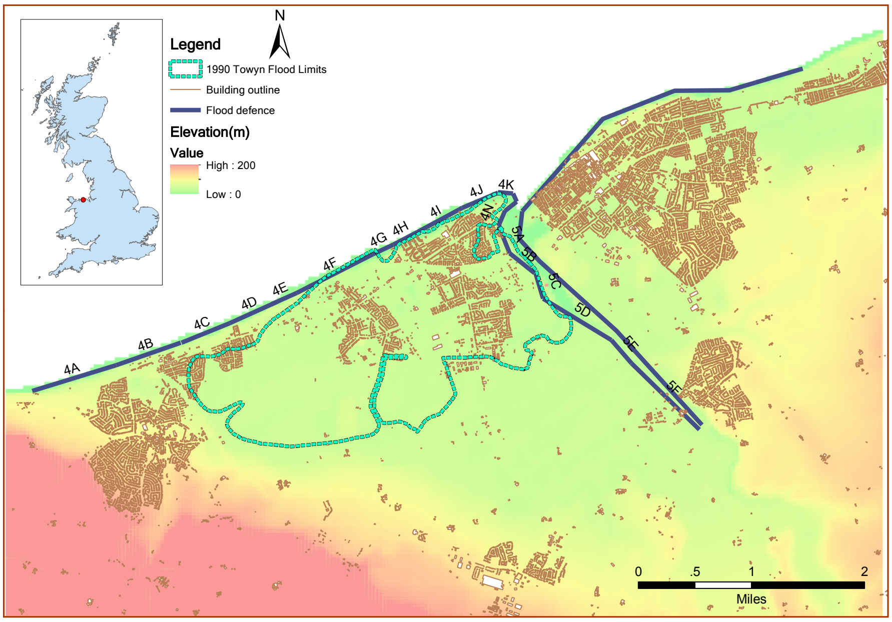


Figure 5-1 Map of Towyn and its surrounded area

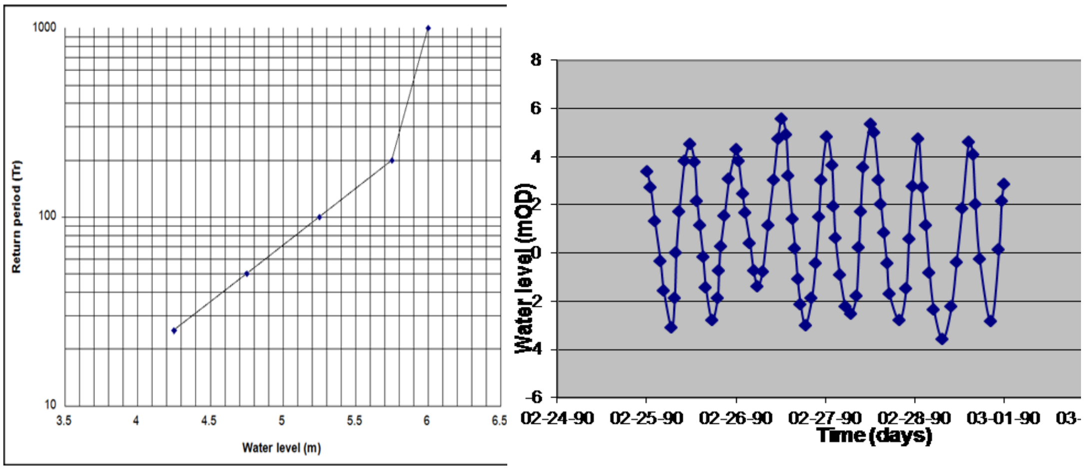
5.3 Model test and validation

5.3.1 Hydrodynamic simulator validation

The flood simulation result is validated according to the 1990 Towyn flood. The Towyn flood of 1990 was one of the most significant coastal tidal floods in Wales. It started on 26th February and lasted over 60 hours. The flood affected 10 square kilometers from Pensarn to Kinmel Bay. Over 5,000 people were evacuated from nearly 3,000 properties and the immersion of agricultural areas resulted in damage to crops. The total cost of the flood was estimated to be in excess of £50 million (Bates *et al.*, 2005).

The Towyn flood of 1990 was due to both physical and human causes. In February 1990, Towyn witnessed a 1 in 500 years combination of low atmospheric pressure, westerly storm force winds and spring tides with a 1.5m surge, which led to extreme 4.5m high waves (MET Office, 2010). The breaching of a 4.67m embankment, which was 140 years old and poorly maintained, resulted in the flood reaching as far as 2km inland with a maximum depth of 2m.

The Towyn flood of 1990 data was used to validate the Shallow2D flood simulation model. In terms of water level data, different values were provided from different sources. Bates used a simple GIS method by assuming a planar water surface across the coastal floodplain at the level of the observed maximum water elevation of 5.85m (Bates *et al.*, 2005). Hall and Wu (2009) provided a relationship between water level and return period for the Towyn flood case. According to Figure 5-2 (a) the 1 in 500 years flood water level should be about 5.8m.



(a) (b)

Figure 5-2 Water level information. (a) Return periods of a range of water levels at the site (Hall and Wu, 2009). (b) Tidal cycles during the Towyn 1990 flood event.

However, according to the tidal cycle during the 1990 Towyn flood event (HR Wallingford, 2003), the water level varied according to the time, the highest tides were at 12:19 on 26th Feb. 1990 which was 5.57m, but at the time the breach happened, at 11:14 on 26th Feb. 1990, the tide was 4.71m. Considering all this information, the water level is set at 5.0m and the flood event time span is 60 hours. The simulation result is shown in Figure 5-3.

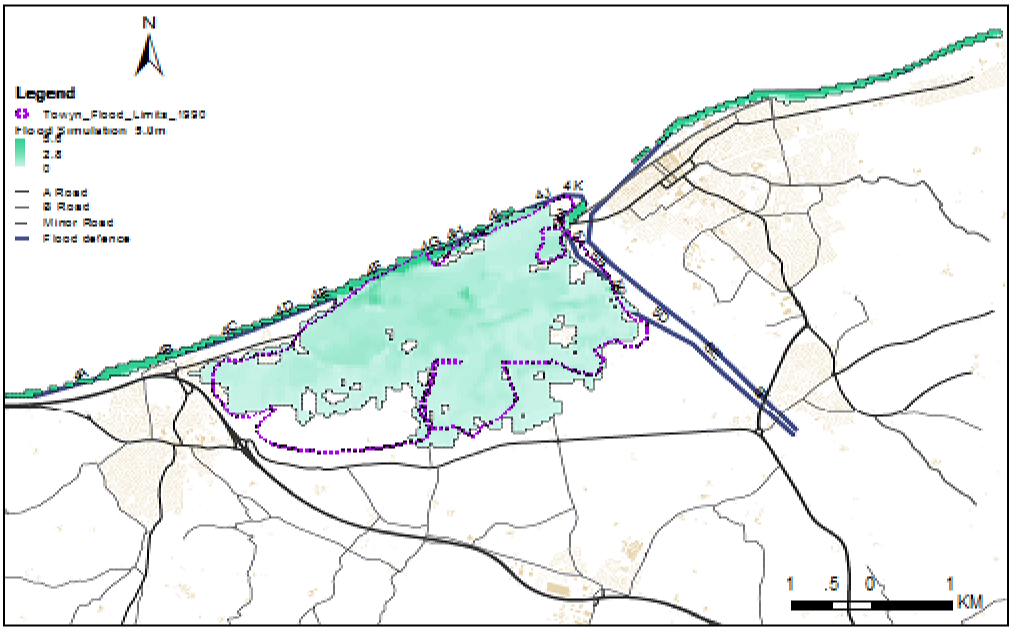


Figure 5-3 Comparison of flood simulation result to the Towyn 1990 flood limits

Fit statistics, which are widely used for measuring flood simulation accuracy (Horritt *et al.*, 2010), are used to compare the flood simulation result and the recorded 1990 Towyn flood water extent. The fit statistics are calculated as:

$$F^1(\%) = \frac{A}{A+B+C} \times 100 \quad \textbf{(5-1)}$$

$$F^2(\%) = \frac{A-B}{A+B+C} \times 100 \quad \textbf{(5-2)}$$

$$Bias(\%) = \frac{A+B}{A+C} \times 100 \quad \textbf{(5-3)}$$

where A is the area correctly predicted as wet by the model, B is the area predicted as wet but observed as dry, and C is the area predicted as dry but observed as wet. For the 60 hour Towyn flood simulation the fit statistics can be seen in Table 5-1. The flooded area in the simulation result covers 80% of the actual 1990 Towyn flooded area.

Table 5-1 Fit statistics for the simulation result of the 1990 Towyn flood

Test Variable	Result
F^1	70.5%
F^2	58.9%
Bias	93.0%

From the flood extent map, it shows that the predicted water extent correlates very well with the observed 1990 Towyn flood limit. However, on the south-western side, there is a region that is within the flood limits not predicted by the model. This is likely to be because in this model the Manning coefficient is set to one single value (0.018 for an urban area), but the south-western part is grassland that would be expected to have a smaller Manning coefficient. If the Manning coefficient can be adjusted according to its landform, there might be an improvement. Another significant inconsistency is on the southern part, south of Quarry Line Path, where it is predicted to flood and contradicts the observed flood extent. The reason for this is likely to be related to the Tirllwyd Industrial Estate building blocks built in the 1980s, where there are 42 units of steel portal framed construction with part brick/part profile metal clad elevations. However, the DEM data used is only the surface data, and no building heights are added. This area has a very low elevation. Therefore, the flood simulation did not reflect the real heights of this area. Given more detailed DEM data which includes building heights, the flood simulation might be more accurate. Comparing the simulation result with the recorded water extent, it is concluded that the hydrodynamic model sufficiently simulated the flood hydrodynamics of the 1990 Towyn flood.

5.3.2 Preliminary testing of human behavior simulator

For demonstrating that the rules can be translated into a functioning human behaviour model, a simple idealised dam break case is tested to highlight a small number of simple interactions. The HBS is first demonstrated in a simple dam break scenario. The behaviour rules of key agents in this example are shown in Figure 5-4, whilst Figure 5-5 shows the output from the implementation in Netlogo.

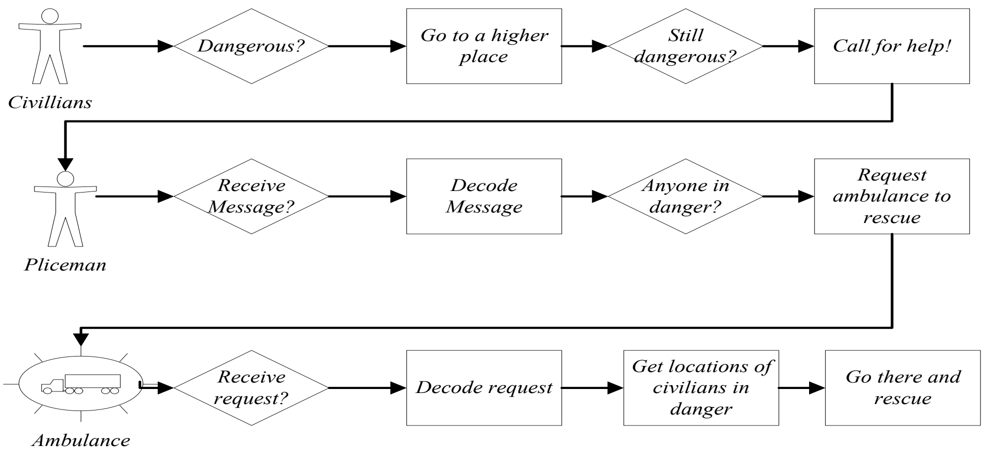


Figure 5-4 Behaviour rules for the key agents in the simple dam break case

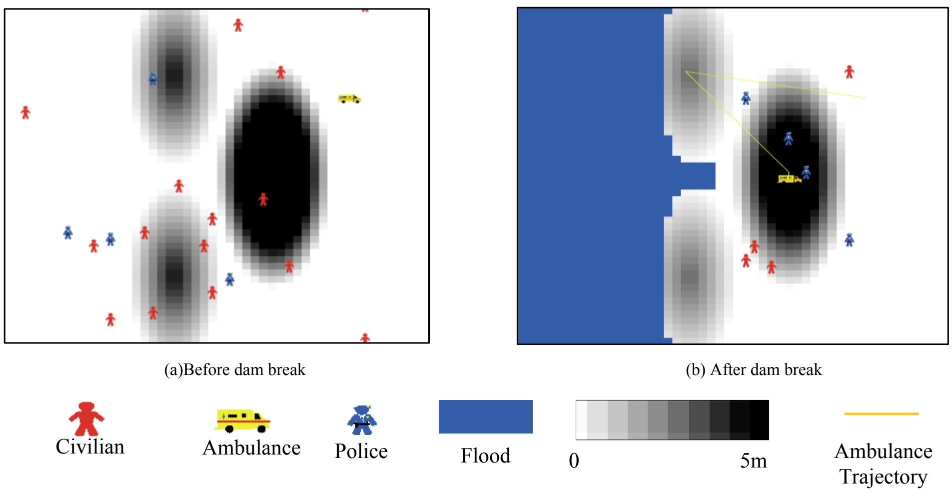


Figure 5-5 Simulation result of the dam break case

At first civilians and police are scattered randomly in the area (Figure 5-5 (a)). The civilian agent visually observes the flood situation when the floodwaters are close by. First the civilian tries to move away to higher ground. However, he still discovers a flood threat so alerts the emergency services. The blue light services (police and ambulance) then respond by carrying the civilian (and others) from the area at risk to the shelter (Figure 5-5 (b)). If the simulation is successful, it is expected that civilians in danger move to higher ground and send help messages. Once the messages have been received by the blue light services, the ambulances will move to rescue civilians from the danger area. Obviously the simulation results agree with the original prospect. Therefore, the simulation system is proved to be able to simulate the agents' behaviour in a flood and their interactions and can model a more complex situation.

5.3.3 Economic flood damage method validation

It is quite difficult to validate the method established for calculating the economic flood damage in the ABM due to the very limited practical data available. The only relevant data found is that the total flood damage estimated for the 1990 Towyn flood is £50 million (HR Wallingford, 2008). The 60-hour 1990 Towyn flood simulation result obtained from the HDS is input to the economic flood damage module and the total flood damage calculated is £47.8 million, which approximates very well (<5%) to the 1990 event.

5.4 Baseline simulation

When the effect of a non-structural measure is to be evaluated, the output of the flood risk under the condition of taking this measure needs to be compared with the output under the original situation when no measure is taken, namely the baseline scenario. Therefore, the first step is to set up this baseline scenario.

The baseline scenario is supposed to be the non-action influenced condition. It assumes that when a flood is coming no non-structural measures such as flood warning, multi-agency communication and flood evacuation are taken into account. It is a scenario where only the flood dynamics and the natural reaction of individual residents are simulated. In this section, the baseline scenario setting is described in detail.

5.4.1 Environment background

The map of Towyn and its surrounding area is loaded as the base map for the simulation, allowing for the possibility of different flood defence breaches as well as the fact that Towyn town residents may travel to the outer area. The loading of the surrounding area makes it possible to visualize residents' travel behaviour in a comparably complete transport system, and the different parts of flood defence breaching can also be simulated. The data used in the base map are listed in Table 5-2, which includes terrain data, building data, and road network data from the Ordnance Survey master map of the Conwy area and the building heights data set from LandMap (The GeoInformation Group, 2013).

Table 5-2 Base map data list

Data Name	Purpose	Source
Digital elevation map	For setting the value of land patches' elevation for flood simulation.	Interferometric Synthetic Aperture Radar data (IfSAR) from Conwy County Borough Council
Building types	For setting the value of land patches' building type.	Environment Agency's national property database
Building heights	For setting the land patches' property type.	Land map elevation collection
Road network	For setting up the road system in the model.	Ordnance Survey master map
Flood defences	Defining breach locations for setting the boundary condition for flood simulation.	Environment Agency's national flood and coastal defence database

The terrain data used in the simulation is in the form of an Esri ASCII Grid format file. The file consists of 249*179 50-metre size cells whose heights are given. The hydrodynamic model uses terrain data for identifying the elevation of each land patch.

The building data provides the location and the building codes of buildings. This information is important for the civilian agents because civilians with different trip types select their trips start points and destinations according to building types. Another use of building data is for calculating flood damage. According to MCM (Penning-Rowsell *et al.*, 2010), a flood damage evaluation not only depends on the depth of flood water but also on the type of land use. The information on building type is stored as a land patch, which can be attributed to the purpose of simulating residents' travel behaviour. In the simulation model, buildings are categorized into 9 classes, as shown in Table 5-3. For the purpose of calculating flood risks, building code with 0 is counted as ***residential,*** and others are being credited as ***non-residential***.

Table 5-3 Building type classification in the simulation model

Building type number in the model	Building type in the model	Building codes in OS master map
-2	Road	
-1	No building	

0	Home	0 ,511, 512 ,513, 514 ,515 ,516
1	Work	-3 ,310 ,311, 410, 430, 411, 412, 413, 650, 651, 810, 820,, 830, 840, 850, 860
3	School	610
5	Shop	23, 211, 212, 213, 214, 215 ,216 ,217, 218, 221 ,223, 224, 238
6	Personal purpose destination	320, 660, 232 ,620 640, 690
7	Social club	236 ,234 ,235
8	Recreation	-5, 517, 518, 519, 521, 522 ,523, 524, 525, 526, 527, 625, 630 ,670

Road network data from the OS master map includes each road's ID number, start node ID, end node ID, road type and road length, which are in each road record. Road spatial locations are expressed as a set of points with coordinates. Road network is read in for the road system in the simulation model, for every road, three types of agents' road, node and rlink are created, as described in section 4.4.2

Defence data is needed for simulating the risks of defence breaching. The defence breaching can be simulated through the changing of defence elevations. When the defence is in good condition, the elevation of a flood defence is set at 10 metres while it changes to 0 when the defence is breached. With these data, the environment background is set up.

5.4.2 Flood simulation

NewChan, a shallow 2D hydrodynamic model (Liang, 2008), is adopted for simulating flood dynamics during a flood event. To improve the computational performance, the flood simulation is done separately first, and then the flood simulation results are imported into the NetLogo platform.

In the simulation model, each time step is identified as one minute, so for a 10-hour flood event, it is a simulation with 600-time steps. For the first 10 minutes after the flooding, every minute's flood water results are provided. For the rest of the time, every 5 minutes' flood water results are imported.

The flood defence breaching from A to K is simulated, as shown in Figure 5-3. This shows that Breach D E, F, G, H and I are the breaches that mostly influence the Towyn area and these 6 breaches are used for the simulation flooding background. According to the return periods of a range of water levels at the site (Figure 5-2), the sea water levels of 4.0-7.0 m are simulated.

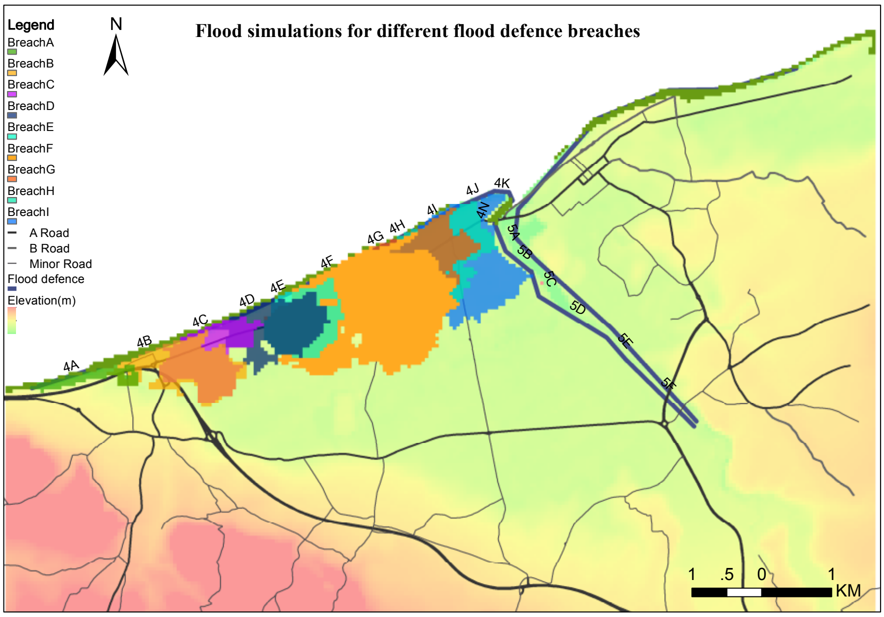


Figure 5-6 10 hour flood simulation results for different breaches

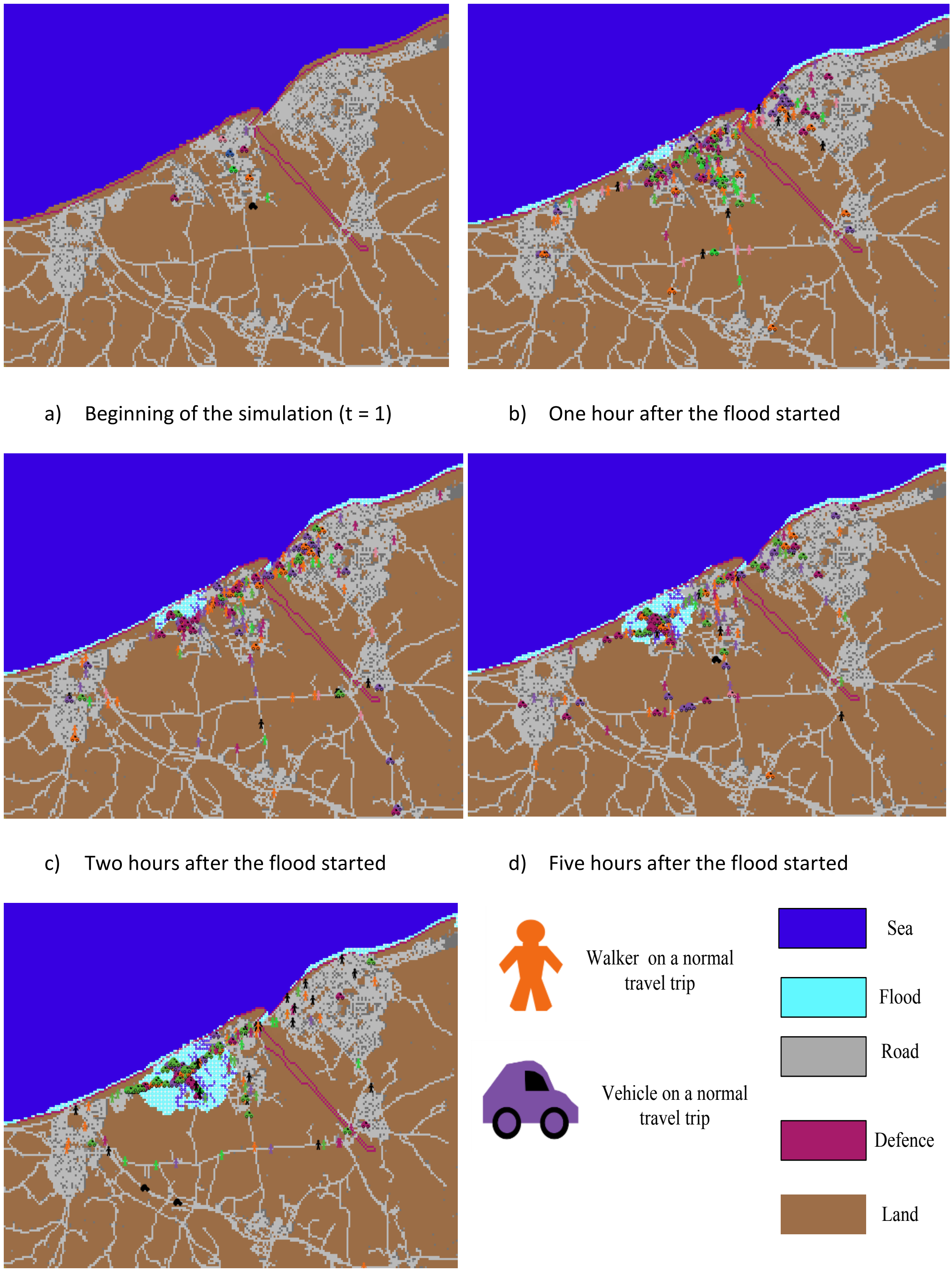
5.5.3 Human behaviour

In the baseline setting, a *civilian* agent is the only type of human agent that appears in the model. It is assumed that the initial status of civilians in the area is their normal status, as described by the Census data. The population of 2,239 of Towyn are simulated (Office for National Statistics, 2011). At time 00:00, all the civilian agents are static agents which mean they are produced at a residential address. Then for each hour, the normal travel trips are produced according to Table 4-5, which means some civilians are randomly selected to start travel trips for different types of activities (as shown in Figure 4-11)

In the baseline model, no human responses to the flood that reduce flood risks are simulated. However, some of the residents' spontaneous responses to the flood are included. When the place is flooded, civilian agents sense the situation and report their dangerous situation. Flood water may impact on a traveller's route choice. If the *road* that the civilian agent needs to walk on is flooded, the agent needs to select another route so the flooded road can be avoided. However, if he tries all the roads near him but fails to find a route, he will report that he is stranded.

5.4.4 Baseline scenario

The time series of a baseline scenario simulated is shown in Figure 5-7. The baseline scenario simulation shows the situation when no non-structure measures are involved during the flood event. At the start, there are only some normal travelers travelling to their targeted destination according to their travel patterns. Civilians remain on their normal trips when the flood starts. After one hour of flooding, the flood starts to affect the road and the properties, and then from 2 hours after the flood started 10 hours after the flood started, there are lots of cars or civilians that are stranded or have been exposed to a dangerous situation. Details of the number of cars and civilians that have been exposed to a dangerous situation will be discussed in Chapter 6.



a) Beginning of the simulation (t = 1)
b) One hour after the flood started
c) Two hours after the flood started
d) Five hours after the flood started
e) Ten hours after the flood started
Legend

Figure 5-7 Time series of the baseline scenario simulation

In view of the experimental design, the function of the baseline scenario simulation is to obtain the expected flood risks of the baseline scenario as the reference for non-structural solutions. The first step of the experiment is to get the random samples of the baseline scenario simulations and based on these samples, the mean μ_0 and the standard deviation δ_0^2 of the baseline flood risk can be identified.

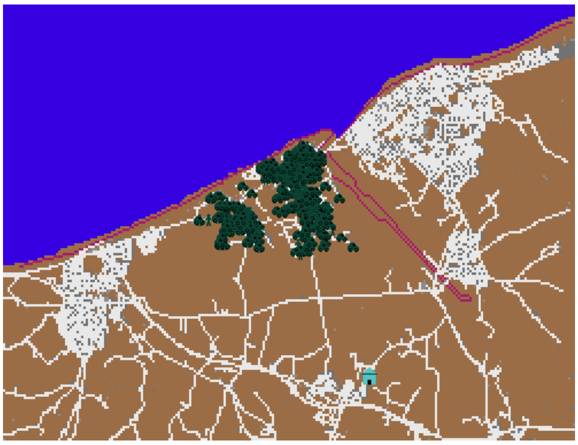
5.5 Flood evacuation scenario simulation

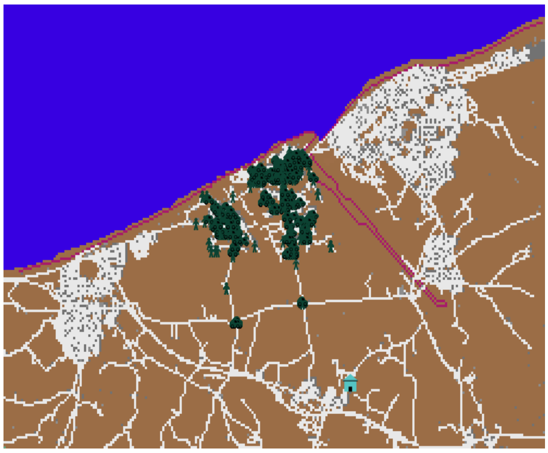
5.5.1 Flood evacuation scenario simulation

The flood evacuation scenario simulation assumed that all the residents start to evacuate to shelters upon receiving an evacuation command. The research starts by developing the flood evacuation scenario simulation first, to see whether the model can contribute to improving traffic control for the flood evacuation plan.

In the flood evacuation model, apart from those civilians' spontaneous flood reactions included in the baseline simulation model, an EA agent is added to send out an evacuation command. In this scenario, to explore the maximum potential benefits of flood evacuation, it is assumed that everyone trusts EA agents and their advice is acted upon, which means that all civilians will receive the command and then evacuate to a shelter immediately.

As shown in Figure 5-8, before the flood comes, the evacuation command is sent out. As a result, all the residents change to evacuees taking shelter as their destination and move towards the shelter. The cars move faster than the walkers and are first to arrive at the shelter. Although slower than the cars, the walking residents also move quickly towards the shelter. Before the flood covers the residential area, all of the residents have successfully escaped to the shelter.



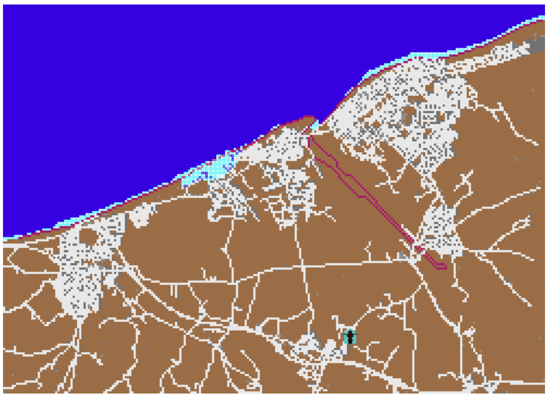


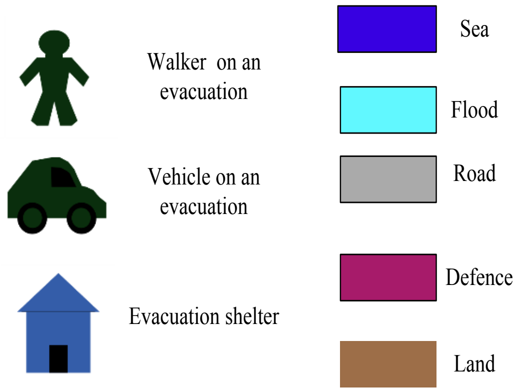
a).Beginning of the simulation (t = 1))

b).Five minutes after the flood started

c).A half hour after the flood started

d).One hour after the flood started





e) One and a half hour after the flood started

Legend

Figure 5-8 Time series of the evacuation scenario simulation

5.5.2 Evacuation scenario simulation experiment design

The objective of setting up an evacuation scenario simulation is to help traffic control in flood evacuation. Based on the building capacities, 12 possible locations were selected

(Dawson *et al.*, 2012), as shown in Table 5-4 and Figure 5-9. To select the most suitable shelter, the evacuation scenarios of 12 different locations under the same flood conditions are simulated. The traffic conditions, specifically congestion for different shelter locations, are compared. The simulation result will be displayed in Chapter 6.

Table 5-4 List of possible shelter locations (from (Dawson *et al.*, 2012))

ID	X	Y	Name
0	294544	377848	Abergele Church
1	294146	377569	Abergele city Hall
2	297244	379402	Towyn Church
3	298869	380156	Towyn work office
4	298918	379907	Towyn factory
5	301021	381555	Rhyl Church
6	300987	381393	Rhyl Court
7	301540	382021	Rhyl Hospital
8	301640	380760	Rhyl School
9	301288	381791	Rhyl Offices
10	302569	378323	Rhuddlan Police Station
11	300458	376014	Bodelwyddan hospital

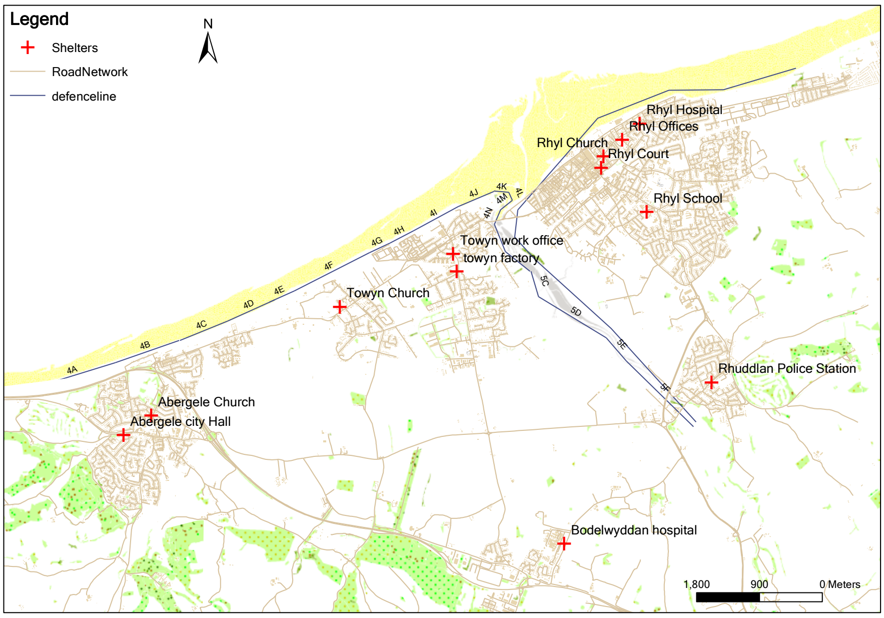


Figure 5-9 Locations of 12 possible shelters for the flood evacuation

5.6 Flood warning scenario simulation

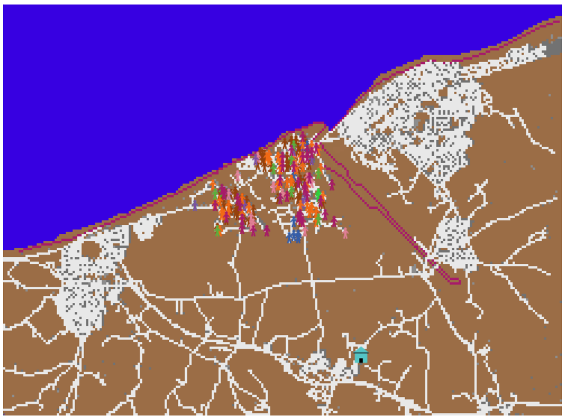
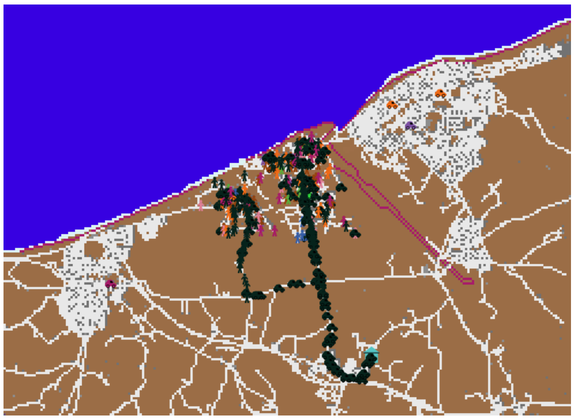
5.6.1 Flood warning simulation model

Although it is widely used for traffic control in an evacuation plan, the assumption of the evacuation model is far from the real situation. As has been noticed, not all civilians take action when they receive a flood evacuation command (Boyd, 2005; Molinari and Handmer, 2011) though very often it is mandatory. By way of demonstration, for this scenario, the proportion of people that receive a warning is 90%, but the number who take action to evacuate to a shelter is assumed to be 50%, as a flood warning is not a mandatory command. As reviewed in Chapter 3, in recent years, it has been noticed that the benefit of flood warning is affected by human factors such as the warning lead time, the receive ratio of flood warning and the human responses to the flood which are determined by the residents vulnerability to the flood.

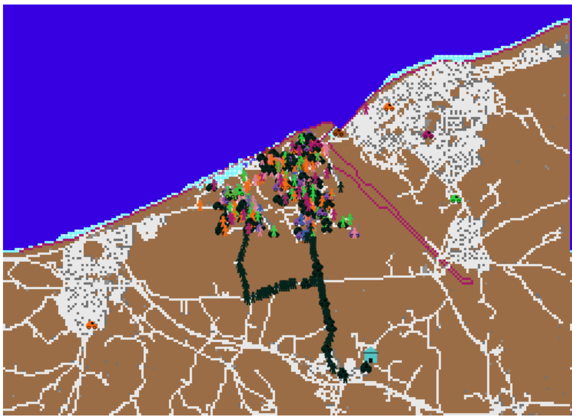
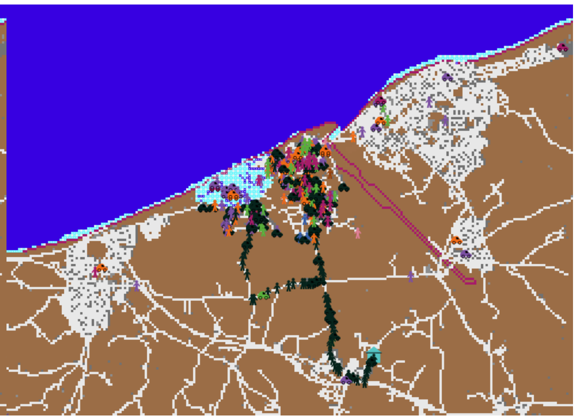
In the flood plan of Conway Council (2009), the EA is responsible for sending flood warning information to both related organizations and residents. In the simulation model, the message sending mechanism has been successfully implemented. However, as there is no practical evidence on the economic benefit of the related organizations' responses, we first just simulate the residents' response to the flood warning to see how flood warning impacts on the flood risks.

The residents' responses to the flood include responses to the flood warning and the flood, which are simulated according to the behaviour rules summarized in Chapter 4.

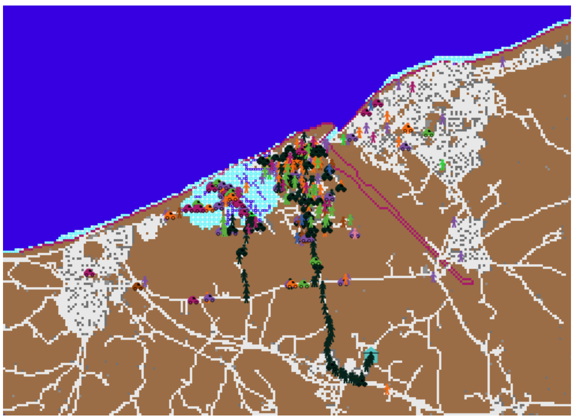
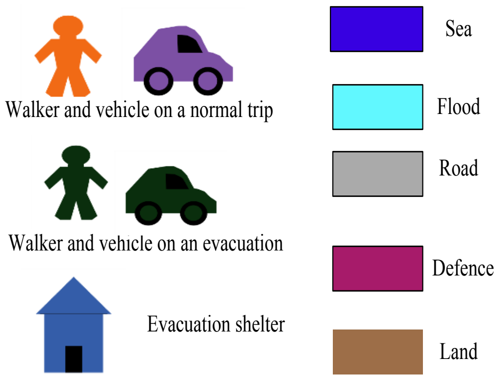
5.6.2 Flood warning scenario simulated

a) Beginning of the simulation (t = 1) b) The flood started

c) One hour after the flood started d) Five hours after the flood started

e) Ten hours after the flood started Legend

Figure 5-10 Time series of the flood warning scenario simulation

Figure 5-10 a) shows the initial status of Towyn before the simulation. The different colours of the agents represent different travel for different purposes such as commuting, business, education, shopping, holidays and so on. Figure 5-10 b) shows when the flood warning is sent out. Some of the civilians respond to the warning and decide to change their destination to the shelter (the house shape on the map). The residents who move towards the shelter change their colour to green. The agents are moving to the shelter. Figure d) shows that when the flood comes there are many travellers who are still doing their normal travel activities. Figure e) shows that at the end of 10-hour simulation, there are still many civilians who did not take any action, despite a flood warning being issued and are therefore exposed to the flood.

5.6.3 Experimental design based on flood warning scenario simulations

The flood warning scenario simulations are to test the non-structural measures' effect on deducing flood risks. It is now expected that some purposeful changes in the input parameters associated with the non-structural measure flood warnings are made so that changes in the output such as flood risk can be observed. This is to answer questions like "Is this non-structural measure influential?" "How does it influence the flood damage?" and "Are different human factors correlated with each other?" Clearly, these answers will be convincing inferences on how to improve the existing flood management system.

Data analysis can be conducted on the statistical experimental data obtained.

1.Human factor as one factor

The human factor that influences the effectiveness of a flood warning can be expressed as the proportion of people who take protective action among the entire community who receives flood warnings. The higher this ratio is, the more effective the flood warning is.

$$R_{action} = \frac{N_{action}}{P} \tag{5-1}$$

Where:

R_{action} is the percentage of people to take actions among the population who receive flood warnings.

N_{action} is the number of people who take action after they receive the flood warning.

P is the population of the area.

Sensitivity analysis on how different levels of R_{action} affect the flood risks will represent how human factors influence the effectiveness of flood warning.

Table 5-5 Input and output variables in, and factor analysis on the flood warning vulnerability

Treatment Level of R_{action} (a = 3)	Estimator: Flood Damage $f_{warn}(\mu_{warn}, \delta^2_{warn})$ (sample size = n)			
	1	2	…	n
1.Low 10%	y_{11}	y_{12}	$\cdots$	y_{1n}
2.Mid 50%	y_{21}	y_{22}	y_{ij}	y_{2n}
3.High 90%	y_{31}	y_{31}	$\cdots$	y_{3n}

The data that needs to be collected are the values of y_{ij}. The analysis of variance can then be based on the data obtained.

2.Human factors as separate d variables

The warning information quality, the level of flood awareness and the level of flood preparedness, as well as the mobility of the residents are all influential factors. If the result of warning information quality, level of flood awareness and the level of flood preparedness to the flood damage needs to be checked, then the multi-factorial experiments have to be designed. Here I chose the flood warning lead time and the flood warning ratio as well as the residents' proportion of evacuation once they have been informed to represent human factors in the flood event. In the experiment, the flood warning ratio and the residents' proportion of evacuation vary from 0 to 100%. The flood warning lead time ranges from half an hour to over 3 hours.

Assuming each factor (treatment) is tested at 3 levels, then it is a three factors, three levels test. Assuming the sample size is n, then $3^3 \times n$ simulations need to be done using a Latin Square design for the multi-factorial analysis.

Table 5-6 Factors and treatment levels selected for multi-factorial analysis on the vulnerability of flood warning

Factors	Level 1	Level 2	Level 3
Warning Rate (%)	10	50	90
Warning Lead time (Hour)	0.5	1	3
Evacuation Rate (%)	10	50	90

3. Comparing human factors with other factors

In order to test whether the model can evaluate structural measures and non-structural measures in one platform, some physical and structural factors (such as water levels, shelter locations and flood defences) that influence the flood risk are selected together with the human factors as the input parameters for the short-term flood risk analysis model. The outputs of the model are in terms of the general flood risk currencies that are residents in danger, vehicles in danger and economic flood damage. Here Saved Content Damage is chosen to show the result of human factors to the flood damage. The global sensitivity analysis used for comparing human factors with structural factors will be introduced in detail in Chapter 6.

5.7 Summary

In this chapter, the case study area Towyn is firstly introduced and then model validation and testing process are described. Three scenario simulations of the case study area are described. The baseline scenario is mainly focused on the simulation of the physical environment such as the land patch, road network and flood dynamics and can be taken as a background reference. The flood evacuation scenario follows assumptions that are generally used for flood evacuation traffic control. Some simple behaviour of civilians is added to see whether the model can be functional for the flood evacuation traffic planning. The most complex scenario – the flood warning scenario - explores the implications of issuing a flood warning but with only a limited proportion of people responding by evacuation. This scenario can form the basis for testing the effectiveness and importance of non-structural measures that relate to human factors.

In the next chapter, the results from the simulations according to the experimental designs described here are demonstrated.

Chapter 6. Results and Discussion

6.1 Introduction

This chapter shows the results obtained from the experiments including the spatial analysis based on the baseline, the evacuation simulation scenario and single factorial and variance-based sensitivity analysis based on the flood warning scenario followed by a discussion of the results.

The simulation of human response includes several variables that are described using random distributions. For example the individual agent's initial location is randomly located on a residential property when it receives a flood warning, there is a probability whether or not it takes an action. Therefore, the number of replicates has to be identified so that the samples are sufficient enough to capture the real feature of the experiment and save the cost of computation at the same time.

To achieve this, 100 ten-hour flood event baseline scenario simulations (assuming the flood defence F breach and the water level is 7.0m) were run to identify the robustness of the simulation result. Figure 6-1 shows that the mean of these simulations results is very stable after 100 simulations.

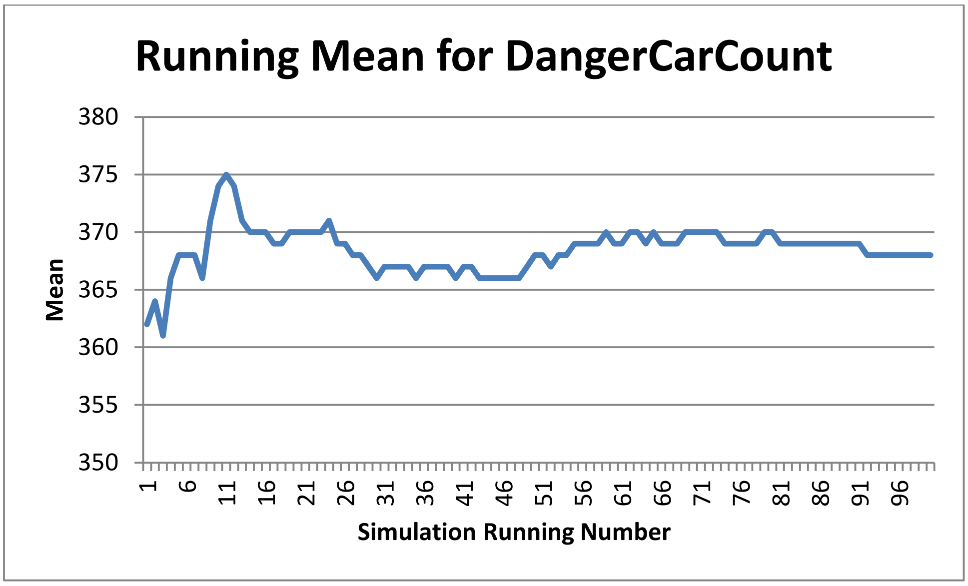
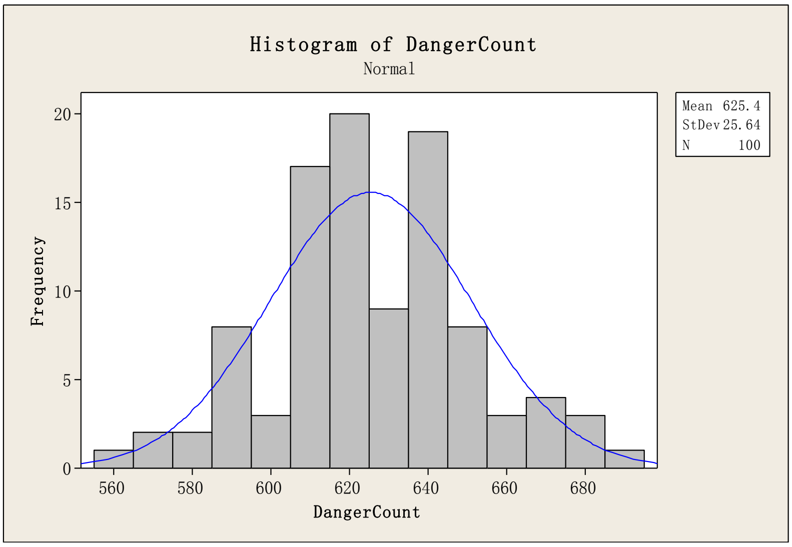
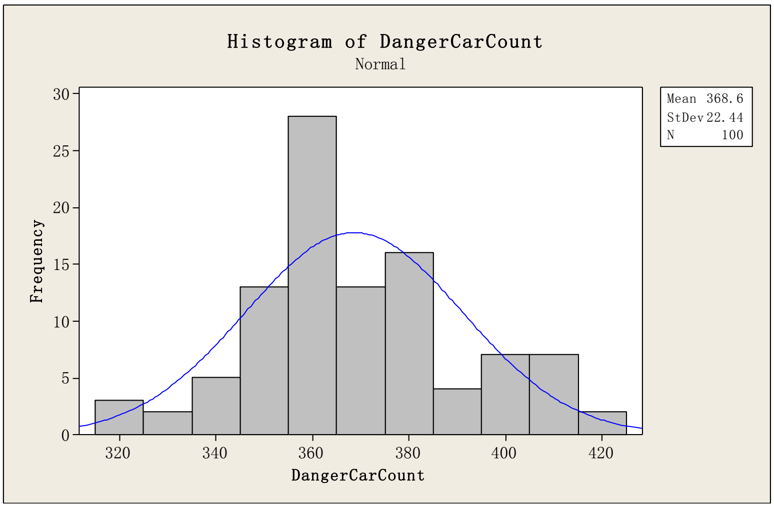


Figure 6-1 Running mean for DangerCarCount

Figure 6-2 shows the mean and the standard deviation of the two main output variables *Dangercount* and *DangerCarCount* based on the baseline scenario simulation result.



Histogram of DangerCount



(b)Histogram of DangerCarCount

Figure 6-2 Histograms of DangerCount and DangerCarCountfor 100 simulations

The Z-score formula to identify the sample size (Montgomery, 1996) is as follows:

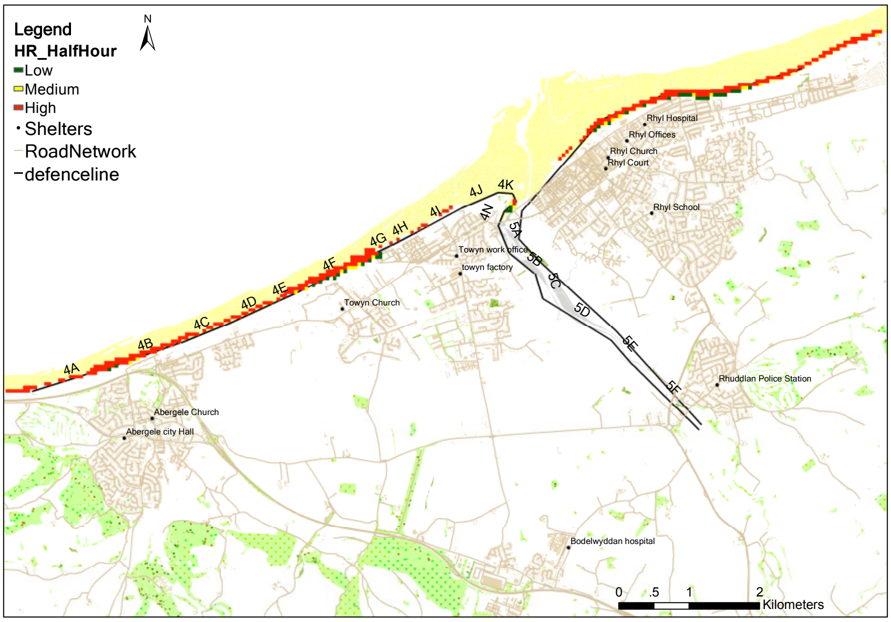
$$n \geq \left(\frac{z_{1-\alpha/2}\delta}{d}\right)^2 \qquad \textbf{(6-1)}$$

Where $z_{1-\alpha/2}$ is the Z score that corresponds to the confidence interval is (1-α), δ is the variance, d is the margin of error. When the confidence interval is set as 90%, and the permissible error is ∓3%, the minimum sample size for the *DangerCount* is 5 and the minimum sample size for the *DangerCarCount* is 9. Therefore, to capture sufficient variability in the results without enormous computational cost, all further simulation results reported in this chapter are based upon 10 replicates.

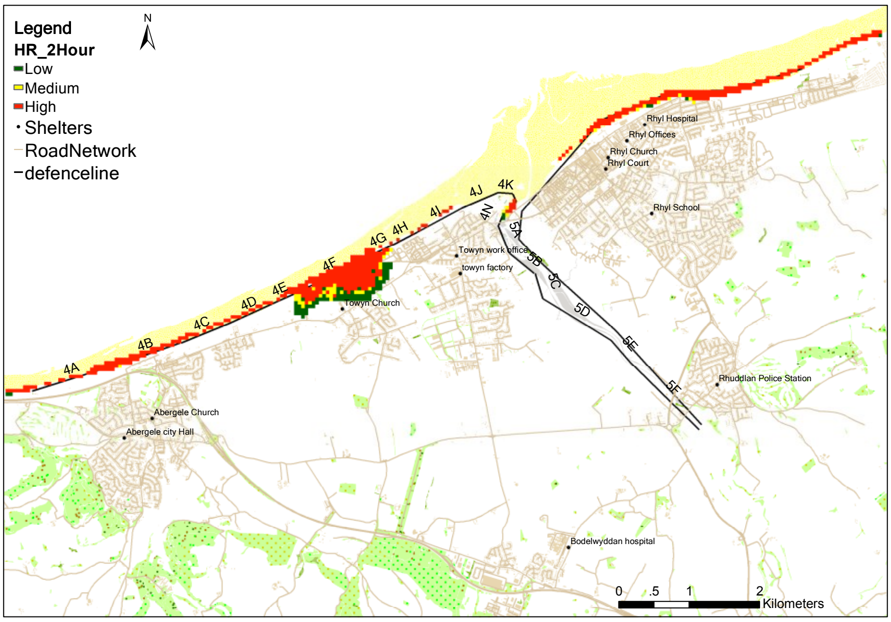
6.2 Spatial risk analysis based on the flood evacuation scenario simulation

6.2.1 Flood risk map

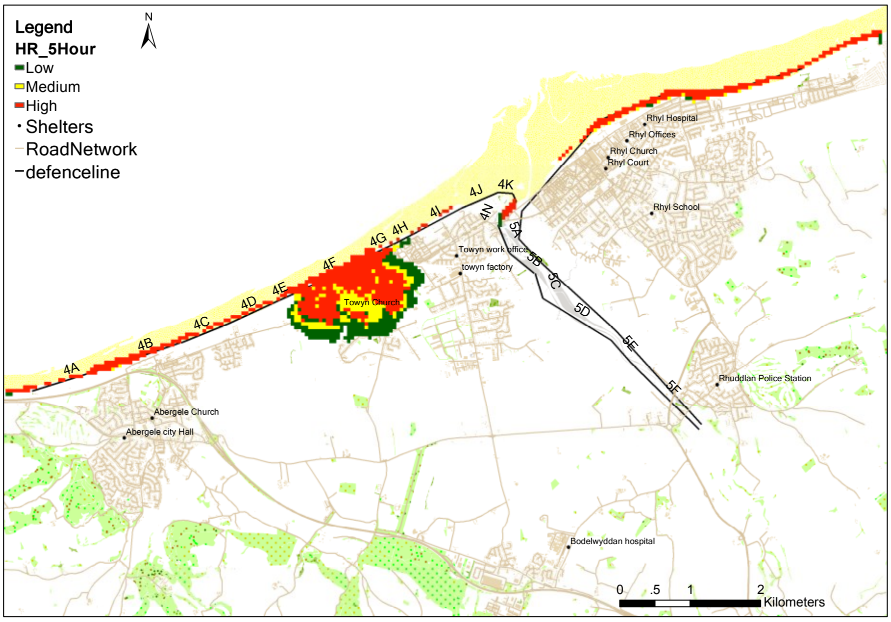
Additional to the flood maps demonstrated in Chapter 5, the flood hazard map is also used for rating the impact of the flood hazard and for calculating the flood risk to people. As described in Chapter 4, the flood hazard rating score (HR), which relates to the depth and velocity of flood water can be visualized as flood hazard maps. Figure 6-3 is a series of flood hazard maps obtained from ten-hour flood event baseline scenario simulations assuming the breach of flood defence F and the water level is 7.0m. It rated the flooded area as a low-risk area (in green), a medium risk area (in yellow) and a high-risk area for people (in red). Furthermore, the model can simulate the temporal change of the flood hazard map. Figure 6-3 (a) – (d) shows the changing of the HR value from the beginning of the flooding to the 10th hour of flooding.



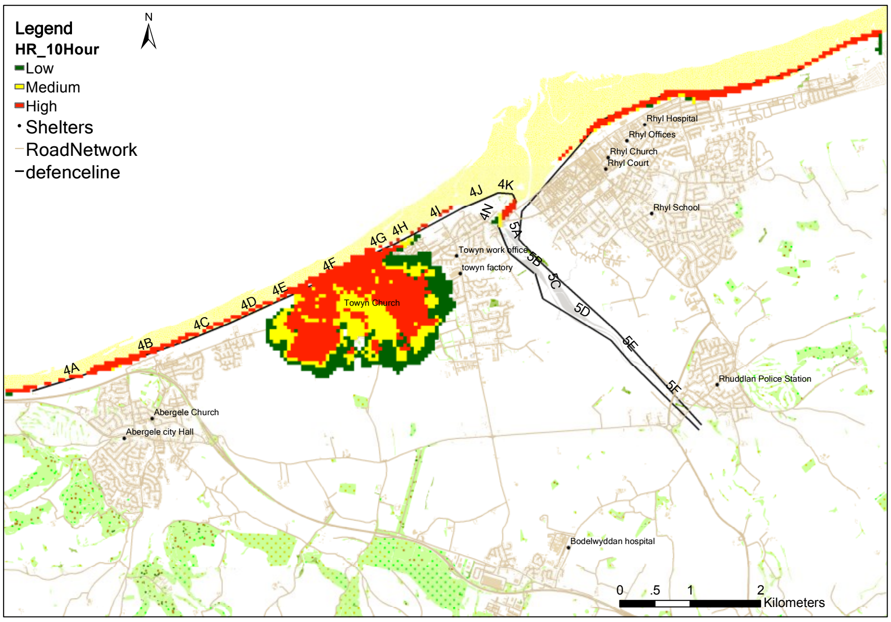
a) Flood hazard rating map half an hour after the flood starts



b) Flood hazard rating map two hours after the flood starts



c) Flood hazard rating map five hours after the flood starts



d) Flood hazard rating map ten hours after the flood starts

Figure 6-3 The temporal change of flood hazard rating in the flood event

The model identifies the highly rated hazard area at one time and then its changes during a flood event. It is useful for flood emergency managers to identify the most vulnerable places according to their flood dynamics. Taking Towyn as an example, for the breach of defence F, the dynamic flood hazard rating can be described as shown in Table 6-1.

Table 6-1 Flood hazard interpretation for breach F

Breach F		
Half an hour after the flood started	Flood extent	0.88 km^2
	High risk area to people	The west side of Golden Sand holiday park is affected.
	Safety of infrastructure	No major roads are affected.
	Safety of shelters	All shelter locations are safe.
Two hours after the flood started	Flood extent	1.46 km^2
	High-risk area to people	Mainly holiday parks north of Towyn Road, east of Caravan Towyn and west of Gaingc View Holiday Parks are affected.
	Safety of major infrastructure	Only minor roads are affected: Peris Ave, Gwytherin Ave, Sandbank Rd, Gaingc Rd.
	Safety of shelters	All shelter locations are safe, but Towyn Church is very close to the edge of the flooded area.
Five hours after the flood started	Flood extent	2.55 km^2
	High-risk area to people	Half of Towyn town is affected, east of Happy Day's Leisure Park, west of Seldons Golden Gate Holiday Park, south of Kinmel Way.
	Safety of major infrastructure	A548 Towyn is seriously affected. Gors Rd is seriously affected.
	Safety of shelters	Towyn Church is in the flooded area.
Ten hours after the flood started	Flood extent	4.25 km^2
	High-risk area to people	Nearly the whole of Towyn town is affected, east of Morfa Leisure Center, Ysgol Y Foryrd Towyn Infant School, Oakfield Caravan Park, west of White House Leisure Parks, Ty Mawr Holiday Park, south of Towyn Way W, Brook Ave.
	Safety of major infrastructure	A548 Towyn is seriously affected; Gors Rd is seriously affected.
	Safety of shelters	Towyn Church is in the flooded area, Towyn work office and Towyn factory are close to the edge of the flood extent.

As stated in Chapter 2, uncertainties associated with the source of the flooding such as waves and storm surges as well as with the pathways such as flood defence breaches (Hall and Solomatine, 2010) make it difficult to anticipate and prepare for a flood event even if a flood plan is carefully designed (Woodward, 2012). Currently, emergency actions are only triggered by three levels of flood warning (flood alert, flood warning, severe flood warning) in most of the flood plans in the UK. The content of a description of the flood situation in a flood warning is only limited to water depth. However, for a coastal flood, as shown in Figure 5-3, even with the same water level, different defence breaches will lead to very different results in flood risk. How to prepare flood plans for different possible flood scenarios is still a challenge.

Furthermore, various organizations such as the Highway Authority, the police and local authorities involved in the flood event management have different responsibilities. Some are human centred while some are the facility or infrastructure centred. How the flood hazard condition information in a flood warning can be interpreted so it is useful information for these organizations so that their emergency operations can be improved is also a challenge. The dynamic flood hazard rating obtained from the model provides a basis for prioritising investment decisions. The areas of highest flood hazard can be identified according to different water levels as well as different defence breach locations, and potential threats to people, properties, road networks or other infrastructures are identified according to their flood dynamics. Therefore, the different organizations can draft their action plans or allocate their rescue resources according to the timeline of the flood.

6.2.2 Road congestion map

Based on the simulation of the flood evacuation scenario, road congestion maps are produced in order to help understand traffic conditions during a flood evacuation. Figure 6-4 is a road congestion map based on the simulation result of a flood evacuation scenario assuming the breach of flood defence F and the water level is 7.0m. The map shows the congested roads at a given time. If the car speed of the road is less than 50% of FFS, it is identified as a congested road.

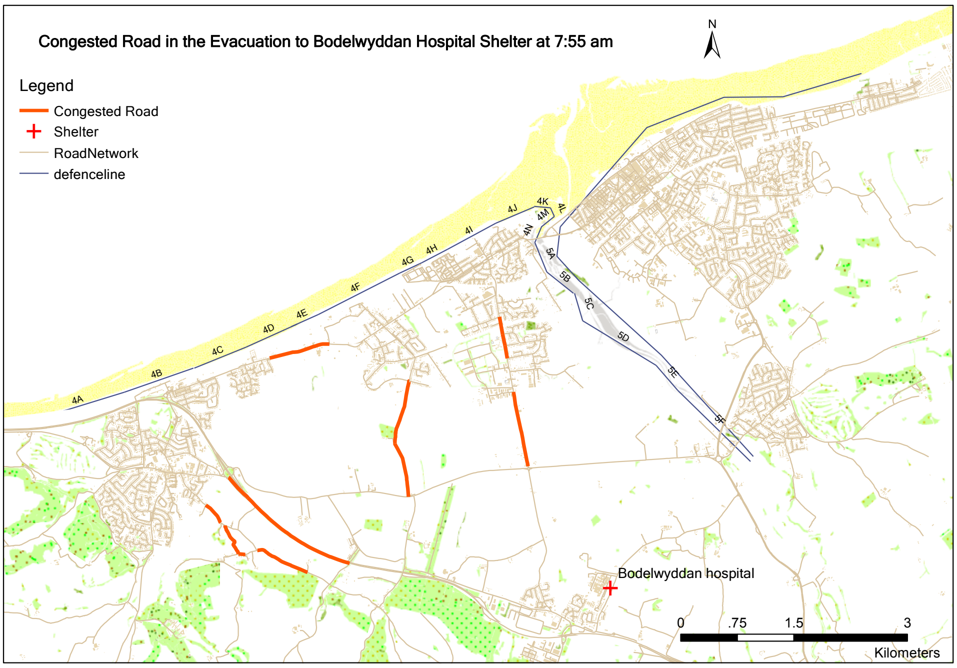


Figure 6-4 Road congestion map at one-time step

Figure 6-4 shows the road congestion time at 7:55 am, assuming the flood evacuation command was sent out at 7:50 am. On the map, the congested roads are visualized. As the evacuation begins, the highly congested areas are mainly the street roads in the residential area in Towyn.

Furthermore, the model can simulate the temporal change of flood congestions in a flood event.

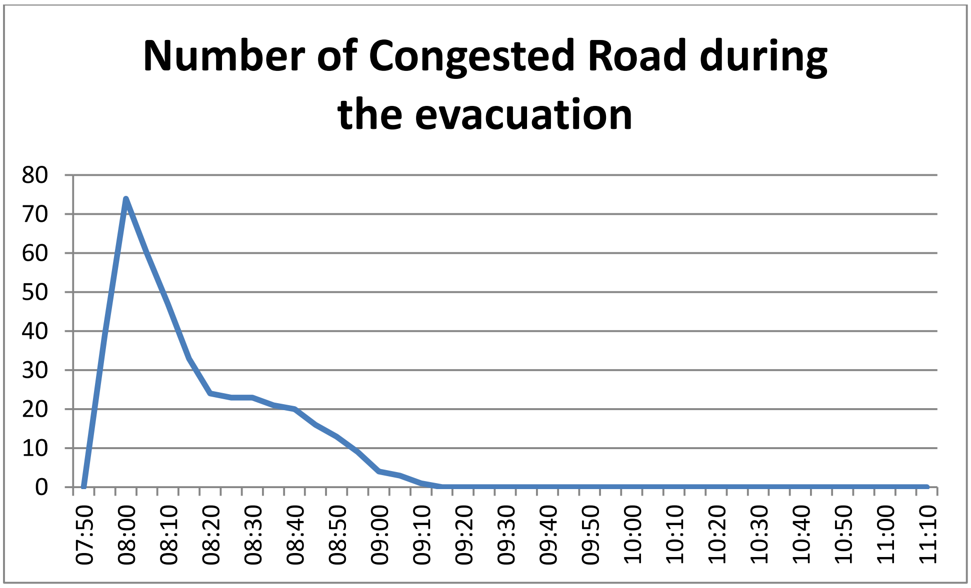


Figure 6-5 Number of congested roads during the evacuation to shelter at Abergele Church

Figure 6-5 presents the statistics of the number of congested roads during an evacuation to the shelter at Abergele Church assuming the evacuation command is released at 7:50 am. It is apparent from this figure that the congested roads appear during the first hour and a half. There has been a sharp rise in the number of congested roads in the first ten minutes, and they peaked at 8:00 am, with the highest number of 74. There is a sharp drop between 8:00 am to 8:20 am and then a steady decline in the space of an hour. At 9:10 am the congestion disappears which corresponds to all the residents being evacuated to the shelter.

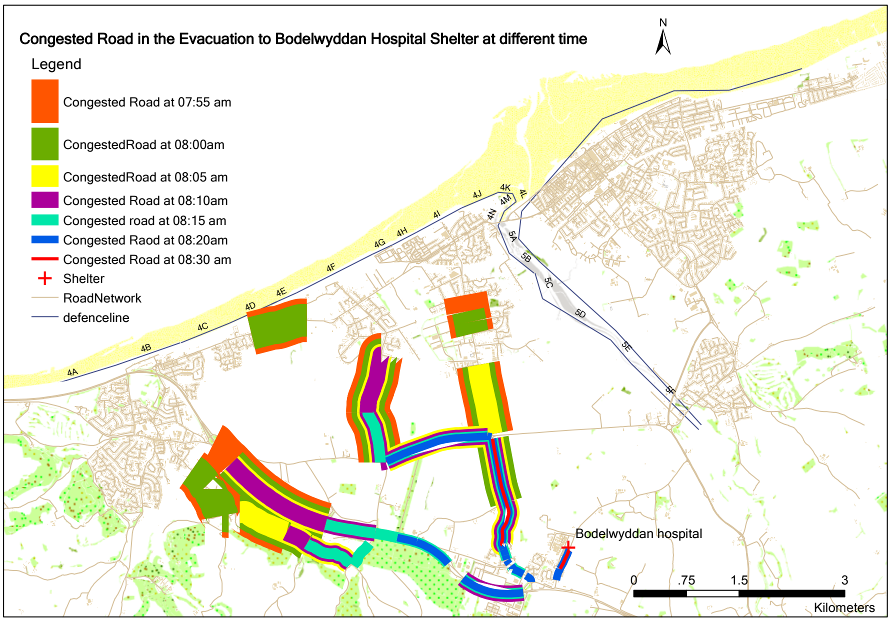


Figure 6-6 Temporal change of the road congestion in a flood evacuation to shelter 11 at Bodelwyddan Hospital

Figure 6-6 shows the spatial change of the congested roads during the evacuation. The map shows that congested locations shift towards the shelter over the model simulation timeline. First, from 7:50 am to 8:05 am the congested roads are in a residential area, then from 8:15 am they are at a main road such as the A55 and A547. Though St. Asaph Avenue and Gors Road are minor roads, they become the main corridor from the flooded area to the shelter; therefore, these two roads are also among the high frequently congested roads. Finally, after 8:30 am, the minor roads near shelter 11 at Bodelwyddan Hospital are congested.

The simulation model's ability to detect the road congestion during the flood evacuation provides a method to compare different traffic control plans for the evacuation. For example, in the Towyn case study the model is used to select a suitable shelter location.

Assuming a flood event of breaching flood defence F when the water level is 7.0, residents needs to be evacuated to a shelter. Which of the 12 potential shelters (as shown in Table 5-4) is the best for traffic control? The model simulated the mass evacuation to these 12 different shelters. The traffic congestion of the evacuations to the different shelters is shown in Figure 6-7.

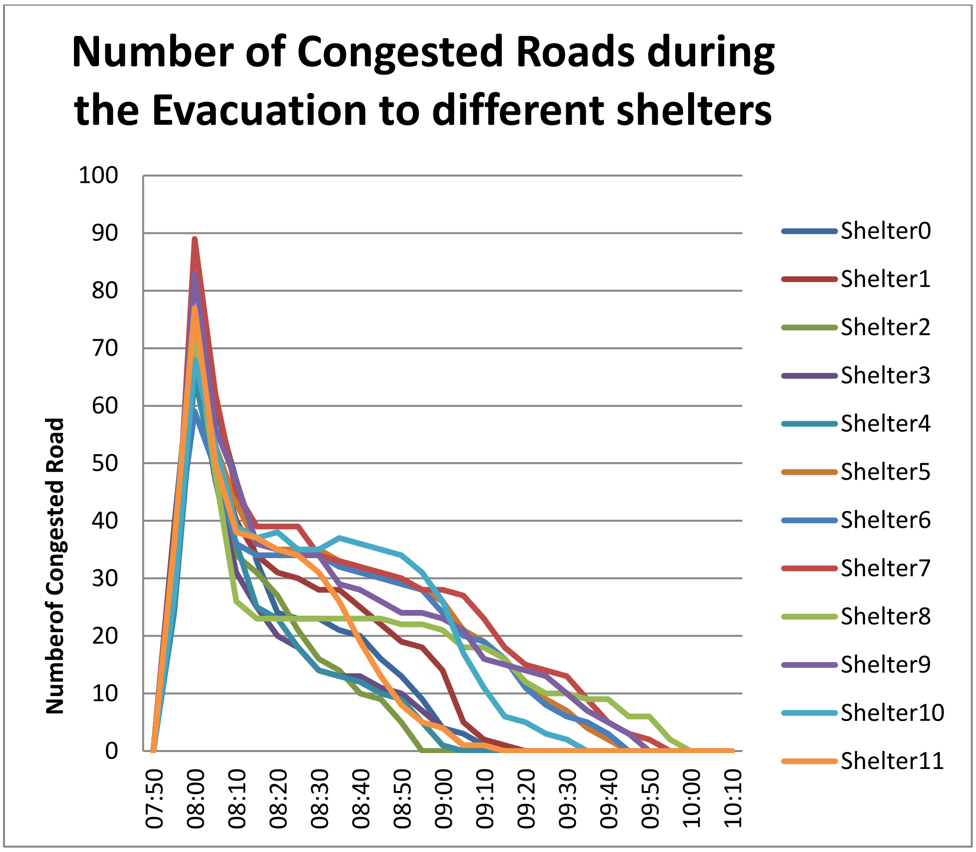


Figure 6-7 Number of congested roads through time, when evacuating to different shelters

For all shelters, given the evacuation command at the same time, they all peak in the first 30 minutes. The peak appears at 8:00 am, however, the peak number of congestions vary from 68 to 89. For some shelters such as shelter 8, the congestion numbers decreased quickly in only 20 minutes, but for some shelters such as shelter 7, the congested number decreased in 40 minutes. There is a significant difference in the time span of the congestions (from the start to all congestion disappearing). The shortest time span of congestions appears in the evacuation to shelter 2; the congestions disappear at 9:00 am, the longest congestion time span is from the evacuation to shelter 8, while the congestions disappear by 10:00 am.

Assuming that the optimization criterion is to minimize both the number of total congestions and the congestion time span, the traffic performances of 12 shelters are shown in Figure 6-8.

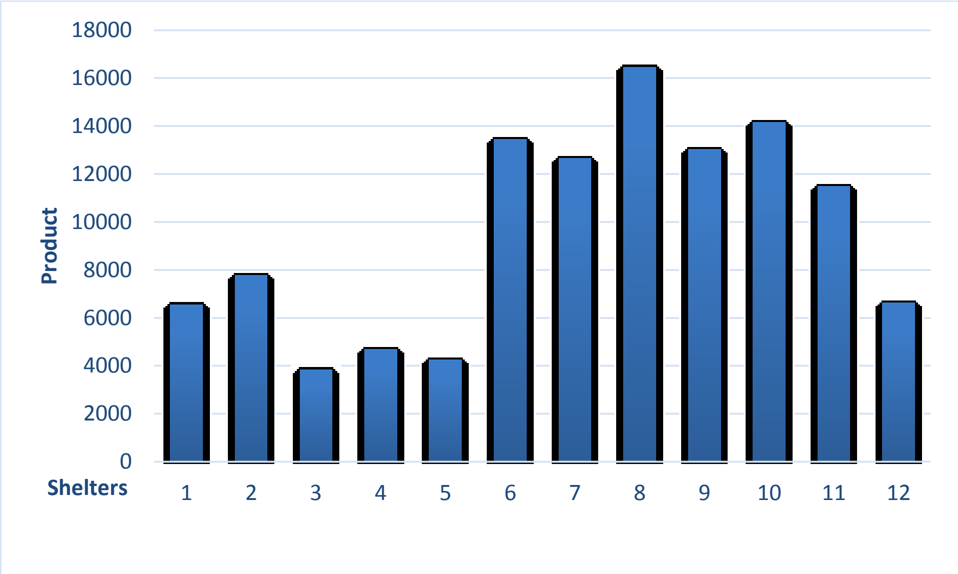


Figure 6-8 Traffic performance indices of the evacuations to each shelter location (The traffic performance index = number of congestions × the congestion time span. The lower the value of the index, the better traffic performance the evacuation has)**.**

Shelters 2, 3 and 4 have the lowest performance indices. Looking at the location of 2, 3 and 4, they are all at the centre of Towyn. However, if a nearby defence (e.g. defence F) is breached then these shelters could be inundated within 2 hours because they are not the ideal shelter locations. Comparatively, shelter 0 and shelter 11 have the second lowest performance indices and are out of the floodplain; therefore, shelters 0 and 11 would seem to be better shelters for a breach of defence F. From the simulation, it is also very clear that the selection of shelter location depends on the flood defence breach locations, as the choice of shelter location varies when the flood defence breach location changes. The model can test different flood defence breach location scenarios and provide rational references for the shelter location identifications in the flood evacuation plan.

6.3 Sensitivity analysis based on the flood warning scenario simulation

Setting up the flood warning scenario simulation does the following:

- Measures the impact of non-structural measures of flood warning to flood risk.
- Analyses how human factors affect the effectiveness of a flood warning.
- Weight the human factors' contribution to flood risks together with physical and structural factors.

The statistical software Minitab is used to operate a hypothesis test on the non-structural measure impact and multi-factorial analysis on the human factors. The statistical software Simlab (Saltelli *et al.*, 2004) is used to perform the GSA.

6.3.1 Influence of non-structural measures

A comparison of the simulation result of flood risks under the baseline scenario and the flood warning scenario with non-structure measures is executed. Breach F with a 7-metre water level is taken as the flood background. In the warning scenario, the warning proportion is set to 50%, the warning lead time is set to 0.5 hour, and the evacuation proportion is set as 90%. The flood risks are measured by *DangerCount* (civilians exposed to the dangerous flood condition) as well as *DangerCarCount* (vehicles exposed to the dangerous flood condition).

A two-sample T-test module in Minitab is used to check whether there is a significant (or only random) difference in the mean of *DangerCount* and *DangerCarCount*. The statistic parameter P-value shows the difference in the mean is significant if the P-value is less than 0.05. In order to perform this test, both samples must be normally distributed.

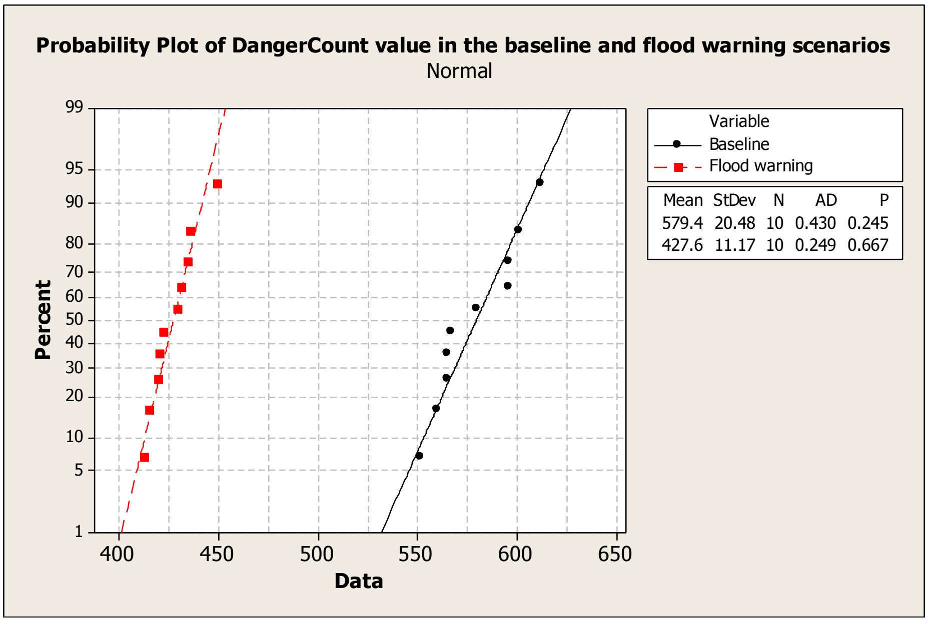


Figure 6-9 Probability plot of *DangerCount* in the baseline and the flood warning scenarios

The probability plot is used to assess the non-normality of a set of data. In Figure 6-9, both samples provide a good fit to a straight line with P-values above 0.05. It can be concluded that both samples are sufficiently well approximated by a normal distribution to allow a two-sample T-test to be used. The two-sample T-test's outputs generated from the statistics software Minitab are as follows:

Two-sample T-test and CI: B_DangerCount, W_DangerCount

```
Two-sample T for B_DangerCount vs W_DangerCount

                N   Mean  StDev  SE Mean
B_DangerCount  10  579.4   20.5      6.5
W_DangerCount  10  427.6   11.2      3.5

Difference = mu (B_DangerCount) - mu (W_DangerCount)
Estimate for difference:  151.80
95% CI for difference:  (135.86, 167.74)
T-Test of difference = 0 (vs not =): T-Value = 20.58  P-Value = 0.000  DF = 13
```

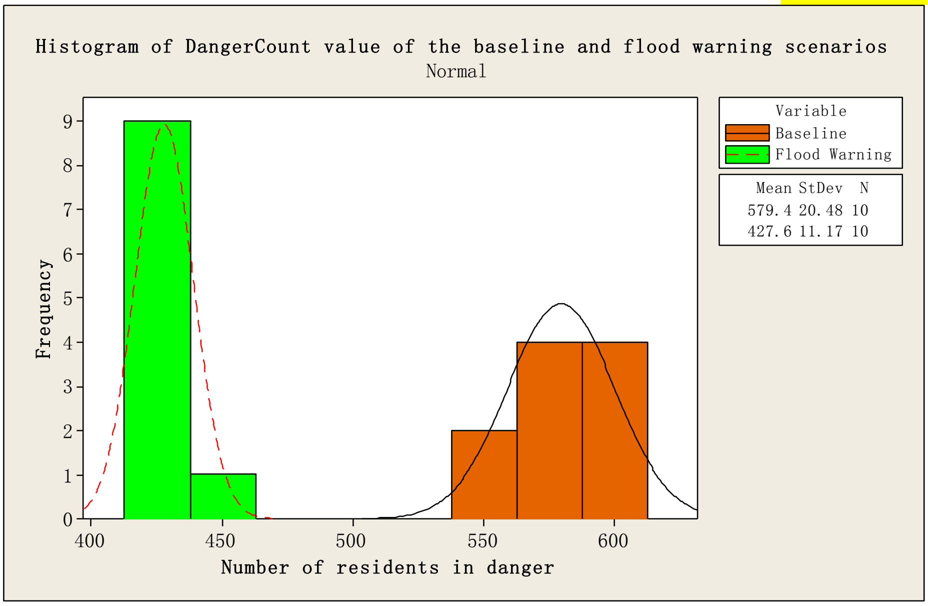


Figure 6-10 Histogram of DangerCount of the baseline and flood warning scenarios

Two-sample T-test and CI: B_DangerCarCount, W_DangerCarCount

```
Two-sample T for B_DangerCarCount vs W_DangerCarCount

                   N    Mean  StDev  SE Mean
B_DangerCarCount  10   191.2   14.7      4.7
W_DangerCarCount  10  131.70   6.18      2.0
Difference = mu (B_DangerCarCount) - mu (W_DangerCarCount)
Estimate for difference:  59.50
95% CI for difference:  (48.49, 70.51)
T-Test of difference = 0 (vs not =): T-Value = 11.77  P-Value = 0.000  DF = 12
```

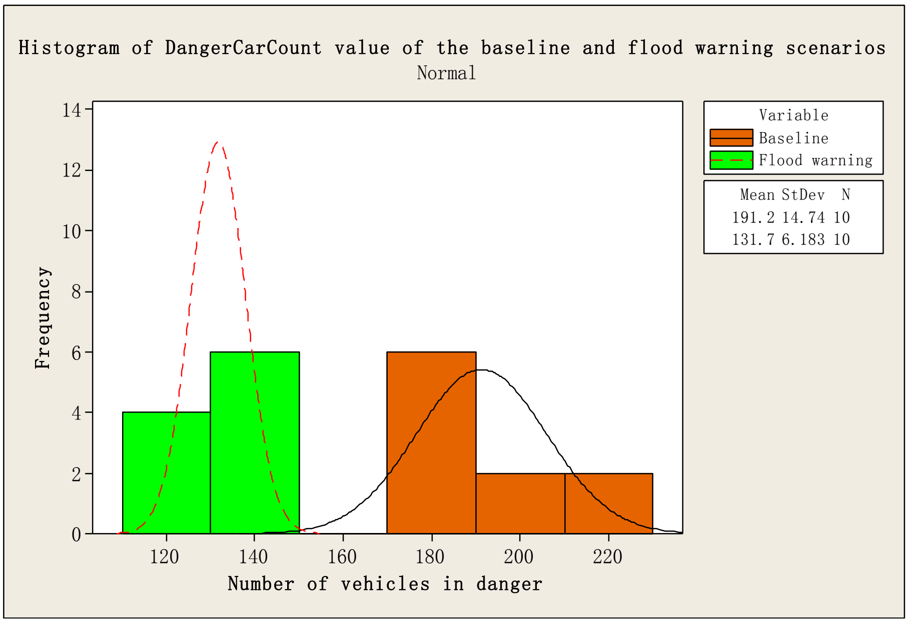


Figure 6-11 Histogram of DangerCarCount value of the baseline and flood warning scenarios

The Minitab two-sample T-test results show that the P-value of both *DangerCount* and *DangerCarCount* is 0.00. This indicates that there is a significant difference between the means of the baseline and flood warning scenarios. Figure 6-10 and Figure 6-11 show that the *DangerCount* difference is 152, and the *DangerCarCount* difference is 69. This indicates that a flood warning significantly reduces the flood risk to people and risk to vehicles, while the flood warning reduces one-third of the flood risks. This proves that the flood warning is an important non-structural measure. The result supports previous research on the benefits of flood warnings (Parker *et al.*, 2007a; Parker *et al.*, 2007b). It is also noted that the variance of the simulation result is smaller in the flood warning scenario than the baseline, which shows that human behaviour under the guidance of a flood warning is more organized than residents' spontaneous flood reaction.

Another sharp contrast is the simulation result from the evacuation scenario and the flood warning scenario. In the flood evacuation scenario, no loss of life occurred. However, in the flood warning scenario, there were still a number of people who died. For these two scenarios, the flood condition, land use and building types are all the same; the only difference was the people's responses to the flood warning and the evacuation command.

6.3.2 Comparison of structural measures and non-structural measures

Though it shows that non-structural measures such as flood warning significantly reduce the flood risk, their benefits still need to be compared with structural measures on the same platform. This is one of the main objectives of this research. Global sensitivity analysis is applied for this purpose.

As introduced in Chapter 3, global sensitivity analysis can be used to analyse each input variable's contribution to the output variance of the model on a global scale, and therefore the importance of the variables can be compared. For global sensitivity analysis, the input variables and its distribution have to be identified.

The input of the model can be classified into three classes: natural disaster, structural and non-structural factors.

The variable that represents natural disaster factors is the water level that is called Surge (SG) in the model. According to practical records, the weight of flood water levels are as follows:

Table 6-2 Weight of flood water levels

Water level (m)	Return period (years)	Weight
4.0	<20	0.9512261
5.0	20-75	0.0355289
6.0	>75	0.0132451

The variable that represents structural variable is flood defences (DF), the fragility curve of flood defences near Towyn has been given as shown in Appendix IV. Let A_i be the flood defences, B the event of breach, C_j the level of water. Then from the table, $P(B, C_j|A_i)$ are given. Thus

$$P(B|A_i) = \sum_j P(B, C_j|A_i) \tag{6-2}$$

Therefore, from Bayes Lemma:

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{P(B)} = \frac{P(B|A_i)P(A)}{\sum_i P(B|A_i)P(A_i)} = \frac{P(A_i)\sum_j P(B, C_j|A_i)}{\sum_i [\sum_j P(B, C_j|A_i)]P(A_i)} \tag{6-3}$$

Assuming $P(A_1) = P(A_2) = \cdots$ then

$$P(A_i|B) = \frac{\sum_j P(B, C_j|A_i)}{\sum_i \sum_j P(B, C_j|A_i)} \tag{6-4}$$

So the probability weight of food defence from D to I can be calculated as:

Table 6-3 Weight of different flood defences

Defences	Weight
D	0.00206
E	0.370879
F	0.027855
G	0.019714
H	0.333368
I	0.246095

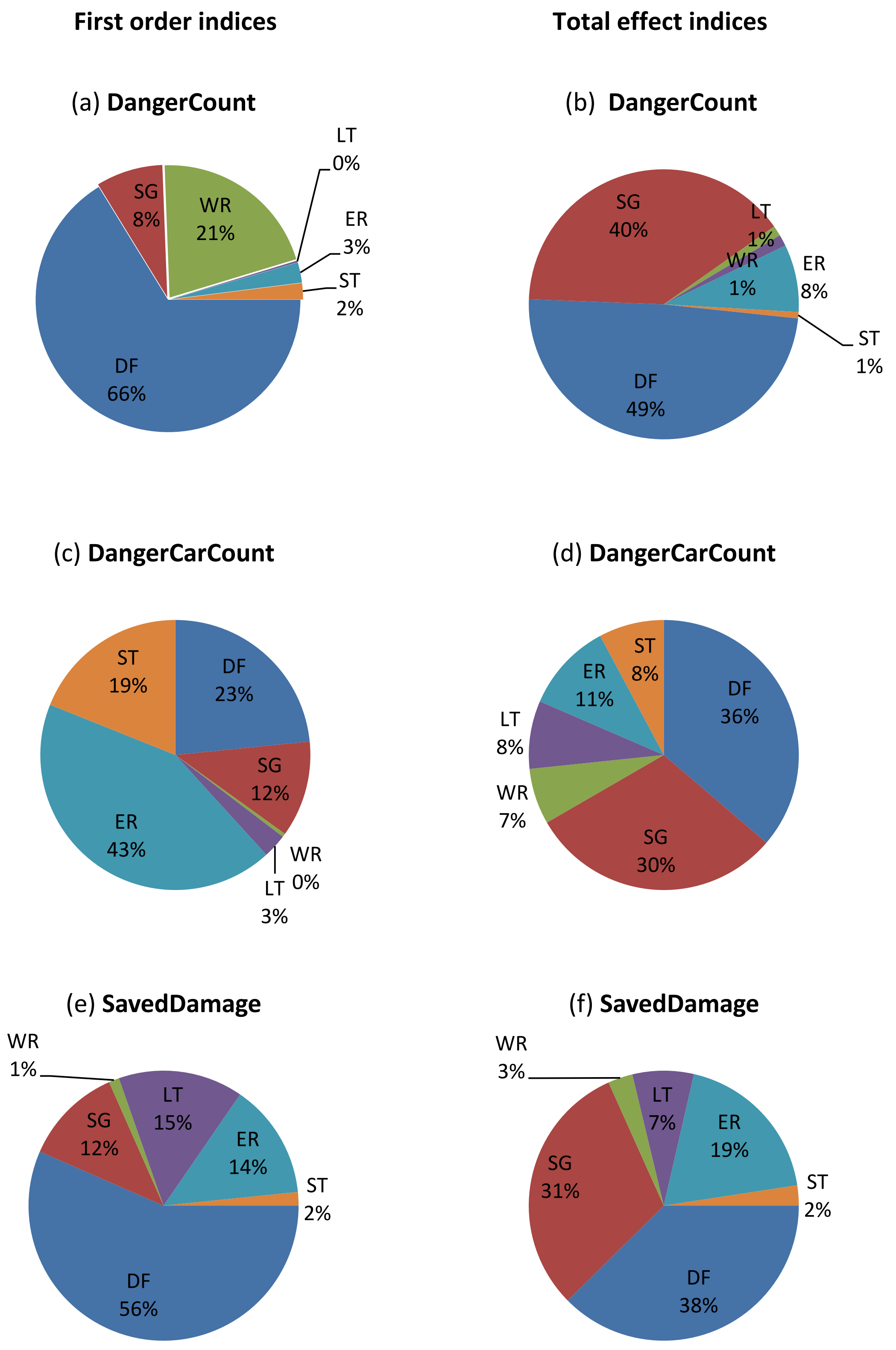
Flood warning is a non-structural measure, but several human factors directly affect the effectiveness of flood warning. As particular interest here is how the human factors relating to flood warning impact upon flood risk. In the model it is related to 4 variables are extracted to represent non-structural measures, which are warning lead time (LT), shelters (ST), warning proportion (WR) and evacuation proportion (ER). The warning lead time is tested in the range of 0.5 hour – 4 hours and the 11 shelters mentioned in Chapter 5 were tested. The warning proportions and evacuation proportions are tested in the range of 10%-90%.

Below is a list of the input and output factors of the model:

Table 6-4 Input factors and output variables in the global sensitivity analysis

	Notation	Range	Units	Level
Input	Breach (DF)	D - I	unit	6
	Water Level (SG)	4.0-6.0	m	3
	Shelter (ST)	0-11	unit	3
	Warning-lead Time (LT)	0.5-3	hour	3
	Warning proportion (WR)	0-100	%	3
	Evacuate Proportion (ER)	0-100	%	3
Output	DangerCount		Person	
	DangerCarCount		Vehicle	
	SavedDamage		Pound	

Based on the sampling result, the first-order indices and total effect indices of each factor for flood risk to people (*DangerCount*), to vehicles (*DangerCarCount*) and to flood damages (*SavedDamage*, *PropertyDamage*, *TotalFlood Damage*) are calculated, as shown in Figure 6-12 in order to analyse how the variations of these factors impact on the sensitivity of the flood risk.


First order indices
Total effect indices
(a) DangerCount
LT 0%
SG 8%
WR 21%
ER 3%
ST 2%
DF 66%
(b) DangerCount
SG 40%
LT 1%
WR 1%
ER 8%
ST 1%
DF 49%
(c) DangerCarCount
ST 19%
DF 23%
SG 12%
ER 43%
WR 0%
LT 3%
(d) DangerCarCount
ST 8%
ER 11%
DF 36%
LT 8%
WR 7%
SG 30%
(e) SavedDamage
WR 1%
SG 12%
LT 15%
ER 14%
ST 2%
DF 56%
(f) SavedDamage
WR 3%
LT 7%
ER 19%
SG 31%
ST 2%
DF 38%

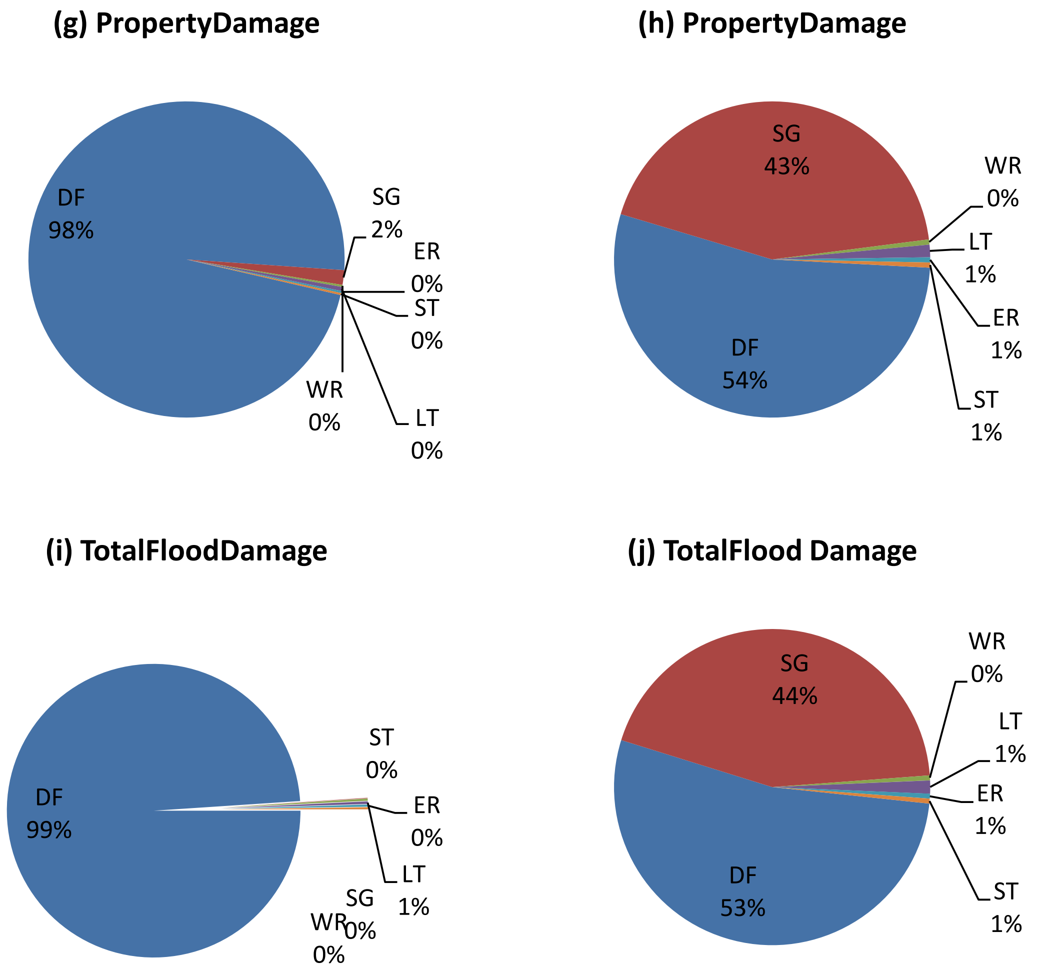


Figure 6-12 Sensitivity indices of the six factors

The first order index S_i is also called the main effect index. It is a measure of the sensitivity of flood risk (output variable) to each individual input factor, taking it independently. The result in Figure 6-12 shows that for flood damages the first order indices of the factor DF are very high, for property damage it is 98% and for total flood damage it is 99%. That means flood defences are the dominant variable that drives the variance of flood damage. The first order indices of human factors WR, LT, ER and ST for risk to people (DangerCount), vehicles (DangerCarCount) and saved content damages (SavedDamage) are 25%, 66% and 32% respectively. They are far greater than the first order indices of human factors for property damages (2%) and total flood damages (1%). This implies that the human factors mainly influence flood risk to people and vehicles. In terms of flood damage, human factors only affect the content damage that can be saved.

For DangerCount the variable in the model representing the flood risk to people, the first-order indices of flood defence DF (66%) makes up the largest contribution to the flood risk variance, and the second largest contribution is from flood warning WR, which accounts for 21% of the flood risk variance. Storm surge accounts for 8%, making it the third important factor for flood risk to people. The combined contribution of other factors is less than 5%.

For DangerCarCount the variables in the model representing the flood risk to vehicles, the evacuation proportion ER has the largest first-order indices (43%), while the second largest is flood defences DF, which makes up 23%. Shelter ST also accounts for 19% of the output variance. Warning proportion and lead time do not contribute that much to DangerCarCount's variance.

For SavedDamage, the variable in the model representing the content damage saved by the residents during the flood event, the first order index of the flood defences DF is the largest, making up 56%. The second important factor is the lead time (LT), which provides 15% of the contribution to the output variance. ER and SG also constitute 14% and 12% respectively. WR and ST are the least important factors for the sensitivity of SavedDamage.

Total effect index S_{Ti} is the measure of sensitivity of the output flood risks to the overall impact of an input factor including its interrelationships with other factors, for example the WR itself has the least impact on the flood risk, however, WR together with LT, have a significant impact on the flood risk. So WR's total effect index is higher than its first order effect index. The total effect index of a factor is not less than the first order effect. The difference between the total effect index and the first order index indicates the contributions the factor's interactions with other factors to the variance of the flood risks.

Table 6-5 Comparison of the value of total effect indices and first-order indices, S_i is the first order index, S_{Ti} is the total effect index

	DangerCount		DangerCarcount		SavedDamage		PropertyDamage		TotalFloodDamage	
	S_i	S_Ti	S_i	S_Ti	S_i	S_Ti	S_i	S_Ti	S_i	S_Ti
DF	0.1581	1.024	0.0382	0.8876	0.1678	0.9068	0.1883	1.0187	0.1697	1.007
SG	0.0195	0.8291	0.0188	0.7442	0.0351	0.7404	0.0029	0.8205	0.0001	0.834
WR	0.0499	0.0261	0.0007	0.1639	0.0037	0.0716	0.0004	0.01	0.0004	0.0095
LT	0.0005	0.0287	0.0047	0.1995	0.0444	0.177	0.0008	0.0242	0.0005	0.0255
ER	0.0059	0.1692	0.0699	0.2618	0.0409	0.458	0.0004	0.01	0.0004	0.0095
ST	0.0048	0.0158	0.0309	0.1911	0.0048	0.0584	0.0004	0.01	0.0004	0.0095
Tol	0.2387	2.0929	0.1632	2.4481	0.2967	2.4122	0.1932	1.8934	0.1715	1.895

Table 6-5 and Figure 6-13 show that the difference between the total S_i and the total S_{Ti} is extremely high for all the flood risk measures. This implies that the function of the flood risk is non-linear, and the interactions between factors significantly impact on the flood risk.

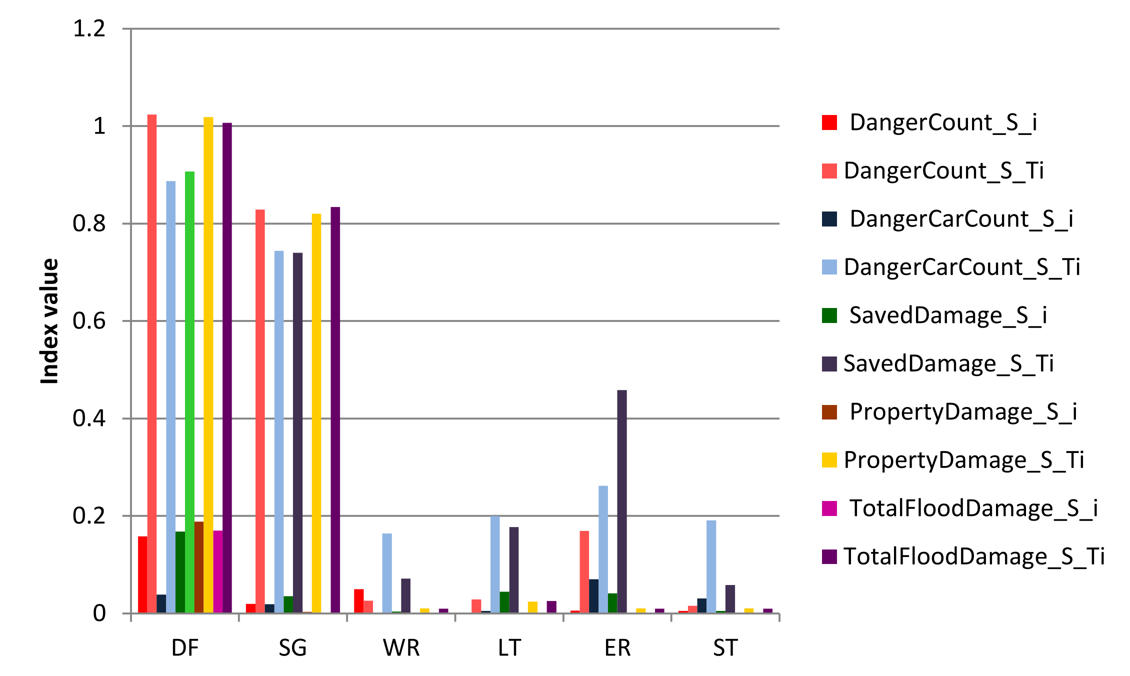


Figure 6-13 Comparisons of total effect indices S_{Ti} with first order indices S_i of the six factors for DangerCount, DangerCarCount, SavedDamage, PropertyDamage and total flood damage.

Interestingly, the importance sequence of the six factors' first order index is different for different flood risk measures. The total effect index importance sequence is the same for DangerCount, DangerCarCount and SavedDamage, which are the three flood risk measures that are closely related to human factors. The sensitivity factor importance sequences are 1) DF, 2) SG, 3) ER, 4) LT, 5) ST and WR. Also, the proportions are very similar, for example, DF ranges from 49% to 36% while SG ranges from 30-31%. This suggests that in a flood event the physical and structural factors of the location of the breaches and surge are the most sensitive factor for reducing the flood risks. However, human factors also significantly affect the flood risks to people, vehicles as well as saved damages. Human factors provide over a 30% contribution to the sensitivity of flood risk to vehicles and saved content damages. Evacuation proportion was the most important human factor that affects the flood risks, especially the risk to vehicles and saved content damage. Flood warning lead time is the second most important human factor.

The result of the GSA is quite helpful for the FEM because it first prioritised the importance of the physical, structural and non-structural measures. For flood risk management, preventing the flood hazard is still the most important issue. However, from the results, human factors contribute over 30% to the sensitivity of flood risks to people. Hence, human factors need to be highly regarded. For flood event managers, it has to be emphasised that residents' effective action to the warning is more important than just sending out the message to the residents. Better flood warning message quality and longer warning lead time are beneficial to the flood warning effectiveness. From the global sensitivity analysis, the effect of non-structural measures can be appraised with structural measures on the same quantitative evaluation platform. Meanwhile, residents' action to the flood can be guided and adjusted, more detailed guidance about the residents' behaviour in a flood event such as how to prepare a family flood plan, how to use the temporary flood defence facilities, and how to find a shelter, etc. should be provided.

6.4 Further discussion

As reviewed in Chapters 2 and 3, it has been noted that non-structural measures play an important role in flood event management. However, due to its close relationships with human factors, the method of assessing non-structural measures in a flood event needs to be explored. In this research, by integrating the hydrodynamic model with human behaviour on an ABM platform, a framework to quantify the impact of non-structural measures of flood risk during a flood event has been developed. The purpose is to measure quantitatively whether the non-structural measures significantly reduce the flood risks and how human factors influence the flood risks in the flood event. Therefore, based on the results obtained, some objective questions as well as the approach and the performance of the simulation model will be discussed.

6.4.1 Concept of flood risk in flood event management

As reviewed in Chapter 2, the flood risk is expressed as a combination of the probability of flood occurrence with its possible consequences. For a long-term strategic and holistic flood risk analysis, the flood risk is expressed as the annual flood damage and loss of life (Messner *et al.*, 2007) based on a damage-probability curve that combines the probability of all different types of flood events.

However, the concept of flood risk needs to change to reflect the timeframe of a flood event in the FEM. For the FEM, the probability of the event is no longer important because the event is occurring. During the event, the management task focuses on the particular flood event and how to deal with it. Therefore, the flood risk concept here is the flood damage and loss of life caused by that particular flood event.

Furthermore, risk management during the flood event is about deciding what to do within the time available. The evolution of the flood hazard characteristics is quite important in identifying the temporal change of the flood risk during the flood event. For example, decision-makers are interested in questions such as 'when and where is the flood water expected to be the highest' and 'where are the vulnerable people staying?' Therefore, just assessing flood risks according to the final flood water extent is not enough. Flood risk needs to be evaluated over a wide range of possible conditions and timeframes. Flood evacuation plans can be improved by taking into account the resultant different consequences due to the variation of storm surge and defence failures or the different structural or non-structural measures applied.

The flood risk definition in the FEM, which is based on a single flood event instead of an annual estimation of flood risk, does not contradict the general flood risk theory. On the contrary, as it can give a better description of the flood risk in a one-off flood event, it can be properly included in the standard risk-based flood management process. Meanwhile, it can be used to prioritise investment or actions during the event itself.

6.4.2 Hydraulic model and human behaviour model integration

Ideally, the hydraulic model and the human behaviour model should be integrated and synchronized on an ABM platform. However, there is a huge difference between the two models' time scales. For the hydraulic model, in order to simulate the flood water dynamic accurately, it is suggested that each time step should be less than 0.1 second. However, for the human behaviour model, one minute for each time step is precise enough. If 0.1 second was taken as one-time step, the simulation would be much more time-consuming. Because there is no human behaviour that will modify flood hydraulics in the model, it was decided that as a compromise, the hydraulic model run previously and the simulation results saved in a folder. When the human behaviour model simulates the human response, the flood data is read from the folder as part of the environmental background.

6.4.3 Managing uncertainties in the ABM

The risk-based human response simulation model is an agent-based model. As reviewed in section 3.6, the uncertainty of the ABM has been highlighted. Therefore, the uncertainty of this model is discussed here.

As demonstrated in Chapter 4， the simulation model has three modules: the hydrodynamic module, the human behaviour module and the flood risk analysis module. Different validation and verification methods were used for the three modules.

The hydrodynamic module simulates the flood water evolution. The model is sturdily based on the theory of fluid dynamics and the mature finite volume fluid dynamic simulation technique. The model has been successfully validated using the observation data of flood extents during a 1990 event to over 80% accuracy.

The flood risk analysis module is more complicated than the hydrodynamic module because more social, economic and demographic variables are involved. Although the FHRC flood damage method used for setting up the module is based on the study of England flood damage, the practical data for the model validation is rare. As with the flood extent, the total flood damage associated with the baseline flood scenario also compares with the recorded Towyn 1990 flood damage, and the calculation is about 95.6% accurate.

However, it is impossible to validate the whole flood risk analysis module due to insufficient data in relation to the survey of human behaviour during a flood event.

Though a simple human behaviour model is set up to verify human behaviour, traditional approaches to model validation that involves validating the model with practical data are still ill-suited to human activity modelling. There are many variables that are related to humans' judgements or decisions. Although statistics from Census data and the National Travel Survey provide some evidence of key activities and behaviour, lots of influencing variables and factors of individual's action selection in the flood event still intrinsically make the uncertainty of the model if all the variables are fix. Therefore, it can be seen that it is not because of the structure of ABM but rather the complexity of the system ABM simulated that makes the model uncertain.

Then the following question is how the uncertainty of a complex system simulation model can be understood. As reviewed in section 3.6, global sensitivity analysis is one of the effective methods that can help. In this research, variance-based sensitivity analysis is used to explore the uncertainty of the model. First of all, the study is not based on one simulation but rather Monte Carlo simulations. Secondly, the variable values are set according to the reasonable sampling procedure. The advantage of the global sensitivity analysis is that it gives an overview of the importance of all the factors in the system. Take Towyn flood risk system in the flood event as an example, global sensitivity analysis provides a platform to compare the impact of human factors with physical and structural factors. It proves that physical factors such as surge and structural measures such as flood defences are the two factors that decide flood risk sensitivity. However, human factors also account for at least one-third of the contribution to the variance of flood risk to people, vehicle and saved content damage. Therefore, this makes it possible to evaluate quantitatively the benefit of non-structural measures such as flood warning. The input factor sequencing will help with screening and filtering the important factors, and then a study of those factors should be conducted in future studies. In this study, the result shows that human factors evacuation proportion (ER) instead of flood warning proportion (WR) should be investigated for better flood warning effect.

Chapter 7. Conclusion

7.1 Introduction

The main aim of this research has been to develop an approach for appraising the benefits of flood event management that is compatible with existing risk-based approaches to evaluate structural flood defences. This concluding chapter summarises the main findings in the thesis and reflects on the original aim, objectives and research questions that were set out in Chapter 1. Key findings and methodological innovations from this work are summarised before implications and recommendations for policy, practice and future research are made.

7.2 Review of research

The research undertook in this thesis involved:

- A review of current flood risk management research and practice, which highlighted the importance of flood event management (research objective 1, reported in Chapter 2).
- A review of technical approaches to flood simulation, human behaviour modelling and flood risk assessment and uncertainty analysis methods (research objective 2, reported in Chapter 3).
- The development of a new short-term flood risk analysis package for flood event management which integrates the flood and human response simulation models (research objectives 3-5, reported in Chapter 4).
- Implementation of this new method in the case study area of Towyn, North Wales (research objective 6, reported in Chapters 5 and 6).
- Global sensitivity analysis on the human factors, physical and structural factors for weighting their importance to the sensitivity of flood risks (research objective 7, reported in Chapter 6).

Flood risk management is a holistic, risk-based approach of flood management based on flood risk analysis. The study described here has, for the first time, applied this risk-based approach to flood event management by integrating the hydraulic and human behaviour simulation models. A new methodology has been applied in a case study, which demonstrates how this approach can support flood event managers to prepare flood plans and to make decisions in an emergency situation. This study has shown that a short-term flood risk analysis tool is effective in flood event management due to the following advantages:

- It can map out the evolution of the flood hazard and report the real-time flood hazard rating.
- It supports multiple objectives by calculating real-time flood risks during the flood event in terms of loss of lives, the risk to vehicles, flood damage and congestion during the flood event.
- It shows the flood risks spatially so that the flood risk information can be interpreted in the interests of the multi-agency organizations involved in the flood event management.
- It quantitatively specifies the benefit of non-structural measures in the flood event such as flood warning and flood evacuation.
- It recognizes the impact of human factors on the flood risks in the flood event.
- It can analyse the importance of human factors, physical and structural factors to the sensitivity of flood risks on the same risk assessment platform.

With the increase in extreme flood events in the UK and worldwide, the importance of flood event management has been regarded as one of the most important components of flood risk management. However, the risk-based approach to flood management, which has long been used for long-term strategic flood management, has never been used for flood event management. A literature review of flood risk management and flood event management detected key research challenges. Key points from the literature review were:

- The concept of integrated flood risk management has a significant impact on the flood risk research. It not only emphasises the probability of flood hazards but also the social and economic consequences of it. Receptors are not only the victims; they can also reduce the flood risk through their flood responses.
- In light of the holistic flood risk framework, non-structural measures are very important for reducing flood risks. However, the benefit of non-structural measures is difficult to evaluate quantitatively due to their close relationship with human responses and behaviour.
- As a dynamic and continuous system, there is a need to integrate the FEM into the flood risk management framework. However, existing flood risk

analysis methods are mainly for long-term strategic management. A short-term risk analysis tool for the FEM, therefore, needs to be explored.

- In flood event management, flood reduction measures are mainly non-structural measures. So the development of a short-term risk analysis tool for FEM hinges on the function of evaluating non-structural measures based on the simulation of human response to the flood event.

A more systematic approach to analysing flood event management has therefore been proposed. This approach comprises several elements that individually provide notable advances in the methods currently in practice, but it is integrated into a computer simulation tool to provide a novel approach to testing FEM strategies and provides policy relevant results for flood risk managers. Sections 7.2.1–7.2.5 consider how the research contributes to the different aspects of the current FRM research studies and FEM practice.

7.2.1 The environment simulation

For setting up the transport system used by the human agents, the road network system and attributes such as its position and the directionality and topology of roads is established within the ABM platform. This is an innovative attempt in the ABM simulation field. The road network system implementation limits human agents to walk or drive only on the network instead of walking or driving on grid cells. It is more practical and reduces the computational cost.

A full shallow 2D hydraulic model has been creatively adapted into the ABM platform to simulate the flood dynamics. Approaches to lower computational costs could be used, but the advantage of this approach is that:

- It can simulate the flood depth as well as flood velocity accurately.
- It simulates all the scenarios under the different water level and defence breach conditions.
- It simulates the evolutions of the flood dynamics because the timeline of the flood is important to the human responses in the flood event.

The flood depth and the velocity data produced can be used to produce a flood hazard rating map.

7.2.2 Human behaviour simulation

The study tentatively applied the human factor and resilience engineering theory and methods as guidance for analysing the human behaviour in the flood event and integrated them into the flood risk analysis approach.

A general prototype of human behaviour in the flood event is designed, in which the input-decision-action cycle and FIPA ACL communication message format are adopted. This general prototype of human behaviour provides an innovative way to simulate individual and organizational agents' interactions and communications.

To simulate the individual residents' normal travel behaviour, an activity-based travel behaviour model is created based on practical national and Wales travel survey data. The advantage of this model is that it provides spatial patterns and distributions of journeys, while maintaining consistency with observed absolute traffic volumes.

Based on the results from disaster sociology research and post-flood survey data, conceptual models for both individual and organizational responses to the flood event have been developed. Key features of the model are that:

- It simulates the interactions between the individuals and the organizations such as receiving the flood warning messages from the EA.
- It can simulate the cooperation of the multi-agency organizations involved in the FEM.
- It simulates the interactions between the individuals and the flooded environment such as the buildings, roads and floods. For example, when the flood is coming, or the road is flooded, the residents might move upstairs or try to change their route to avoid the flooded road.
- It simulates the different decision-making behaviour under different non-structural measures; for example, flood evacuation and flood warning are all taken into account.

7.2.3 Flood risk calculation

Loss of life, the risk to vehicles and flood damage are selected to be flood risk measures in the study, in addition to the road congestions, for the special purpose of flood evacuation planning. One of the unique features of the flood risk calculation is that it is a bottom-up calculation. The calculations are based on individual residents or land patches. Therefore, the original FHRC model for calculating social flood risks to people and flood damages needs to be discretized to the individual agent level, for example, the flood risk to individuals and flood damages to each land patch.

Another innovative new trial is the process of calculating flood risk to vehicles based on the formula for predicting the incipient velocity of flooded vehicles according to the mechanical condition of sliding equilibrium (Xia *et al.*, 2011). The model calculates the number of vehicles that are threatened by the flood water instead of just predicting how many roads are inundated by the flood water. For the demands of flood evacuation traffic control, congestions in the flood evacuation were also calculated according to Highway Capacity Manual (HCM, 2000) methods.

The advantages of the flood risk analysis module developed are:

- The module is multi-objective; it can calculate the risk to people, vehicles and economic flood damage at the same time.
- The module is based on the scenario obtained from the simulation integrating the hydrodynamic and human behaviour models. The influence of non-structural measures can be calculated because the model accounts for social vulnerabilities and human behaviour.

The model can calculate the evolution of flood risks throughout the flood event, which will help the flood emergency decision-making by providing spatial and temporal features the flood risks at a time point.

7.2.4 Integrated agent-based model

A unique feature of this research is that the hydrodynamic module, the human behaviour module and the flood risk analysis module are all integrated with the ABM platform of NetLogo for the first time. The integration of these models in ABM has brought about several advantages:

- The model can simulate the whole system. In the Towyn case, the whole SPRC flooding system, which includes the source, pathway and the receptors, were all simulated. In the ABM, the components of the flooding system are represented by different agents. The simulation model has implemented the residents' and all the organizational behaviour of every organization involved in the FEM in Towyn. This whole system simulation is very suitable for use in integrated flood risk management.
- The model can simulate the dynamics of the system and, therefore, capture the temporal change of the system. In the simulation, both the flood and the human travel behaviour are changing along with the times, and, as a result,

the real-time flood hazard map and the real-time traffic flow data can be obtained.

- The model can simulate the interactions between different agents. This is the key issue for studying non-structural measures. Because only when the human interactions with the flood and the organizations are modelled, can the triggers for their flood responses be simulated.

The ABM model is a bottom-up micro simulation model. Therefore, it can simulate the behaviour of a small unit of the system. However, the system feature in macro scale can be captured. For example, the economic flood damage calculation model calculated the 1990 Towyn flood total damage accurately. It is quite similar to the finite-volume method used in CFD, and although the fluid is discretised as finite volumes, the aim is to capture the movement of the fluid as a whole. ABM discretised the complex system into small agents, but we can observe the system as a whole.

7.2.5 Global sensitivity analysis on the Agent based model.

As described in Chapter 6, the global sensitivity analysis (GSA) on the ABM simulation model analyses the source of the model uncertainties. By comparing the uncertainties of the three main modules, it can be concluded that the complexity of the problem instead of the ABM model itself causes the uncertainty in the established model. The GSA has proved to be a practical way of understanding the influence of uncertainties in the agent-based model of a complex system.

By using GSA, the contributions of all the input factors, which include human factors, physical factors and structural factors, to the sensitivity of the flood risks, are sequenced. Additionally, it evaluates the contributions of the interactions between the input factors to flood risks. Thus, the input factors can be screened, which is useful for filtering the most important factors and takes a further step to explore the most important factors in the system.

7.3 Implications for flood risk analysis and flood event management

Some implications for the flood risk management and flood event management are concluded here based on the results obtained.

In view of the practical operation of flood risk management in Towyn, suggestions include:

- As a coastal town, a different location of flood defence breach produces a different flooding scenario. The main flood threats come from a breach of defences F, G and H. The maintenance of these flood defences should be highly regarded.
- Towyn is located at a lowland area and within a two-kilometre buffer area of the sea line. When a flood caused by the breach of F, G or H happens, the flood arrives at the high-density residential area within a very short period. Taking breach F as an example, in an extreme flood (water level > 6.5), the flood arrives at the town centre in 1.5 hours, and the main part of the town can be flooded in 5 hours. The time for emergency management is very limited.
- Towyn's building characteristics make it very vulnerable because many holiday parks with caravans and bungalows are located in high flood hazard rating areas. This might cause higher flood risk to people. There are opportunities for spatial planning to reduce flood risk.
- In the process of flood evacuation planning, traffic control should be considered when selecting evacuation shelters. According to this research, for a breach of defence F, shelters at Bodelwyddan Hospital or Abergele Church are the best options for flood evacuation. Besides, during the evacuation, the main roads that connect the town with another area such as A55, A547 or A548, Gors Road and St. Asaph Avenue are the most congested roads. It has been suggested that multi-shelter plans should be designed to reduce the load on these main roads. Evacuation route guidance provided to residents in which multiple shelter choices should be included is also suggested, in order to assign the traffic loads on several roads.

In the context of the practitioners of flood risk management, suggestions based on this research are:

- FEM is an important component of FRM, and it should be integrated into the FRM approach.
- In order to appraise the benefits of non-structural measures in the FEM, it is necessary to consider human behaviour in the flood event. This research provides a method to integrate the human responses into the flood risk assessment approach.

- For the risk analysis for the FEM, real-time flood risk analysis is a key issue. By integrating the hydrodynamic model and the human behaviour model, this model provides a way to analyse the flood risk evolution during a flood event.

In terms of FEM policy, suggestions from this research are:

- Flood plan should be based on potential flooding scenarios instead of the flood water level. Taking Towyn as an example, although the water level is the same, the flood scenarios are very different due to the different locations of the flood defence breaches. Therefore, a flood plan, at one flood warning level, and flood responses to different flooding scenarios should be drafted. This model can simulate scenarios of different water levels and breaches. It will help to reduce the uncertainties caused by the physical and structural factors by providing all possible flood event scenarios.
- The benefit of the non-structural measures to the economic flood damage reducing is limited. Long-term measures such as land use planning, building flood resilience engineering and insurance policy should be applied for to reduce flood damage.
- Flood defence breach occupies the 98% contribution to flood damage. Therefore, more efficient temporary structural measures such as temporary flood defences should be considered for reducing flood damage during a flood event.

7.4 Future challenges

7.4.1 Development of existing model

The risk-based human response simulation model can be improved in several ways.

In the flood simulation, the Manning coefficient is set to only one value. In fact, in the case study area, there are different forms of land use such as residential areas, farmland and industrious land. The model can be improved by setting different Manning coefficients for different land forms.

Due to the time limit and lack of practical data, organizational behaviour simulation is only implemented for a simple example. The model can be improved by adding organizational behaviour to the case study of Towyn, such as the behaviour of the local council, the police, flood wardens and the rescue teams, which will help to improve organizational cooperation in the flood event.

In the model, only single shelter locations were tested. For a better spatial analysis for the traffic control, combinations of the shelters deserve to be tested.

In the process of implementing the simulation model, a problem encountered is that the human response can be simulated, but their impact on the flood risk cannot be embodied in the flood risk calculation. For example, when a flood comes, well-prepared residents might switch off the utilities such as water and electricity. The action of switching off the utilities is easy to simulate, but it is difficult to calculate the economic value of this behaviour because there is no practical data that supports the calculation. Therefore, further investigations into the economic impact of the human behaviours need to be carried out.

7.4.2 Broader FEM research challenges

The first challenge is the data integration for the FEM risk analysis. The simulation model itself has the potential to be utilised for analysing flood risks to an urban area. Though the case study area is a small coastal town, the data used from different sources are already quite complex. In the study, for flood simulation, sea water level and tidal information, flood defence fragility data and DEM data need to be obtained. Land use data and road network data are required for setting up the building and transport system. For simulating individual behaviour, travel survey data, demographic data and sociology data are needed. To calculate flood risks, data on traffic flow and vehicle types, flood damage curves, loss of life and water depth function are all needed. If the model is used for an urban area, there must be a challenge of mass data storage and query for implementing the simulation. Therefore, there is a need to design a better data storage and query method than just using flat files. It is suggested that ABM should be integrated with database and data mining techniques for modelling a complex system. This is also a process of smart civil engineering because ABM is part of artificial intelligence (AI). ABM, together with database and data mining, should contribute to a sustainable urban development.

Secondly, the human behaviour in the FEM system should be surveyed holistically. In the research only 3 human factors relevant to the flood warning and the flood evacuation are considered, but actually there are many other human factors that influence the flood impact, for example, residents' social vulnerability. Human factors are pervasive in the whole system of FEM. Therefore, a database for recording how people responses to the flood and what people did do and how their actions' economic and social impact should be set up for supporting risk-based FEM decision makings.

7.4.3 Recommendations for policy and practice

FEM is a complex system that involves physical and social-economic aspects. Human factors play a very important role in the process. Decisions in the FEM are difficult due to the complexity of the system and an emergency situation. This process can be improved in several ways.

For better decision-making, the FEM should be considered as a holistic system. All the components of the system should be considered. A database for the FEM could be set up to integrate all the data from different sources such as flood hazard related data and economic damage calculation data. The SPRC model can be borrowed to depict the FEM system; flood risk analyses can be applied to screen the system and to prioritise flood risk reduction options.

As a very important component of the FEM, human behaviours during the flood event should be fully investigated, and an operation research study on the optimization of human response to the flood based on that is needed to reduce the flood risk. The system involves many organizations and their responses should also be fully investigated, and a mechanism for evaluating an organization’s performance during the flood should be set up.

7.5 Summary

As highlighted in section 7.2, the original research aim and objectives have been delivered. Similarly, the cross-cutting questions posed in section 1.2 have been explored and highlight that:

- The effects of non-structural flood event management measures need to be quantitatively analysed.
- Individual human actions during a flood event have limited economic benefits because much of the damage is locked into immoveable items and assets – however, human actions can have enormous benefits on saving lives.
- By integrating over a range of flood events, the benefits of flood event management measures, expressed in terms of a reduction in expected loss of life (or other damages) enable the benefits from structural and non-structural measures to be compared within the same framework.

Furthermore, the sensitivity of flood risk to a range of flood event management issues, including physical flooding processes and the engineering reliability of defences and human behaviour, can be diagnosed using global sensitivity analysis. This enables policy makers to identify and prioritise the most significant contributors to risk while to account for model uncertainties – and hence provides a basis for prioritising investment decisions.

Although a number of challenges remain, the results presented in this thesis have made a valid contribution to improve flood event management.

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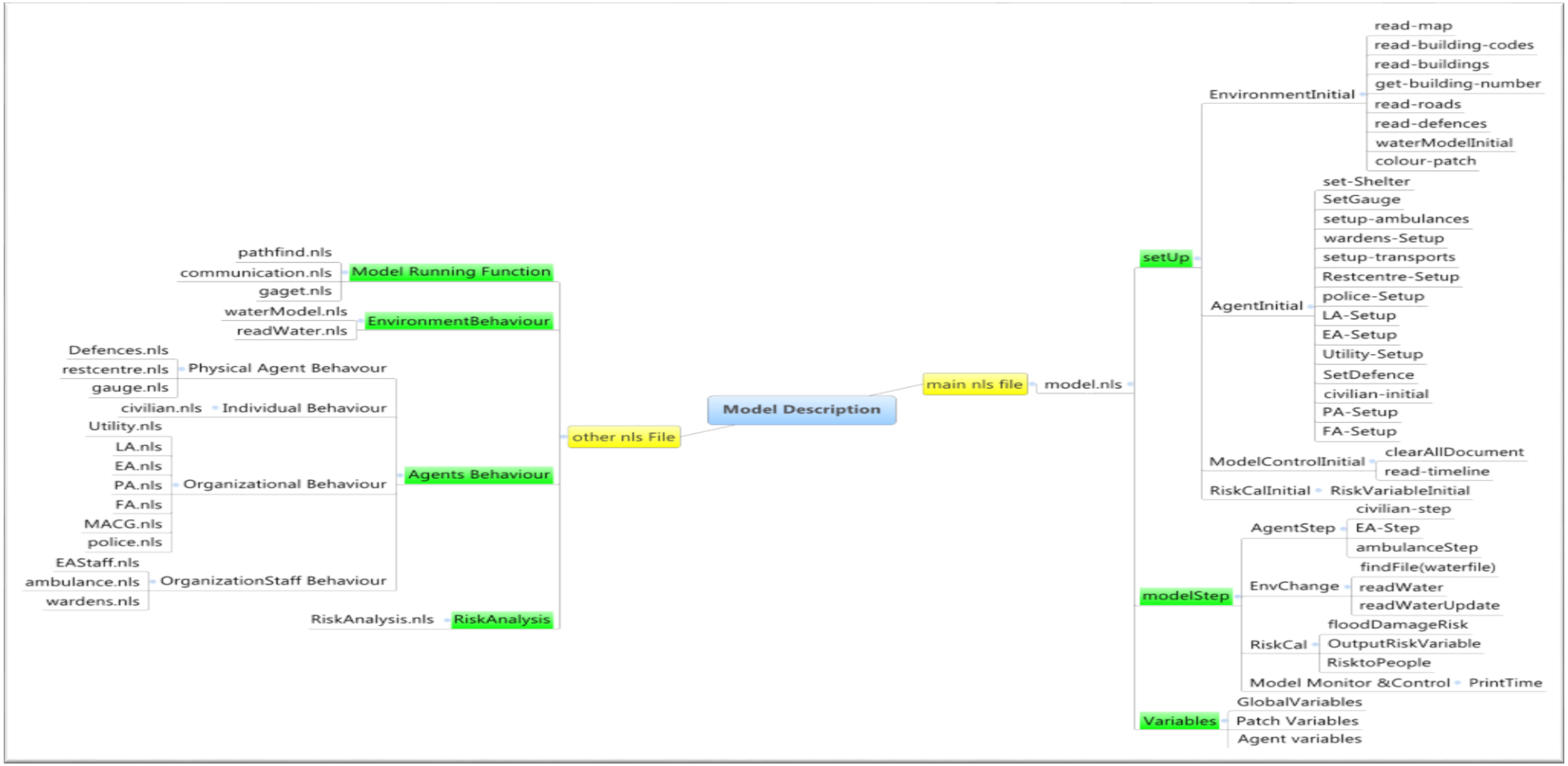
Appendix I Simulation software introduction

This Appendix is a help document to understand the software used for the simulation. The author developed this software on the ABM platform Netlogo. In Netlogo, the source codes are saved as nls files with extension names of *.nls*. As shown in Figure I-1, the main programme is in *model.nls* file. Other sub-routines are saved in other nls files. This document introduces main functions in *model.nls* file before introducing functions in other sub-routine nls files. Organizational behaviour model are describe in detail in the document.

Figure I-1 Overview of the code organization structure



Main programme

Code in *model.nls* file is the main programme of the simulation model. In the main programme, all variables in the model are claimed. It initializes the whole system with the function *Setup*. *ModelStep* function is responsible for scheduling all the agents behaviour actions.

1) Variables

Global variables

Global variable is the one value variable , and every agent can access it. The global variables that related with civilians behaviour can be catergorized into 4 groups:

1) Global variables related initializing civilians: the variables are used when initializing the civilians. For example, population is usesed to identifiy how many civilian agents produced every houre, *ReadHour* names the which houre is the start hour to read from data file to get the *Numberlist,* then the number of commute travellers , buisiness travellers , education travellers which are represented by *commuNum*, *busiNum*, *eduNum* are read from *Numberlist*.

2) Global variables related with civilians travel behaviour: the variables are used when simulating civilians travel behaviour. Some variables are the probabilities of making an action choice , For example for a commute agent, they have probabilities of travelling from home to work or travelling from work to home identified by the variable *ComuteProb*, or the probabilities of choosing a car , which is represented by *ComutModeProb*. The value of these variables are mainly from Census data and national travel survey data. There are also some veraibles that identify general feature of civilians such as travel speed which is represented by *civNormalSpeed* or *freeCarSpeed*.

3) Global variable related with civilians flood response: the variables are used to simulate civilians response to the flood, flood warning and flood evacuation. The variables are the probabilities that civilians react to a emergency situation such as receiving a message, confirm a message, aware of the danger of flood, prepare for the danger and doing the right action to reduce flood damage.

4) Global variables related with statistics summary: the variables are for summarizing the statistics. For example *DangerCount* represent the number of people who are in danger situation. *DangerCarCount* represents the number of vehicles that are in danger situation; *SavedDamage* represent the potential flood damages saved by peoples flood reduction actions; *TotalFloodDamage* represents the total flood damage caused by the flood and *floodedArea* represents the area flooded.

Agent variables

Agent variables refers to the variables only used by one type of agents. For example, patch owned variables can only be used by land patch. Civilian owned variables are specially for the civilian agent. Each type of agent has its specially defined agent variables. Here only lists some important agent variables.

1. Patch owned variables

Important patch owned variables includes:

Tabel I-1 Main patch owned variables

VARIABLE NAME	MEANING
CX	x coordination of a patch
CY	y coordination of a patch
height	Height of ground (metres above mean sea level).
kind	Land type, (undefined, Sea, Land)
residential/ nonresidential	Number of residential /non-residential properties in the patch
crossing	rlinks crossing this patch (agent set).
vehicle-count	Number of vehicles on this patch
h	Water level (metres above mean sea level)
v	Water velocity
civi-resi-count	Numbers of residents who stay at the patch
buildingType	Property building types which are classified as nine class.
NRP_21 ,NP_22, NRP_23, NRP_3, NRP_4, NRP_51, NRP_52, NRP_6, NRP_8, NRP_9	Number of property numbers of different non-residential property types.

2. Road ,rlink, node variables

Road, rlink and node are three agents that represent the road system in the model. Some important variables of them include:

Table I -2 Main road, rlink, node owned variables

VARIABLE NAME	MEANING
road-d	Distance along current road, in map units
road-traveltime	Estimated time to travel along road, in seconds.
road-covering	Array of patches the road covers.
road-type	Road type
road-oid	The ID number of a road corresponding to the OS master map data
rlink-n0/ rlink-n1	Nodes at start and end of a link respectively
rlink-road	Actual physical road of a rlink
rlink-d	Distance along a rlink
rlink-depth	Depth this rlink is flooded to
rlink-walker-count	Number of civilians who walk on the rlink
rlink-car-count	Number of vehicles travelling on link.
rlink-car-speed	The average car speed according to the car amount, expressed by cell/minute
node-out/ node-in	rlinks out of/ in this node (agentset) respectively
node-oid	External identity of this node
node-x/ node-y	Position of a node, in patch coordination
node-patch	The patch the node stays on

3. Civilian owned variables

Civilian owned variables can be categorized into two types. One is Attribute Control Variable (ACV) ,which means the variable shows the value/degree of an attribute of the civilian agent. Another type is Process Control Variable(PCV), which means the variable shows whether a process has been implemented at one time step. PCV names are often begin with "*deal*". For example, goodMessage*?* is an Attribute Control Variable, it shows the quality of the message the civilian agent obtained , if the message quality is good, *goodMessage? =1* or else *goodMessage? =0. dealmessage?* is a Process Control Variable, it shows that at this time step, whether the civilian agent has had a judgement on the quality of the message it obtained. If *dealMessage?* =1, it means the civilians has finished the process of judging the message quality, therefore, to the next time step, the process of message quality judgement will not be done again. Some important civilian owned variables include:

Table I -3 Main civilian owned variables

VARIABLE NAME	MEANING
civ-patch	The land patch a civilian agent stays at.
civ-speed	The speed of a civilian agent when it is on a trip
civ-rlink	The rlink a civilian agent travels on
civ-route	The route from where the agent stays to the destination point.
civ-TRoute	The route from the start point to the destination point
civ-wet-links	The rlinks of the route that are inundated
civ-pos	The position of a civilians on the rlink it travels on
incoming-queue	Array to store the incoming information obtained
civ-tripType	Trip type of a civilian agent
civ-bn/ civ-bn1	Buiding type of the start point/ dest point
civ-startPatch	The start patch of a civilian agent
civ-startNode	The start node of a civilian agent
civ-HomeID	The patch ID of the start patch, if the start patch is a home
civ-destPatch	Destination patch of a civilian agent's trip
civ-destNode	Destination nod of a civilian agent's trip

civ-modeType	Travel mode a civilian agent chooses
civ-tripNumber	The number of trips a civilian agent has
civ-lingerT	Lingering time when a civilian agent arrives at a destination
civ-waitingTime	Waiting time for starting a journey once a civilian is produced.
civ-mobility	the civilians' vulnerability related vairable , =1 weak mobility, = 2 good mobility
civ-carType	the car type used by the people travel by car. civ-carType = 0 no car, civ-carType = 1 small sized car, civ-carType = 2 Medium sized car, civ-carType = 3 LargeSized car.
civ-hc	hc parameters used in vehicle instability formula
civ-M	M parameters used in vehicle instability formula
civ-alpha1	Alpha partial submerged ,parameters used in vehicle instability formula
civ-alpha2	Alpha submerged ,parameters used in vehicle instability formula
civ-beta1	Beta partial submerged, parameters used in vehicle instability formula
civ-beta2	Beta submerged, parameters used in vehicle instability formula
civ-Uc	Incipient velocity of the car instability
confirmTime	Time costs for confirming warning message.
civ-buildingHGT	Building height of the patch civ agent stands, mainly for static agent, for active agent, civ-buildingHTG = 0
receiveWarning?	True if a civilian receives a warning
goodMessage?	True if the message quality is good

confirmed?	True if the warning message is confirmed after confirmation seeking,
aware?	True if a civilian is aware of the danger of a flood
prepared?	True if a civilian has very well planned for a flood
Insurance?	True if a civilian bought insurance
knowUti?	True if a civilian knows switching off utilities
floodKit?	True if a civilian has flood kit
Move?	True if a civilian agent has moved the household inventory upstairs
evacuatePlan?	True if a civilian has evacuation plan
sandbagReady?	True if a civilian has sandbags ready to use
moveUp?	True if a civilian moves upstairs
receiveEvacuation?	True if a civilian receives an evacuation plan
active?	True if a civilian is an active agent
civ-danger?	True if a civilian agent is a walker and is in danger
civ-carDanger?	True if a civilian agent travel by car and is in danger
toEvac?	True if the a civilian decides to evacuate to a shelter

2) Main functions

Setup function is for initializing the simulation model. It includes environment initialization, agent initialization, risk calculation initialization and model control initialization.

Environment initialization functions reading the GIS data such as road, elevation, building types from map and prepare for the water simulation model. Agent initialization includes all the agents original status setting, risk calculation initialization mainly set the parameters that are related to flood risks and initialize them for calculating flood risk indicators such as DangerCount, DangerCarCount, SavedDamage etc. Model control initialization includes functions for resetting the result folder or read some the time line of the simulations

ModelStep is an function for scheduling every agent's behaviour. It includes changing the environment such as update water data, update each agents action and update the risk calculation result each time step.

Sub-routines

Sub-routines are stored in other nls files. Sub-routines are for four purposes: Environment behaviour, Agent behaviour, Risk analysis and Model running.

In the model running sub-routes, *pathfind.nls* is to implement A* algorithm for finding a path; *communication.nls* is to implement FIPA ACL communication approach. *gadget.nls* includes some small utility functions used in the model such as parse the time string, interpolation etc. .

Environment behaviour sub-routines include *watermodel.nls* , which is for simulating hydrodynamics, and *readWater.nls*.for reading flood simulation result into the ABM model.

For agent behaviour sub-routines, *defence.nls*, *gauges.nls* and *restCentre.nls* are for the change of the physical agent's behaviour. (These three are only used in the simple dam break case.); *Civilian.nls* is for the individual behaivour; *Utility.nls*, *LA.nls*, *EA.nls*, *PA.nls*, *FA.nls*, *MACG.nls*, *police.nls* are for organizational behaviour; *EAstaff.nls, ambulance.nls* and *warden.nls* are for organizationStaff behaviour (They are also only appears in the simple dam break case).

RiskAnalysis.nls is for calculating flood risks.

As most functions are introduced in the flood simulation, individual behaviour simulation and risk analysis modules in the thesis, here only the organizational behaviour functions are described in detail here.

Organizational Behaviour

Organizational behavior described here includes both organizational agents' behavior and the behavior of the individual staff in the organization. Considering shaping the model as simple as possible whilst realistic enough to be useful for simulating the scenario, organizations that have similar functions are merged as one agent. For example, Wales Fire and Coast Guard are all the organizations for rescuing vulnerable, so only one agent named FA (Fire Authority) is set to represent both Wales Fire and Coast Guard. Similarly, water and Power Company are merged as Utility agent. Civil Contingencies Unit (CCU) , Conwy County Borough Council. (CCBC) is merged into Local Authority (LA) agent, Strategic Co-ordinating Group (SCG) is merged into Police Authority (PA) agent. As a result, in the model organizational agents include the EA (Environmental Agency), PA, LA, MACG, FA. The individual staff agents includes EA staff, flood wardens and ambulance. In this part, each organization's responses to a flood event will be explained separately with the flowcharts for each organization agent based on the former sequence UML chart.

EA and EAStaff

EA plays the most important role of implementing government policy on flood risk. The EA's flood responses flow chart Figure I-2 shows that during a flood event , EA is responsible for producing flood risk maps and issuing flood warning as well as maintaining flood defences and giving flood support to the civilians as required.

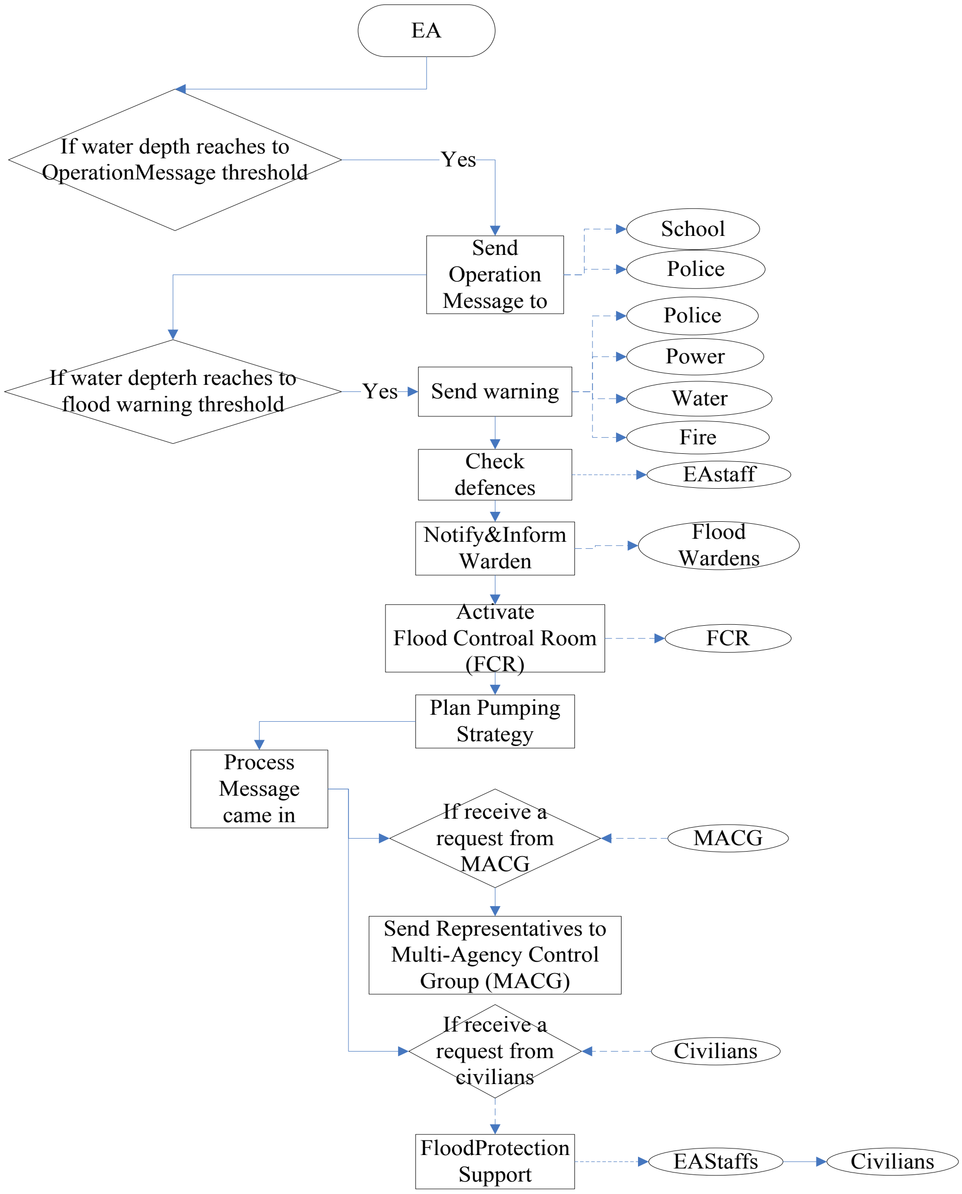


Figure I-2 EA flood responses flow chart (names in the oval box are organizations or individuals that EA 's actions act on)

The trigger of EA's response actions are 1)flood water depth, 2) other organization's command or request 3) Civilians/individual's request. Messages sent out includes: operational message and flood warning. The operational message and flood warning issuing are according to whether the flood water depth of some gauges has reached to a threshold. Operation message are sent to schools and the police. Flood warning messages are sent to the police, the power and water, Fire and rescue organizations. Flood warning messages are also broadcasted to all flood wardens. The form of any messages in this model includes 6 parts like this:

["inform" "sender:34" "receiver:38" "content:" "FloodWarning" "senderType:EA" "receiverType:Utility"]

The 1st part notes the message type such as inform, request, query, the 2nd part identifies sender's ID (each agent in the model has one unique ID number once the model is initiated), 3rd part is the receiver's ID, 4th part is the content of the message, the 5th and 6th part are the types of the sender and receiver such as EA, PA, LA, FA, EA Staffs, Flood wardens, Utility etc.

Except sending out messages, EA also receives messages from other organizations such as from MACG and from individuals asking for flood support. Functions set up enable EA agent to activate related actions according to the different types of the messages. For example, if EA receives a flood support request from a civilian, EA staffs would be send out to give flood support such as sending sandbags to the civilian.

The action functions refer to functions that change attributes of agent itself or other agents. Activating Flood Control Room (FCR), sending representatives to MACG, planning pumping strategy are action functions that the EA change the attributes of itself or others. Checking flood defences and flood protection support are two actions that allocate a specific action to EA-Staffs. Flood protection support is activated once EA receives a flood support request from an individual, once been activated, EA-Staff agents are sprouted and sent to the individual's location and pass the sandbags to the related individuals. Checking the flood defences is activated by the flood warning issuing, once been activated, one EA-Staff agent is sprout near flood defences responsible for checking and maintaining flood defences. If there is a breach on the defences, the EA-Staff will take time to fix it or call for help from the EA if the situation is out of his ability.

PA and the police

The Police play a key role in a flood event for public responses coordination such as providing advice and assistance at the scene and controlling traffic or evacuating the public from properties at risk. Tasks in relation to the police in the flood event are implemented by both the PA agent and the police staff agents as shown in Figure I-3 and Figure I-4.

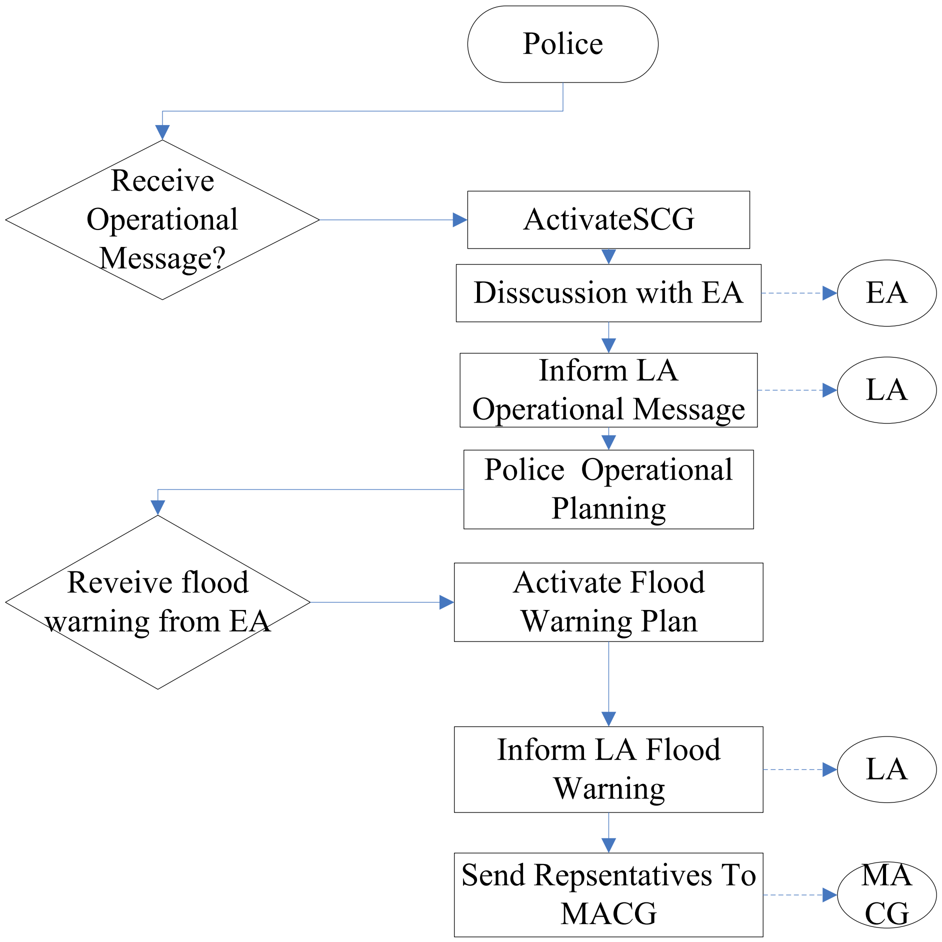


Figure I-3 Police authority flood responses flow chart (Names in the oval boxes are organizations the police authority's actions act on**)**

1. Police Authority

The trigger of PA's response actions are EA and other organization's command or request. PA receives messages from EA and other organizations like MACG . The main messages PA received are operational message and flood warning from EA, the processed messages enable PA agent to activate related actions

Once the operational message is received, PA's responses include activating SCG, activating operational planning and informing LA the operation message.

If a flood warning is received, PA would send the information to LA, when MACG is activated, PA will send representatives to MACG and at the same time the flood warning plan is activated.

4. Police Staff

Police communications with the individuals are via police staffs, the individual policemen carry out the tasks of evacuating the public from properties at risk, providing advice and assistance at the scene and controlling traffic.

Police staffs are randomly scattered in the area, and they patrol randomly, if there is a flood near them, they would escape as normal individuals, however, they accept the message from individuals for help and they will help and ask the ambulance to rescue the individuals in danger. This procedure is implemented in the function of *Police-step.*

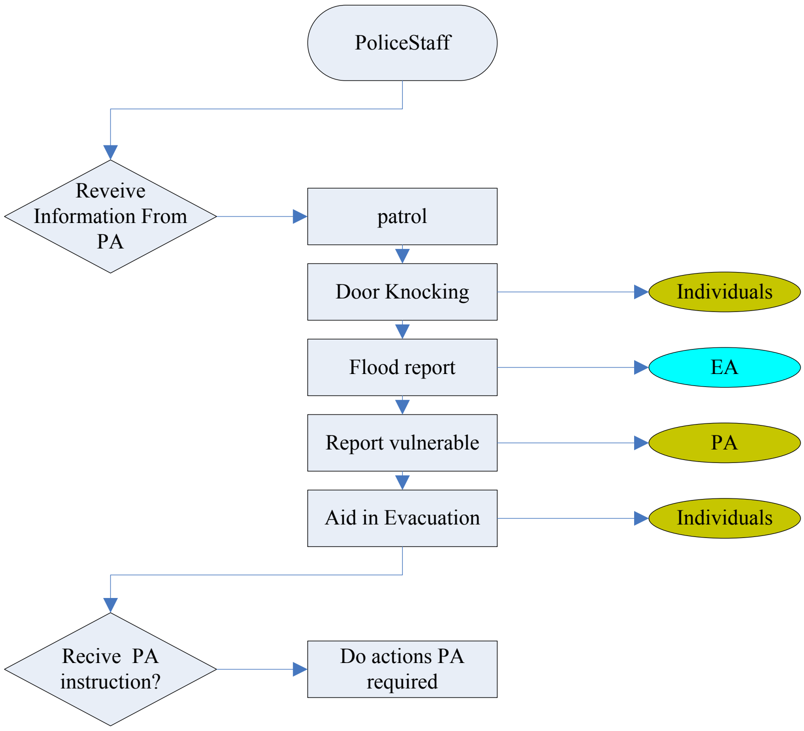


Figure I-4 The police staff flood responses flow chart (names in the oval boxes are organizations and individuals police staff's actions act on **)**

Local Authority

The Council has a diverse range of roles in a flood event which includes setting-up rest centres , arranging transport, reporting vulnerability, providing flood support, setting-up public information helpline and coordinate the voluntary sector response. The flowchart Figure-6 shows the main flood responses from the local authority.

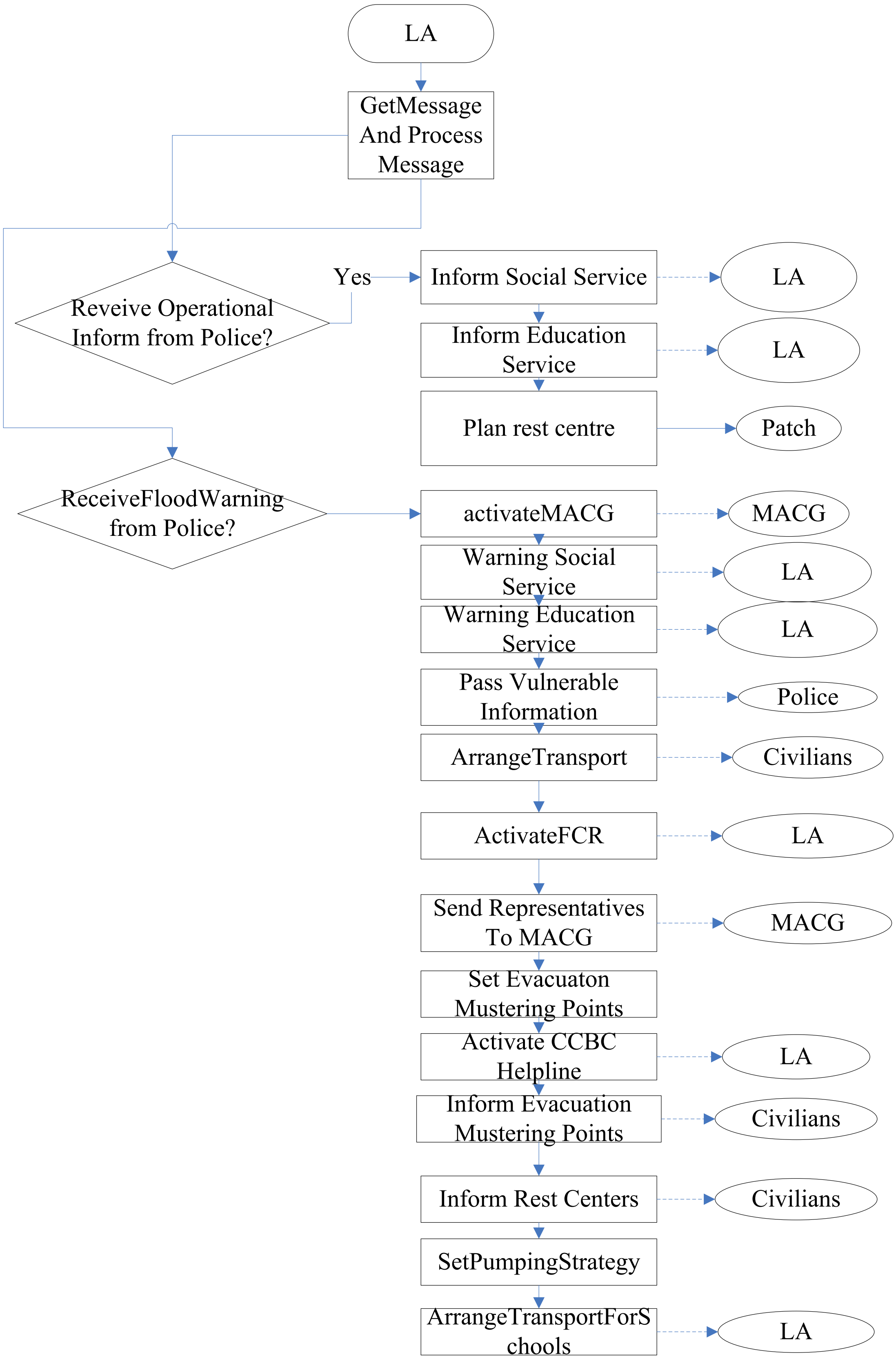


Figure I-5 Local Authority flood responses flowchart (names in the oval boxes refers to the organizations or individuals the LA actions act on)

The triggers of LA's responses are EA's messages. The main messages LA received are operational message and flood warning from PA. LA agent activate related actions according to the different types of the messages.

Once the operational message is received, LA's main responses include informing Education service and social service which are departments in LA. LA also set up a physical agent that represents rest centres (shelters).

When LA receives the flood warning from the PA, LA will inform social service and education service as well as rest centre. There are quite a few action functions for simulating LA's flood responses, such as activating MACG, passing vulnerable information to the related organization, , activating FCR, sending representatives to MACG, setting evacuation mustering points and activate CCBC helpline , arranging transport for schools and setting pumping strategy.

MACG

MACG is a central control organization been activated by flood warning, it is an organization made up with representatives from other key organizations, it is the brain for flood emergency decision making. MACG's main responses to the flood includes Setting marshalling are, cordons, evacuation mustering points and protecting vital route, decisions about evacuating vulnerable and lifesaving are also made by MACG.

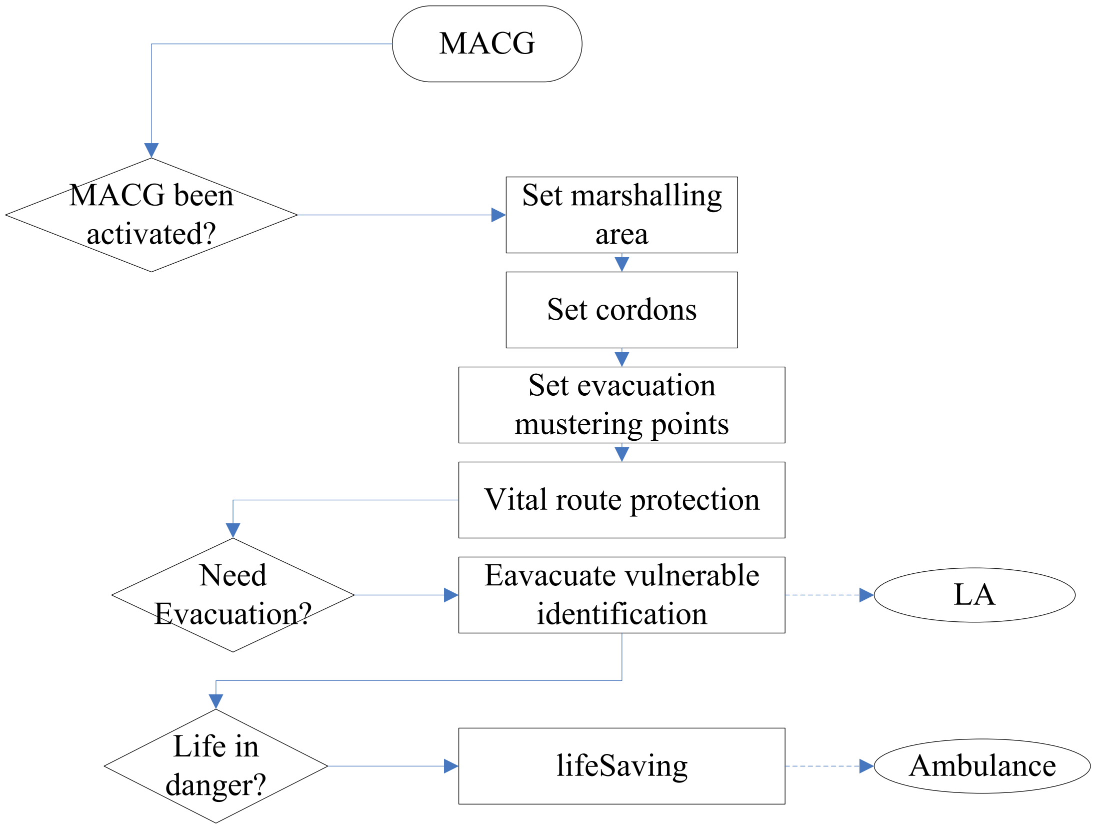


Figure I-6 MACG flood responses flowchart

In order to simulate these MACG responses, the following action functions are set up, which are setting marshalling area, setting cordons, setting evacuation mustering points and setting vial route protection, identifying evacuate vulnerable and life saving actions. Technically, there is no barrier for implementing these functions, as long as the pre-designed marshalling area ,cordons, mustering points or vital route needed to protection are provided, the functions are about reading related map into the simulation model. However, since these functions are strongly related with the specific case study area, it is expected these functions to be implemented in the real case study modelling.

Fire Authority (FA)

The FA represents both Fire Rescue and Coast Guard. The basic rules for FA are shown in Figure I-7.

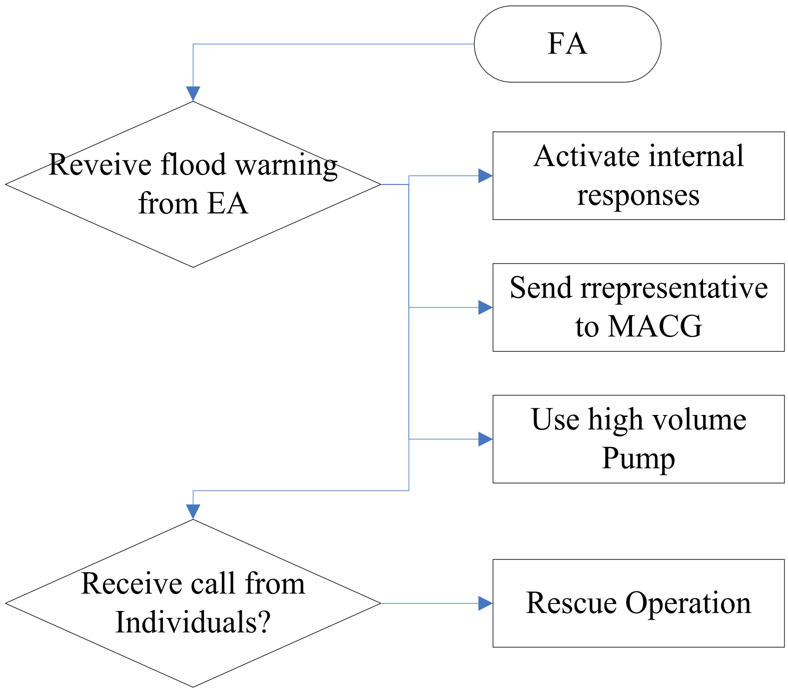


Figure I-7 Fire Authority flood responses flowchart

Flood Wardens and ambulance

Flood wardens' behaviour rules are the same with the police staff agent. The ambulance agents' behaviour rules are show in Figure I-8.

Ambulance

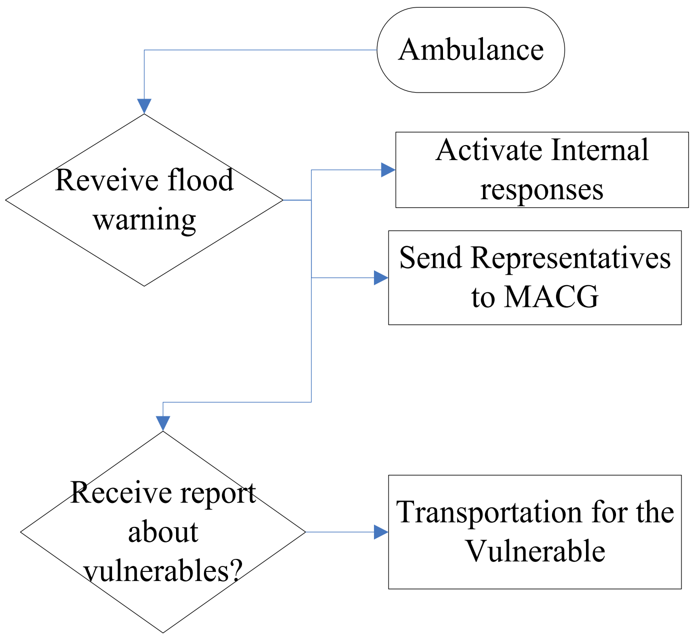


Figure I-8 Flow chart of ambulance flood responses

Ambulances' responses are triggered by the message sent by police staff or flood wardens asking for transportation of vulnerable individuals. Once receives a rescue request, the ambulance would go to the location where the vulnerable trapped and rescue it.

Appendix II Activity-based travel behaviour model

An activity-based travel behaviour model is developed for simulating people's travel behaviour in a flood event. This document is a description to the process of model implementation.

Identifying Activities types

In Wales Travel Survey (see Table II-1), Seven travel purposes are listed which are; 1)Commuting and Business 2) Education and escort education 3) Shopping4) Other escort 5) Other personal business 6) Visit friends 7) Leisure and Just walking. Travel purpose seems to be good criteria for the activity pattern decomposition. However some activities within one purpose group might be quite different in terms of their destination building types. For example, travellers are classified with a commuting and business purpose, where commuters refers to the trip from residential properties to offices, but business travellers mainly travel between non-residential properties. Education travellers are mainly students, but Education escort travellers not only go to school but also have more trips such as shopping after escorting their children to school.

Table II -1 Trips per person per year: by purpose, length and main mode – persons (Source (Welsh Government, 2012))

Average number of trips	2002/03	2004/05	2006/07	2007/08
By purpose:				
Commuting and business	187	188	179	165
Education and escort education	111	109	110	101
Shopping	200	204	195	199
Other escort	98	99	99	96
Other personal business	102	101	96	95
Visit friends	169	180	162	168
Leisure and just walking	129	152	146	144
All purposes	996	1,031	986	969
By length:				
Under 1 mile	207	194	202	187
1 to under 2 miles	179	194	174	162
2 to under 3 miles	117	130	100	115
3 to under 5 miles	144	143	139	144
5 to under 10 miles	170	175	171	168
10 to under 25 miles	127	134	142	139
25 miles and over	51	61	58	53
All lengths	996	1,031	986	969
By main mode:				
Car / van:				
Driver	447	479	438	422
Passenger	252	260	251	246
Total	699	738	689	668
Walk	204	208	211	206
Other modes	92	85	86	95
All modes	996	1,031	986	969

In the National Travel Survey a more reasonable 12 travel purposes are categorized: 1)Commuting 2) Business 3) Education 4) Escort education 5) Shopping, 6)Other escort 7) Other personal 8) Visit friends at private home 9) Visit friends elsewhere 10) Sport/entertainment 11) Holiday/Day trip 12) Other including just walk as shown in Table II-2.

Table II-2 Average trips by day of week and purpose: Great Britain, 2005/09 (Source National Travel Survey)

Average trips by day of the week and purpose: Great Britain, 2005/09

Trips/thousands

Purpose	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Unweighted sample size (trips 000's)
	Trips per person per year							
Commuting	27	29	29	29	27	10	6	265
Business	5	6	7	7	5	2	1	61
Education	12	13	13	13	12	0	0	117
Escort education	8	9	9	9	9	0	0	86
Shopping	25	25	25	27	31	45	24	348
Other escort	13	14	14	14	14	14	10	166
Other personal	16	17	16	17	16	10	11	185
Visit friends at private home	13	13	14	14	15	22	23	209
Visit friends elsewhere	4	4	5	6	8	11	9	85
Sport/entertainment	8	9	9	9	8	12	9	120
Holiday/day trip	5	4	4	4	5	8	9	77
Other including just walk	6	6	6	6	6	6	7	83
All purposes	143	150	152	153	157	139	110	1,802
Unweighted sample size: trips (000's)	259	271	276	275	281	245	195	

Comparing the national and Wales day trip survey data, the trends are very similar (Figure II-1) , therefore, the Wales travel survey data can be divided to smaller groups according to the purpose percentages taken from the national travel survey data.

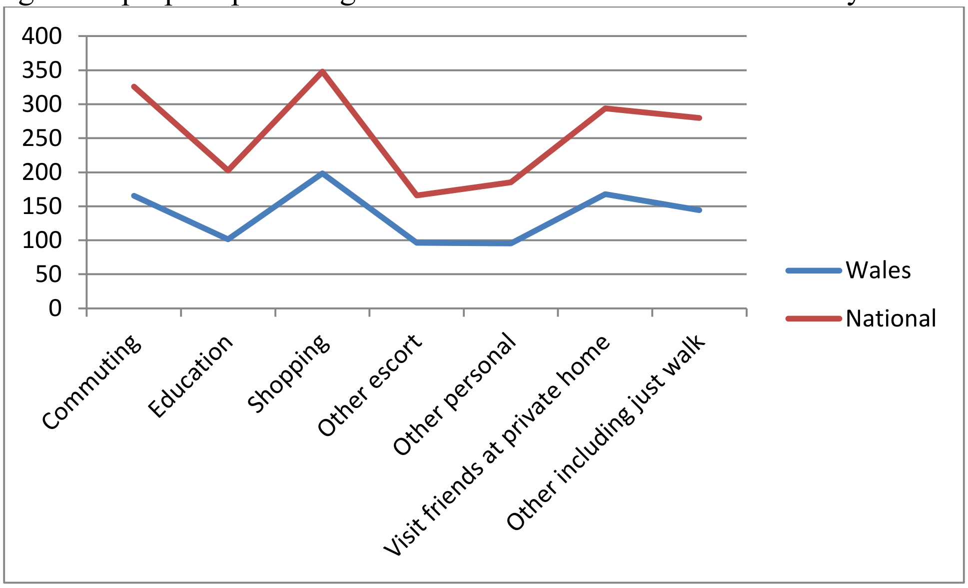


Figure II-1 Similarity of National travel behaviour and Wales travel behaviour (Source National Travel Survey)

Specifically for our research on flood event management, 9 types of activity types are set up for modelling travel behaviour (See Table II-3). The first 8 activity types are to describe civilian agents' normal travel behaviour, the last one 'evacuation type' is to simulate agents' emergency behaviour to the flood situation.

Table II-3 Civilian agents activity types and their travel routs

Behaviour Type	Activity Type	Travel route
Normal Travel behaviour	Commuting	Home-workplace Work place-home
	Business	Workplace-workplace
	Education	Home-school School-home
	Escort Education	Home-school-home
	Shopping	Home-shopping centre-home Education-shopping centre-home Work-shopping centre-home Other purpose-shopping centre-home
	Other escort/personal business	Home-doctors/bank/betting/library/church-home
	Visiting Friends	Home-home/leisure centre
	Leisure and Just walking	Home-interesting places Camping Site/Hotel-interesting places
Emergency behaviour	Evacuation	Any places - Evacuation Shelters

It has to be mentioned that agent's types can change according to the environmental condition during the simulation. For example, static agents change to active agents and start an evacuation travel trip once they receive the evacuation command from the EA. An active agent turns to a static agent once their normal travel trip is finished and normal travel activity can be changed to evacuation activity during the trip.

Identify number of active civilians

The total number of active agents are calculated using the following equation:

$$TR_T = P \times TR_D \quad \textbf{(II-1)}$$

Where

TR_T: Total trips in one day

P : Population

TR_D : Average trips per person per weekday

Population can be easily obtained from Census data (Office for National Statistics, 2011). For example, the daytime population of Towyn is 2239.

Data from Table II-2 is used is used for calculating the average trips per person per weekday. In Table II-2, average trips by day of the week and purpose is given, which shows that people make more trips on weekdays than weekends – an average of 151 trips per person per year on each weekday. Assuming there are 52 weeks for one year, for each weekday, the average trips per person per weekday should be 2.9trips according to the following equation:

$$TR_D = TR_Y / W \quad \textbf{(II-2)}$$

Where

TR_Y: Average trips per person per year each weekday, which are 151

W : Total weeks in one year, which is 52

For Towyn ward, the total trips in one weekday therefore can be estimated to 6493 trips.

According to Table II-2, the percentage of each normal activity pattern in the total number of one day total trips can also be deduced and then, for one day, the number of trips of each normal travel activity type can be obtained (Table II-4).

Table II-4 Towyn one day trips divided by activity types

Activity Types	Percent in the total one day trips	One day trips for the activity type
Commuting	0.14	909
Business	0.03	195
Education	0.06	390
Escort Education	0.04	260
Shopping	0.21	1363
Other escort/personal business	0.20	1298
Visiting Friends	0.17	1104
Leisure and Just walking	0.15	974
Total	1	6493

Time allocation of each activity type trips

In Table II-5, the time sequence of each trip mode are clearly listed, which gives the possibility to allocate each activity type, trips into each time slot. Based on this the time sequence of one day trips of each activity types for initializing the number of active civilian agents is obtained as shown inTable II-6.

Table II-5 Trip purpose by trip start time (Source National Travel Survey)

Percentage/ thousands

Start time	Commuting	Business	Education	Escort education	Shopping	Other personal business and escort	Visiting friends/ entertainment/ sport	Holiday/ Day trip/ Other	All purposes
0000 - 0059	-	-	-	*0*	-	-	-	-	-
0100 - 0159	-	-	-	-	-	-	-	-	-
0200 - 0259	-	-	-	-	-	-	-	-	-
0300 - 0359	-	-	-	-	-	-	-	-	-
0400 - 0459	*1*	-	-	-	-	-	-	-	-
0500 - 0559	*3*	*1*	-	-	-	-	-	*1*	*1*
0600 - 0659	*6*	*3*	-	-	-	*1*	-	*2*	*2*
0700 - 0759	*16*	*7*	*7*	*2*	*1*	*4*	*1*	*4*	*5*
0800 - 0859	*15*	*10*	*41*	*36*	*3*	*8*	*2*	*5*	*12*
0900 - 0959	*4*	*8*	*2*	*8*	*8*	*9*	*4*	*7*	*6*
1000 - 1159	*2*	*7*	*1*	*1*	*12*	*8*	*5*	*9*	*6*
1100 - 1159	*2*	*7*	*1*	*2*	*13*	*8*	*6*	*7*	*6*
1200 - 1259	*3*	*7*	*2*	*2*	*11*	*8*	*6*	*6*	*6*
1300 - 1359	*4*	*7*	*2*	*1*	*9*	*7*	*6*	*7*	*6*
1400 - 1459	*3*	*7*	*3*	*8*	*9*	*7*	*6*	*8*	*6*
1500 - 1559	*4*	*8*	*32*	*33*	*9*	*8*	*7*	*9*	*11*
1600 - 1659	*10*	*9*	*5*	*4*	*7*	*9*	*8*	*9*	*8*
1700 - 1759	*15*	*7*	*2*	*2*	*6*	*8*	*9*	*7*	*8*
1800 - 1859	*6*	*4*	*1*	-	*5*	*6*	*10*	*7*	*6*
1900 - 1959	*2*	*2*	-	-	*4*	*4*	*10*	*5*	*4*
2000 - 2059	*2*	*1*	-	-	*2*	*2*	*7*	*4*	*3*
2100 - 2159	*1*	*1*	-	-	*1*	*2*	*6*	*2*	*2*
2200 - 2259	*1*	*1*	-	-	-	*1*	*4*	*2*	*1*
2300 - 2359	*1*	-	-	-	-	-	*3*	*1*	*1*
All day	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*
Unweighted sample size: trips (000's)	237	54	115	83	229	267	257	100	1,342

Table II-6 Towyn sequence of one day trips by activity types

Towyn time sequence of one day trips by activity types								
Start time	Commuting	Business	Education	Escort education	Shopping	Other personal business and escort	Visiting friends/ entertainment/ sport	Holiday/ Day trip/ Other
0000 - 0059	0	2	0	0	0	0	0	0
0100 - 0159	0	2	0	0	0	0	0	0
0200 - 0259	0	0	0	0	0	0	0	0
0300 - 0359	0	0	0	0	0	0	0	0
0400 - 0459	9	0	0	0	0	0	0	0
0500 - 0559	27	2	0	0	0	0	0	10
0600 - 0659	55	6	0	0	0	13	0	10
0700 - 0759	145	14	26	5	14	52	11	39
0800 - 0859	136	20	160	94	41	104	22	49
0900 - 0959	36	16	8	21	109	117	44	68
1000 - 1159	18	14	4	3	164	104	55	88
1100 - 1159	18	14	4	5	177	104	66	68
1200 - 1259	27	14	8	5	150	104	66	58
1300 - 1359	36	14	8	3	123	91	66	68
1400 - 1459	27	14	12	20	123	91	66	78
1500 - 1559	27	16	125	86	123	104	77	87
1600 - 1659	91	18	19	10	95	116	89	88
1700 - 1759	136	14	8	5	81	104	100	68
1800 - 1859	55	8	4	3	67	77	111	68
1900 - 1959	18	4	4	0	55	52	111	49
2000 - 2059	18	1	0	0	27	26	77	39
2100 - 2159	10	1	0	0	14	26	66	19
2200 - 2259	10	1	0	0	0	13	44	10
2300 - 2359	10	1	0	0	0	0	33	10
All day	909	196	390	260	1363	1298	1104	974

Set destination

Every time step, an active agent first needs to make sure a destination is identified according to its activity type. A trip of each activity type is decomposed into several steps and the probability of each steps are identified according to the National Travel Survey data for the purpose of the next trip. After normalizing the trip numbers into percentages, the general travel chain behaviour feature can be listed in Table II-7:

Table II-7 Purpose of next trip: Great Britain, 2009(Adapted from National Travel Survey)

	Previous Trips			
Next trip purpose	All purposes	Work or business	Escort education	Shopping
Work or business	11	10	8	3.02
Education	3	0	2	0.26
Escort education	3	1	3	0.32
Shopping	11	6	4	6.50
Other escort	6	3	4	1.48
Personal business	5	2	2	1.50
Visit friends[1]	9	3	3	4.98
Other leisure[2]	9	2	1	2.49
Home	43	74	73	79.46
	100	100	100	100.00

Trips in Table II-7 can be divided into 2 categories; direct trips and second order trips. Direct trips are the trips where the next trip purpose is "Home". If the next trip purpose is not home, the trip can be called a second order trip. The percentage of direct trips and second order trips by purpose can be used as the probability of each activity steps. In the next part, each activity type will be decomposed into a combination of direct trip and chain trips. It has to be mentioned that for commuting and education trip types, due to lack of practical data, the probabilities for the agent choosing the start point are based on estimation.

1. Commuting

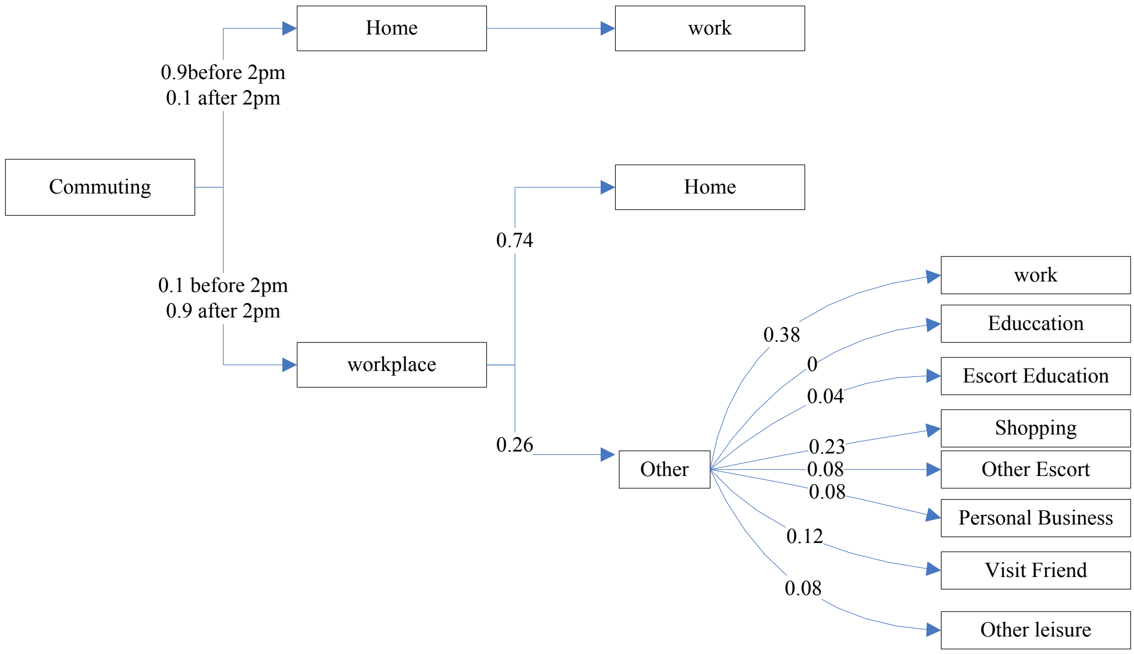


Figure II-2 Travel behaviour of Commuting trips

2. Business

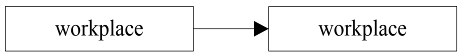


Figure II-3 Travel behaviour of Business trip type

3. Education

Since the Education travel chain data is not listed separately, the all- purpose travel chain data is used instead.

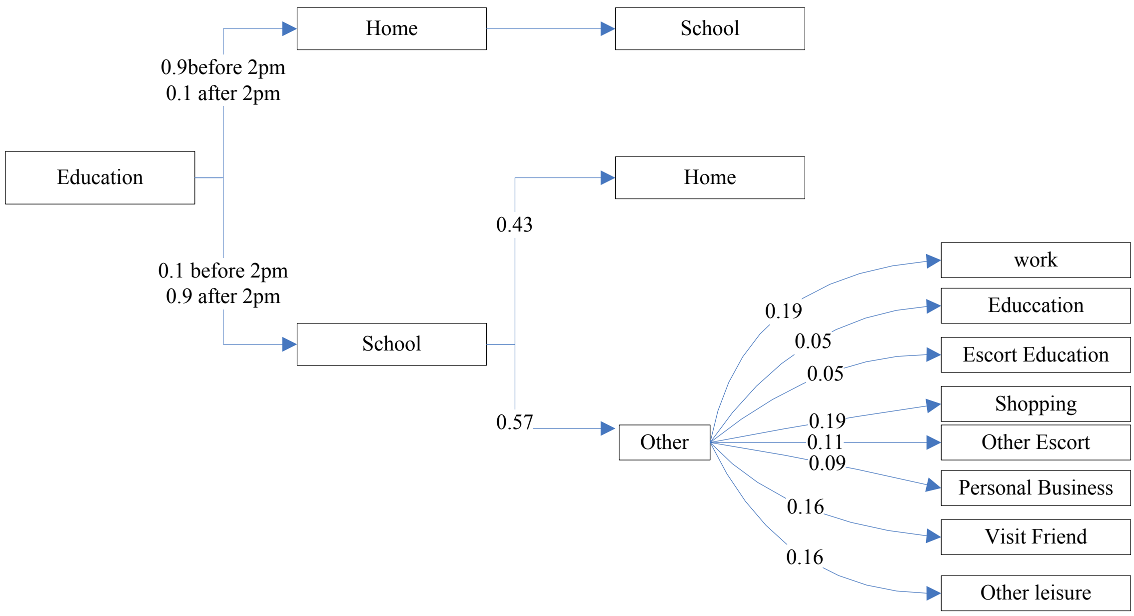


Figure II-4 Travel behaviour of Education trip type

4. Escort Education

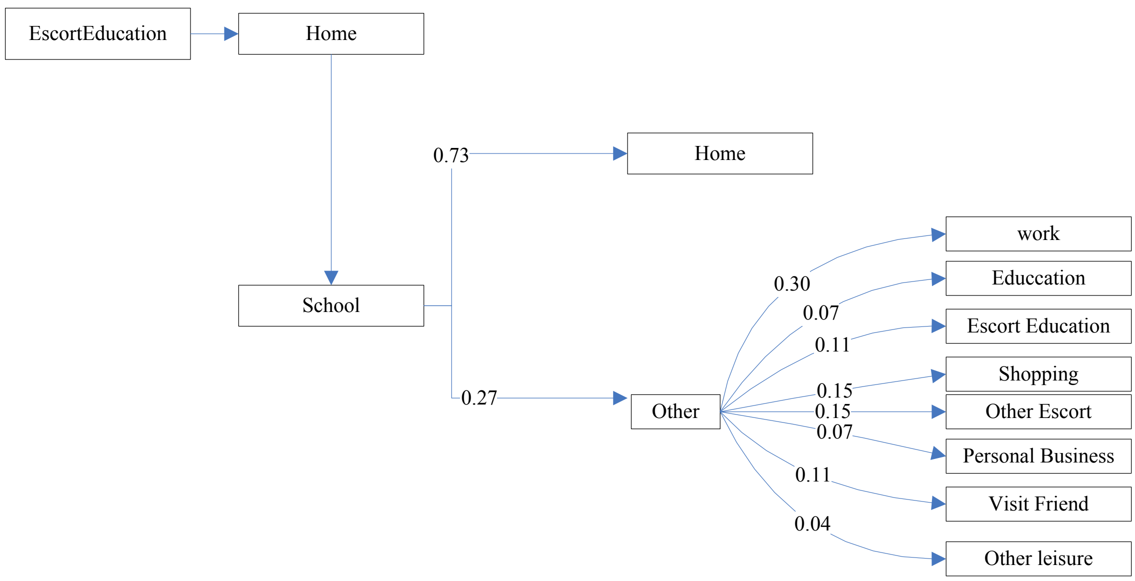


Figure II-5 Travel behaviour of Escort education type

5. Shopping

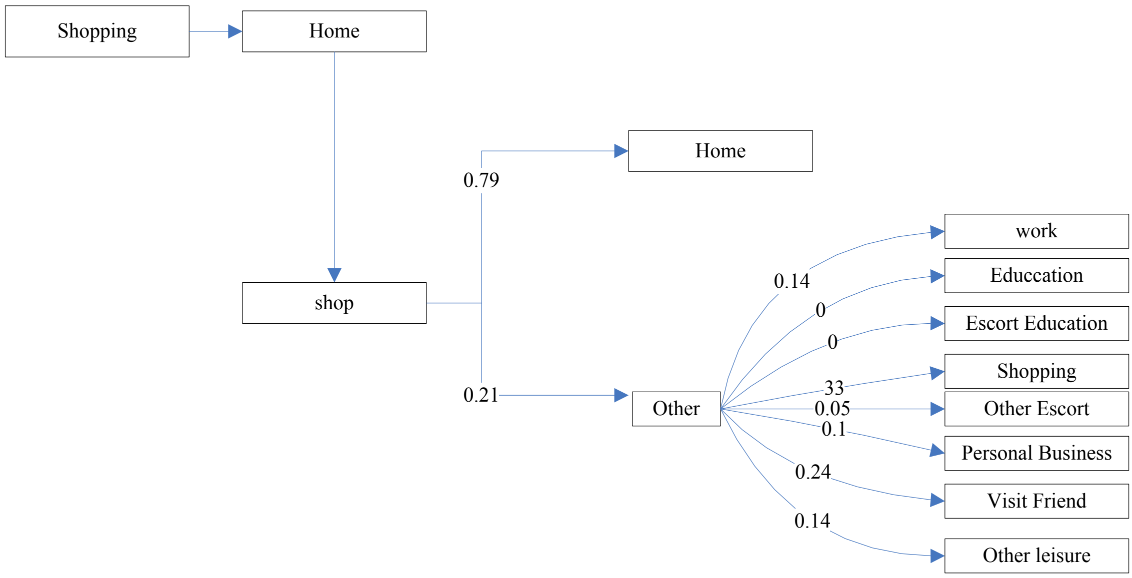


Figure II-6 Travel behaviour of Shopping type

6. Other Escort /personal business

Since the Other Escort personal business travel chain data is not listed separately, the all-purpose travel chain data is used instead. Similarly, Visiting friends and Other leisure type, also need the all-purpose travel chain data as their substitute.

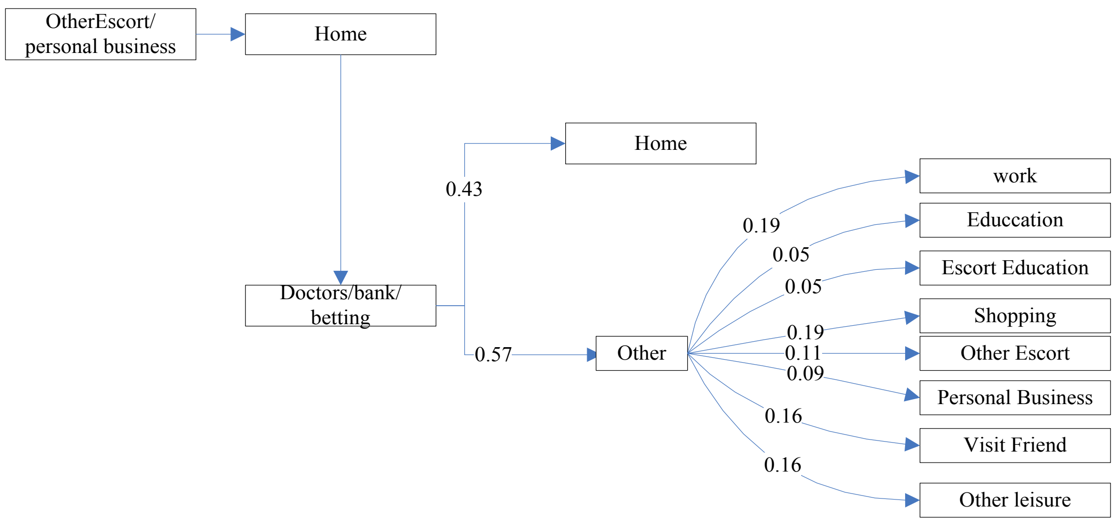


Figure II-7 Travel behaviour of Other escort/personal business type

7. Visiting friends

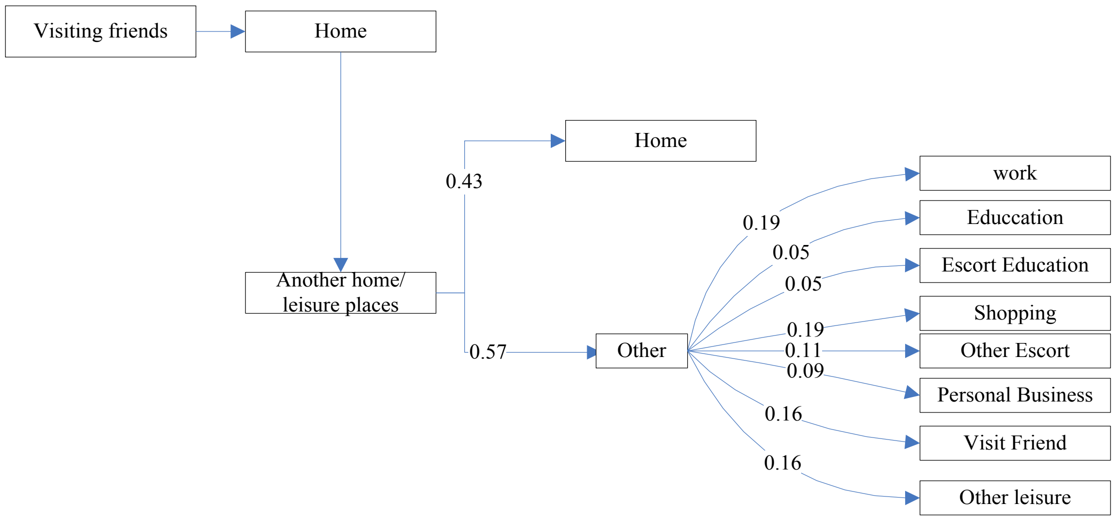


Figure II-8 Travel behaviour of Visiting friend type

8. Other leisure

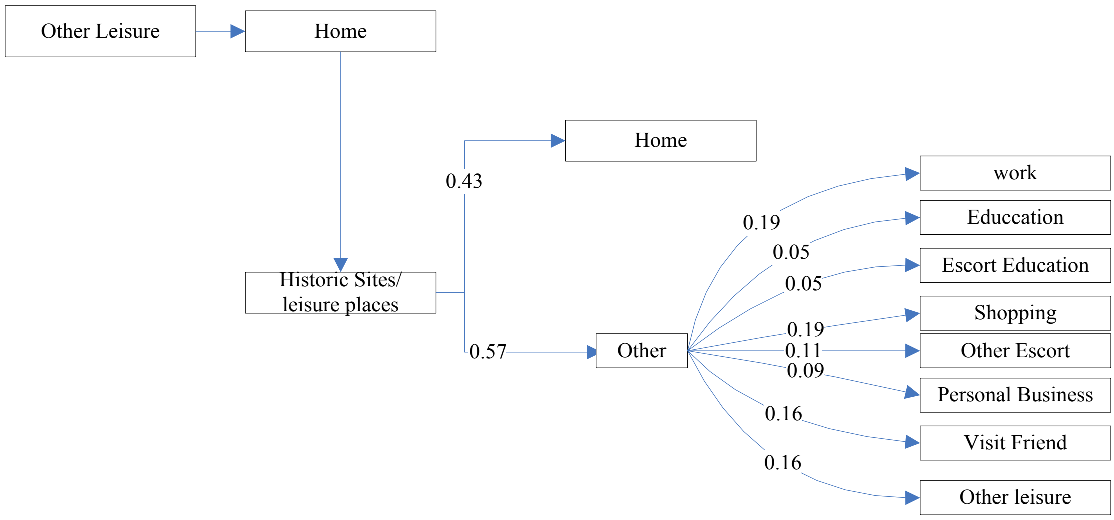


Figure II-9 Travel behaivour of Otehr leisure type

9. Evacuation

Evacuation type is the behaviour of an agent who decides to evacuate. It might be triggered by the flood danger encountered or receiving a flood warning or an evacuation command. The evacuation trips can be started from any place but the destinations are all shelters.

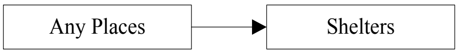


Figure II-10 Travel behaviour of Evacuation type

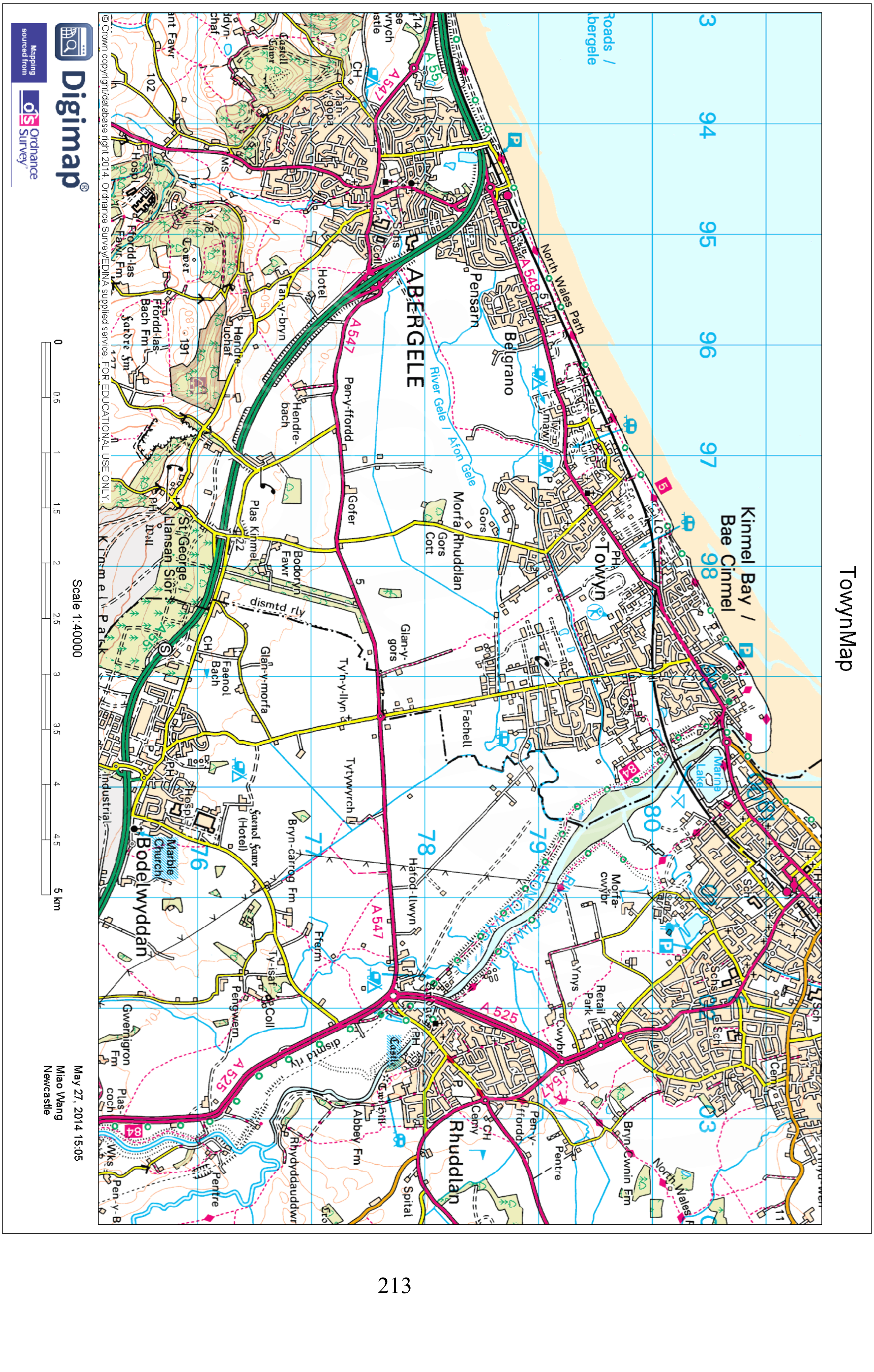
Activity-type trips with car mode

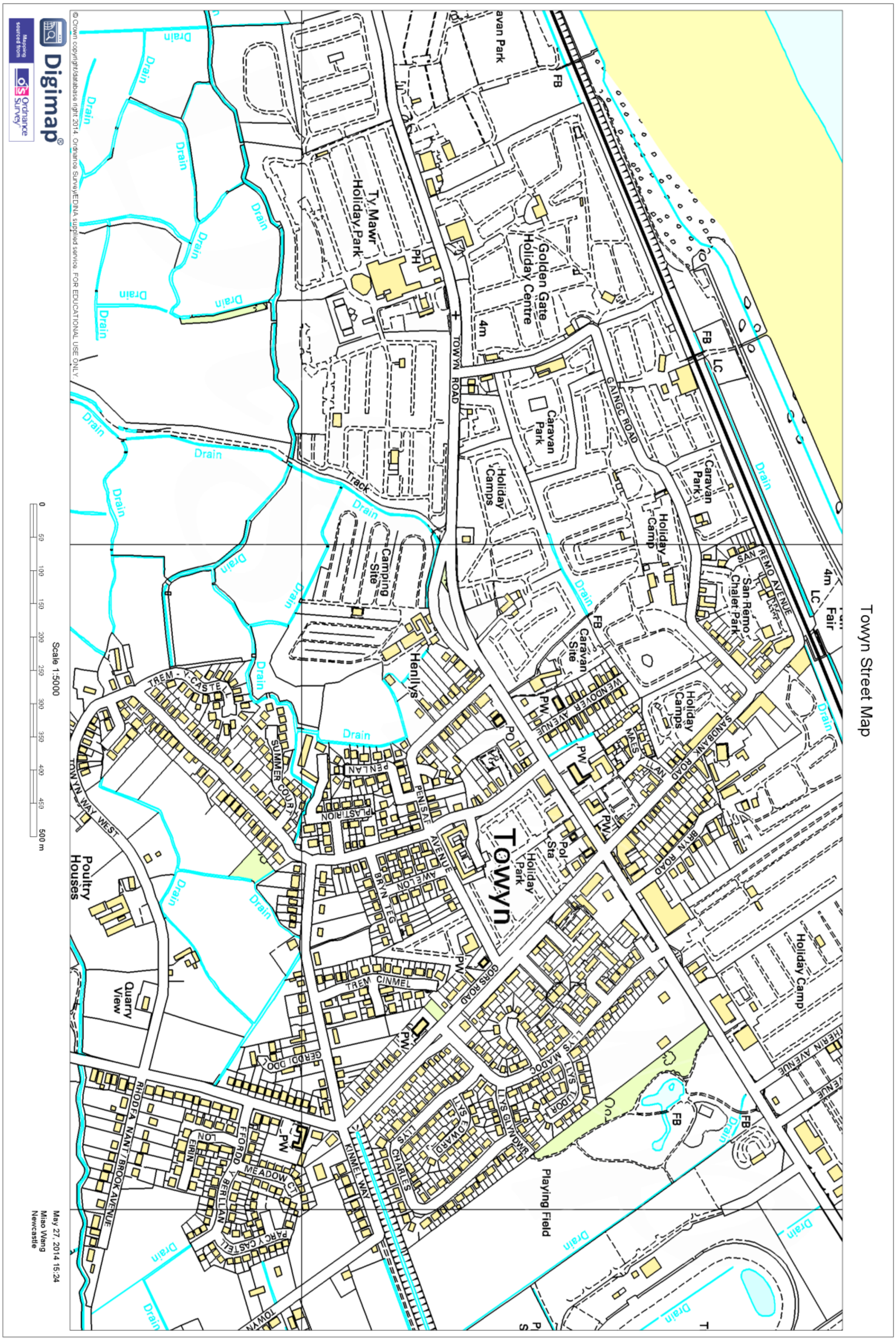
The one day trips include all travel modes such as walking, Car/van, bus, train, local bus and other. In order to analyse the car traffic, trips by car/van mode needs to be extracted from the total one day trips by activity types. This can be done, based on the National Travel Survey, and the percentage of each travel mode can be obtained, as shown in :

Table II-8 Percentage of each travel mode by activity types

Percentage of each travel mode by activity types						
Purpose	**Walk**	**Car/van[1]**	**Local bus**	**Rail[2]**	**Other[3]**	**All modes**
Commuting/business	0.105748	0.698549	0.077071	0.064286	0.054346	1
Education/escort education	0.414768	0.415856	0.096741	0.017785	0.05485	1
Shopping	0.238487	0.635009	0.094174	0.007607	0.024723	1
Other escort	0.122	0.840544	0.023334	0.003826	0.010296	1
Personal business	0.238571	0.64644	0.072369	0.011677	0.030943	1
Leisure[4]	0.176215	0.696408	0.052716	0.021479	0.053182	1
Other including just walk	0.989029	0.01057	0.000401	0	0	1

Appendix III Towyn Map




Towyn Street Map
Digimap
Mapping sourced from Ordnance Survey
© Crown copyright/database right 2014. Ordnance Survey/EDINA supplied service. FOR EDUCATIONAL USE ONLY.
Scale 1:5000
0 50 100 150 200 250 300 350 400 450 500 m
May 27, 2014 15:24
Miao Wang
Newcastle
Towyn
TOWYN ROAD
TOWYN WAY WEST
SANDBANK ROAD
GAINC ROAD
SAN REMO AVENUE
WENDOVER AVENUE
GORS ROAD
TREM-Y-CASTELL
SUMMER COURT
PENLAN
PLASTIRION
PENISAF
BRYN TEG
AVE LON
TREM CINMEL
KINMEL WAY
RHODFA NANT / BROOK AVENUE
LON EIRIN
FFORDD BERLLAN
MEADOW CT
PARC Y CASTELL
GERDDI DOL
LLYS EDWARD
LLYS CHARLES
LLYS GLYNDWR
LLYS TUDOR
LLYS MADOC
BRYN ROAD
Ty Mawr Holiday Park
Golden Gate Holiday Centre
Caravan Park
Holiday Camps
Holiday Camp
Camping Site
Caravan Site
San Remo Chalet Park
Holiday Park
Henllys
Poultry Houses
Quarry View
Playing Field
Drain
Track
PH
PW
PO
Pol Sta
FB
LC
4m
Fair

Appendix IV Flood Defence Fragility Curves

Figure IV-1 Fragility curves of flood defences near Towyn