A Strategic Modelling Framework for Victim Estimation in Floods by Linking Flood and Evacuation Modelling
A Case Study: Land van Maas en Waal

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ABSTRACT

Many countries in the world in the 21st century are confronted by the increasing flood risk, which is the result of impacts from both global climate change and local environment challenges. The Netherlands, a low lying country known by the world for its long history of struggling with flood risk, from both sea and river, has been recognized being facing with increasing flooding risk. After 2000, a new round national assessment of flood risk was carried out for all dike-ring areas in the country by RIVM. It was discovered that in many dike ring areas, the flood risk is increasing primarily because the water defence systems used to protect the dike ring areas are gradually becoming less robust with increasing natural hazard and dynamic social economic shifts. The serious reality entails more adaptive emergency reactions, risk mitigations measures which should be undoubtedly founded on solid assessment of flood risk.

Literally, flood risk is defined by the combination of flood probability and consequences caused by flood. Normally the consequences of flood consist of multiple components, including loss of human lives, economic loss, environmental and recreational losses, etc. Among these components, loss of human lives is always regarded as the most prominent, which suggest the importance of the methodology for victim estimations.

Usually, methods of victim estimation in flood have taken both hazards of flood and people's responses into account. The methodological development in victim estimation has been evolving since 1980s with historical data support and new modelling methods. Recently, the modelling endeavours have engaged both flooding characteristics and human actions (evacuation, sheltering, rescue, etc.) by proposing a complete process-based modelling framework (Jonkman, Vrijling, et al. 2008). Particularly the join of flood simulation and evacuation modelling has been a focused topic. However, given abundant studies in evacuation modelling, the new models for flood victim estimation has not very successful. Through literature review, it is discovered that the comprehensibility of linked flooding – evacuation models and spatial specification of estimation results are not desirable. Lack of explicitly explained modelling and less area-specific modelling results may obstruct the adaptability and practicability of existing models.

Taking the one of the Dutch dike ring areas, Land van Maas en Waal as the case, this research links flooding simulation with evacuation modelling in a more open and detailed way by explicitly defining spatial-temporal relations between floods, transport infrastructure, floods advancing and people's evacuation process which usually consists of prediction, warning, response, departing and evacuating to exits. Particularly, this research looks into and models each phase of these processes, by proposing a clearly explained, justified conceptual model which is based on solid existing research basis and then implemented by six interconnected operational modelling modules.

First, the flooding characteristics from a pre-simulated flooding scenario are represented and categorized for specification of 3 types of flood zones (breach zone, zone with rapid rising water, remaining zone), which is based on Waarts's and Jonkman's works. Second, dynamic availability of roads and exits are generated by looking at the spatial-temporal impacts of floods. Third, the demand for evacuation (basically vehicles departing over time) is estimated by dynamically inspecting people's departing behaviours, also under impacts of flood threats and different settings of evacuation scenarios. Fourth, the evacuation routes and costs are specified between departing origins and destinations (exits) by applying different algorithms (shortest path or capacity-aware-shortest-path). Later, estimation of population's participation and departure, evacuation routes and costs, congestion on roads are respectively used for estimate exposed population in flood at home or on evacuation routes. For the later one, a new data structure "Evacuation Milepost Series" (EMS) is innovated and processed in a newly developed programme to

identify en-route exposure incidents. Finally, based on Jonkman's proposal on mortality rate function, number of victims is estimated by multiplying exposed population with mortality rate estimated, for each scenario. In this study, in order to address the issue of uncertainty and complexity of human/social behaviour in emergent situations, different scenarios with varied departure patterns, exit choices, routing methods, etc. are specified, analysed respectively, compared and eventually aggregated to reach the estimation of total level: 266 victims, which is relatively higher than previous estimates of HIS platform.

The distribution pattern of victims in space is analysed by spatial statistics. Different patterns on different scales are identified. There is no significant global clustering of victims, while local clusters of high or low number of victims are specified as statistically significant. In addition, different groups are classified by varied risk level and types in different situations, which may offer insights into area-based mitigation measures.

It is concluded from this study that generally the loss of human lives in a serious flood event is considerable, 266 victims estimated. In quantity, home-based victims are more significant, while in space en-route victims are much more clustered. From the comparison between scenarios, it is found that the model is to some extend quite sensitive for the final prediction hence potentially less robust in dealing with complex situations. This conclusion needs to be further verified by future sensitivity analysis, which is yet absent in this study.

As proposed, this research, and the model proposed in some aspects achieved the objective "strategic modelling". It also earns credits in validity, practicability and adaptability. However, it is also quite obvious that this study has limitations of less calibrated model, oversimplified assumptions, less dynamism-supporting transport modelling (no real dynamic traffic modelling), rough and inconsistent spatial/temporal analytical resolution and less platform integration. Further improvements may focused on applications of survey based, cooperative approaches in preference/behavioural studies, utility/agent based modelling in departure and en-route routing simulation, application of dynamic traffic assignment approaches, development in sensitivity and error analysis, better integration of modelling environments.

Keywords: Victim Estimation, Flood Risk Assessment, Flooding Simulation, Evacuation Modelling, strategic modelling, Comprehensibility, Adaptability, ArcGIS, Geoprocessing, MatLab Scripting, Home-based Exposure, En-route Exposure, CASPER.

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LIST OF ACRONYMS

FLORIS	Flood Risks and Safety in the Netherlands
DTA	Dynamic Traffic Assignment
GIS	Geographic Information System
CASPER	Capacity-Aware-Shortest-Path-Evacuation-Routing
SP	Shortest-Path
MCE	Multiple Criteria Evaluation
AHP	Analytic Hierarchy Process
LAA	Learning and Action Alliance
PAR	Population at risk (In flood situation)
CDF	Cumulative Distribution Function
LND	Log-normal Distribution
PNN	Probabilistic Neural Network
LVQ	Learning Vector Quantizer
TTF	Time to Flooding
EMS	Evacuation Milepost Series
brcZone	Breach Zone in a flood
rapRisZone	Zones with Rapid Rising Water
remZone	Remaining Zone
ETW	Evacuation (Departure) Time Window
OSM	OpenStreetMap
GMSV	Google Map Street View
I/O	Input/Output Relations
S11	Evacuation Scenario: No Prediction – No Evacuation
S12	Evacuation Scenario: No Prediction – Disorganized Evacuation
S21	Evacuation Scenario: Prediction Available – Disorganized Evacuation
S22	Evacuation Scenario: Prediction Available – Organized Evacuation

1. RESEARCH PROPOSAL

1.1. Introduction

1.1.1. Flooding Risks in the Netherlands

It has been widely recognized that sustainable solutions dealing with water play an important role in the national security of the Netherlands. Given the nature of this country's geography of socio-economic distribution, more than 65% of area accommodating majority of residents and economic activities is prone to threatens of sea or river induced floods (van Zuilekom & Zuidgeest, 2008). In February 1st, 1953, the last major catastrophic flood in history surging from North Sea swept the south western part of the country and caused 1836 casualties and thousands of cattle loss. Afterwards, as reaction the Dutch government and agencies took great efforts in water management with regards of organization, planning and legislation. By the end of 1950s, the world's largest water control structure: the "Deltawerken" was completed (van Maarseveen, 2005).

Though established water defence structures have contributed a lot in protection against water, there are still a variety of discussions at the moment about the situation in the new millennium when both global and local changes simultaneously make the situations increasingly serious(van Maarseveen, 2005; van Zuilekom & Zuidgeest, 2008) than before. At global scale, climate change is causing rising up of sea level and increasing uncertainty of river water levels. Locally, due to exploitation of gas resources, Dutch soil has been sinking (van Zuilekom & Zuidgeest, 2008) and eroded (van Maarseveen, 2005). To explore the consequences of global and local reasons, both long-tern scenario-based simulation (Katsman et al., 2011) and short/mid-term studies (S. N. Jonkman, Kok, & Vrijling, 2008; Maaskant, Jonkman, & Bouwer, 2009; Rijkswaterstaat, 2006) have indicated increasing flooding risk in the Netherlands. New challenges of protecting the country against flooding have urgently entailed efforts in emergence management.

The underlying safety standards of the country's water defences are gradually incapable to meet the requirements of the new era (RIVM, 2004), since the increasing sea level, climate change and further economic and social development have challenged the safety standards based on insights of 1953-1960. Based upon long-term experiences of fighting against floods and implemented by the Flood Defence Act (Rijkswaterstaat, 2006), the flood-prone area has been divided into 53 subareas , namely dike-ring areas which are protected by surrounding dikes, dunes or hydraulic structures. The protection level of water defences were built on a basis of risk assessment which have been set up by the Delta Committee during 1950s (1953-1961) (Rijkswaterstaat, 2006). Although the current safety standards for dike-ring areas are relatively higher than many other countries in the world (in Europe, the USA and Japan) (RIVM, 2004), due to global and local challenges they are becoming inadequate and out-dated (RIVM, 2004). RIVM (2004) has mapped the weak links in National water defence system (as shown in Figure 1-1), suggesting a growing risk in the system(RIVM, 2004).

Figure 1-1 Safety standards for dike-ring areas (left) and weak links along the coast (right)

(Source: RIVM Report 500799002, p42, p55.)

1.1.2. Case Study Area: Land Maas en Waal

The study area, Land van Maas en Waal lies in the centre of the Netherlands, in the province of Gelderland, at the west of the city Nijmegen. This area is surrounded by River Maas in the south and River Waal in the north thus relatively isolated from the surrounding regions. The area is right now protected by dike-ring system but still facing with possible threats of river floods according to related studies (Alkema & Middelkoop, 2005; Hesselink, Stelling, Kwadijk, & Middelkoop, 2003). There are no big cities in this area, but most of the total 200,000 residents living in the larger towns (West Nijmegen, Beuningen, Druten, Beneden-Leeuwen) in the north side next to the river Waal and the out-skirt of Nijmegen, is still considered at potential risk of floods (Hesselink, et al., 2003), since as shown in Figure 1-2, seepage and high river level can together lead to dike breach. Again, as the distribution of road infrastructure in space is concentrated, there might be problems of congestion and malfunctioning of existing transportation system if an evacuation is needed in a short/no notice flood event.

Figure 1-2 High Level of River Waal (Photo: P.C. Beukenkamp)[1]

[1] Source: Department of Physical Geography - Faculty of Geosciences. (2007). Flooding. Retrieved Feb-5, 2013, from http://www.geog.uu.nl/fg/palaeogeography/results/flooding

Figure 1-3 Location of Land van Maas en Waal in the Netherlands[2]

1.1.3. Research Options

As discussed the threat has risen considerably. Many response actions have been taken but the main focus is still on technical efforts to further fortify the dikes and dams and to reduce the chances of breaches (RIVM, 2004). Nevertheless, it has been argued that, as a sole solution, it is no longer sufficient in the future and hence more comprehensive spatial planning measures should be taken into account (RIVM, 2004; van Herk, Zevenbergen, Ashley, & Rijke, 2011; van Herk, Zevenbergen, Rijke, & Ashley, 2011; van Maarseveen, 2005). In order to address the problem of growing risk of flooding, it is reasonable that proper flood management measures should be based on a solid assessment of potential flooding risk in risk prone areas under proposed flood scenario. In studies of flood risk assessment, estimation of flood consequences has always been a central problem.

An effective estimation of flooding consequences should engage major processes of a flood events, including the dynamic flooding process and society's responses, because the consequences of floods depends on both invasion of water and people's reactions to it. The flood is propagated by scenario-based simulations assuming presumptive failures of water defence. Because the dynamic nature and complexity of flood simulation, the study of flood process needs effective modelling tools. In practice, there have been efforts in modelling flooding process including famous modelling suite SOBEK developed by WL | Delft Hydraulics (Deltares, 2012). In typical flood modelling paradigm, flood is modelled in 2D surface by given elevation and land use bases and hydrologic boundary conditions, which is more deterministic. On the other side, human responses to floods (i.e. evacuation process) is also so complicated that efficient and strategic models are entailed for simulation of human's behaviours in floods.. In the Netherlands, responsible authorities in many dike-ring areas have prepared evacuation plans. In academic realm, evacuation modelling has received considerable attention. Different parties have been collaborating together to develop a comprehensive evacuation decision support system named as HIS-EC (Evacuation Calculator) based on the MaDAM traffic assignment algorithm and the OmniTrans platform (van Zuilekom & Zuidgeest, 2008). It would bring benefits to implement flood risk assessment by integrating modelling tools of both domains.

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[2] The region Land van Maas en Waal in Dutch national dike-ring area system is indexed as the 41st dike-ring area, or informally named as "polder".

In practice, the benefits of both flood modelling and transportation-based evacuation models have been integrated to perform comprehensive flood risk evaluations. A national scale project , FLORIS ("Flood Risks and Safety in the Netherlands") was initiated and completed by the Dutch Ministry of Transport, Public Works, and Water Management (Rijkswaterstaat, 2006). Other more specific studies have been focusing on dike-ring area scale and evaluation of partial flooding consequences like victim estimation in forms of either individual or societal risks (S. N. Jonkman, Jongejan, & Maaskant, 2011; S. N. Jonkman, Kok, et al., 2008; Maaskant, et al., 2009).

Despite existing achievements, there are still areas for further exploration. Comprehensibility of existing models needs to be improved because in most frameworks which have been applied in the Netherlands, evacuation models are highly implicit and complex, rather than explicitly constructed and explained. Lack of comprehensibility may undermine the practicability and adaptability of the models in communicative planning and decision-making processes. Both Rijkswaterstaat (2006) and Jonkman(2008) have applied a dynamic evacuation model(van Zuilekom & Zuidgeest, 2008) in dike-ring areas and indicated the major functions of the model and various factors taken into account. However, the evacuation model was not clearly defined, including issues like amount and locations of evacuees, road infrastructure adopted for evacuation, evacuation routing methods, etc. Furthermore, how the essential output of the evacuation model, the evacuation time is estimated was not explained. Although Zuilekom and Zuidgeest (2008) have proposed modelling procedures for evacuation time estimation, the complex dynamic traffic assignment (DTA) used in the proposed methods is still difficult to comprehend for non-expert users. Also, the relation between flooding model and evacuation model was not fully clarified. Several studies (S. N. Jonkman, Kok, et al., 2008; Maaskant, et al., 2009; Rijkswaterstaat, 2006)focusing on linking models have provided examples for building model linkages between flood-model and evacuation model domains. Possible linkages primarily include two issues: first, how water characteristics generated by flood simulation affect evacuee distribution and the availability of infrastructure; second, how to estimate the people exposed in floods by inspecting interaction between departure-evacuation process (modelled by evacuation model) and flooding process (simulated by flood model). However, none of these studies has explicitly specified these relations. Hence, the general objective of this study is to further develop a strategic modelling framework for one of the central issues in flood risk assessment, the estimation of victims, by linking already applied flooding and evacuation modelling methods.

1.2. Research Problem

According to statements in "Research Options", this study is focusing on the domain of **"Linked hazard and evacuation modelling for flood consequence estimation (loss of human lives)"**.

As mentioned, lack of comprehensibility of models not only makes a model difficulty to understand but also undermines its potential in wide application, particularly for those non-expert decision makers. Also the lack of comprehensibility of existing modelling framework leaves less space for participation of stakeholders in planning and decision-making process.

Therefore, the main research problems of this study are:

How to adapt and link flood simulation and evacuation models into a strategic framework for victim estimation in flood?

A conceptual model based on Jonkman and Vrijling's general approach for flood victim estimation (S. N. Jonkman, Vrijling, & Vrouwenvelder, 2008) has been developed in this study to show the major domain variables, concepts and their relations.

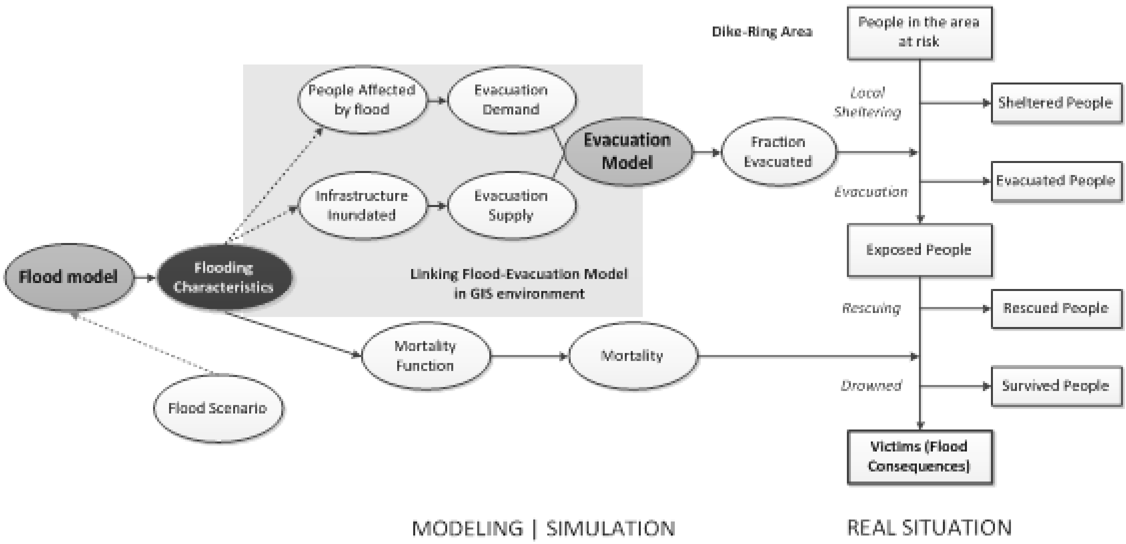

Figure 1-4 A conceptual model for victim estimation by linking models[3]

As highlighted in Figure 1-4, the two research problems are to be answered by intensive study of the relationship between flooding process and evacuation demand/supply, the evacuation routing and optimization process and the spatial difference represented by maps of victim distribution. Finally the distribution of estimated victims could provide insights into risk mitigation strategies.

Further developed on this conceptual model, as the essential issue of the research problem and the main objective of the study, an adaptive modelling framework for victim estimation in flood is characterized by following criteria:

1. Clarification of modelling outputs and objectives.
2. Clarified 1) definitions, and 2) processing methods of variables and parameters contained in models.
3. Explicit assumption about human behaviour in emergent situation (short/no notice flood event) by clarified scenario settings.
4. Clarified methods/tools applied for evacuation routings (optimization) which are specific for evacuation scenarios.
5. Explicit linkages between major concepts for victim estimation framework (proposed by Jonkman, 2008): flooding process, exposed population and evacuation, mortality. These linkages should be defined by <u>unambiguous spatial/mathematical relations</u>. Possible linkages are:
    a. Impacts of flood on demand/supply of evacuation.
    b. Temporal-spatial relations between flooding process, evacuation process (participation, departure and routing) and different types of exposure (home-based and en-route exposure).
    c. Effects of water characteristics on mortality rate estimation.
6. An open modelling procedures delivered by a user-customizable interface realized by coupled-modelling using widely accepted geoprocessing and modelling platforms.

These criteria are complied with throughout the study, to reach the objectives of the strategic modelling.

[3] The conceptual is based on the framework proposed by Jonkman and Vrijling, 2008.

1.3. Research Objectives

In order to address the main research problem, several research objectives guided by criteria of strategic modelling are expected to be achieved.

OBJ1: To further develop a strategic modelling framework for victim estimation in a flood, with improved comprehensibility and adaptability. In this framework, relations between flooding and evacuation processes are clarified; modelling linking relations are highly adaptive to each other.

Sub-objective 1.1: The development of a conceptual model clearly specifying the relations between impacts of flood, evacuation process and mortality. It also indicates primary input/output relations. This conceptual model is based on Jonkman and Vrijling's work (2008), whereas it will be improved by clarifying relations between the 3 major concepts proposed (S. N. Jonkman, Vrijling, et al., 2008) and complete lists of variables/parameters for each modelling module.

Sub-objective 1.2: A GIS based evacuation model consisting of three interconnected modules: evacuation demand generation, evacuation supply generation, evacuation routing/ time estimation. Each of these modules is sufficiently clarified about how it dynamically utilizes the results of flood simulation (water characteristics). For the sake of comprehensibility, this evacuation model would take a balance between simplicity of the algorithm and approximation of the complex reality. A semi-dynamic time-sliced approach may be adopted. This semi-dynamic approach is an alternative to existing evacuation modelling in risk assessment. It might have constraints like lower ability in dynamic modelling comparing to regularly applied Dynamic Traffic Assignment (DTA) algorithm. But it is supposed to improve the comprehensibility and adaptability of modelling, because it has engaged the impacts of floods to evacuation by constructing 2 independent modules in GIS. Moreover, by carrying out such a routing algorithm, routing for each time instant is fully controlled and configurable.

Sub-objective 1.3: A computational model and accordingly data structure for exposure and victim estimation for each spatial analytical unit (raster grid or neighbourhood, depending on analytical resolution) in the study area.

OBJ2: To estimate victims of one proposed flood scenario by applying developed estimation modelling framework in the study area: Land van Maas en Waal.

Sub-objective 2.1: Visualization (charts, maps, animations and web applications) of victim distribution in study area. Maps and animations are to be generated to visualize the processes of flooding, evacuation and the final results of victim estimation. Web-based GIS applications are proposed to be possibly generated to promote the public awareness of flood risk and facilitate feedback-engaged modelling processes.

1.4. Research Questions

Research questions are all related to sub-objectives and grouped under the same topic.

Q1. What are the major functions/outputs of models (representation of flooding simulation results, evacuation model, exposure and victim estimation model)? **(Sub-OBJ 1.1)**

Q2. What variables/parameters should be specified for each model? How to define these variables? What data is required according to model specification and what are proper methods for data processing? **(Sub-OBJ 1.1)**

Q3. How to specify and formulate linkages between major concepts by spatial/mathematical relations? (Water characteristics → Demand/Supply of evacuation; Time available/needed for evacuation → Exposure estimation; Water characteristics → mortality level, etc.) **(Sub-OBJ 1.1, 1.2, 1.3)**

Q4. What kinds of human behaviour for evacuation in a flood scenario might happen? How to generate evacuation scenarios based on assumptions about human behaviour? In which way an evacuation scenario would be formulated and adapted to evacuation modelling? **(Sub-OBJ 1.2)**

Q5. How many people need to be warned and evacuated and where are these people? What are people's departing behaviours over time under particular flooding scenario (departure curve over time)? Through which transport mode(s) the residents would be evacuated? How to generate the remained road network available for evacuation considering partition of the network is inundated by certain depth of water? What is the threshold of least flooding level (described by water characteristics) to disable a road segments? How to specify in space the safe area and exits for evacuation? **(Sub-OBJ 1.2)**

Q6. What are the evacuation routing methods in different evacuation scenarios? How to optimize evacuation routes by taking road capacity and congestion level into account? **(Sub-OBJ 1.2)**

Q7. How many people are exposed to the proposed flood? What is the number of fatalities in this flood? What is the spatial distribution of victims? Which areas in the study area suffered more above average level and thus more prone to flood threatens? What is are the major cause(s) for high number of victims? **(Sub-OBJ 2.1)**

1.5. Anticipated Results

Based on framing of research problem, objectives and existing study of flood risk assessment (S. N. Jonkman, Kok, et al., 2008; Maaskant, et al., 2009; Rijkswaterstaat, 2006), flood consequences (e.g. victims) are determined by both flood characteristics and people's actions. Characteristics of the flood in this study is basically taken directly as inputs resulting from existing flood models, hence is not the focus of this study. Rather, this study is diving deep into the relations between water characteristics and evacuation process, and to unfold the complicated black box of evacuation simulation by setting up a GIS-based model. In FLORIS (Rijkswaterstaat, 2006) project, a comprehensive framework of consequences was adopted by appraisal of economic, human-life, natural and environmental losses. However, due to time and resource limitation, this study is going to focus on loss of human-life (victims) for which a conceptual model linking flooding simulation and evacuation modelling has been developed as illustrated in Figure.

The general framework of risk evaluation for this study is based on Jonkman and Vrijling's proposal (2008), but with elaborated linkages between flood and evacuation modelling, which is demonstrated as in Figure 1-4. According to this conceptual model, **a clarified modelling framework and procedures that links flood simulation results with a GIS-based evacuation model, related modelling documentations and programs, maps and animations visualizing distributions of victims depending on one flood scenario,** would be major results of the study. Afterwards, highly-suffering areas could be detected for further analysis and mitigation recommendations. Meanwhile, as procedural outputs, flooding characteristics, evacuation routing and timing, evacuated people distribution are expected to be generated, these subsidiary outputs are supposed to enhance understanding of flooding nature and evacuation processes.

1.6. Research Design

1.6.1. Research framework and general approach

Based on the existing general approach for victim estimation proposed by Jonkman and Vrijling (2008), an elaborated research framework including anticipated results, major processes and models involved and general data requirements is developed. The whole research is divided into six phases: **research initiation**,

linked modelling, **victim estimation**, **visualization and analysis**, **finalization**. Detailed tasks in each phase are elaborated in Figure 1-5.

As illustrated in Figure 1-5, first, the research essentials including research problems, objectives, questions and research design are explained in the initiation phase. Second, in the linked modelling phase, then data and models necessary for flood scenario simulation and evacuation modelling are collected and prepared, which is followed by formulation of an evacuation scenario tree with help of intensive literature studies and expert consultation. Evacuation modelling is performed by subsequently setting up demand and supply generation modules by linking flood characteristics with demographic and transportation data, and then use dynamic demand and supply of evacuation generated, with specified routing algorithms (shortest path or CASPER) to generate evacuation route, cost and road congestion statistics which would be further utilized in exposure estimation in the third phase. Third, victim estimation results would be mapped and visualized in ArcGIS and the spatial pattern of victim distributions in study areas would be analysed. Finally, conclusions about the case study and discussions about methodology development are drawn succeeded by summarizing of whole research process and thesis composing.

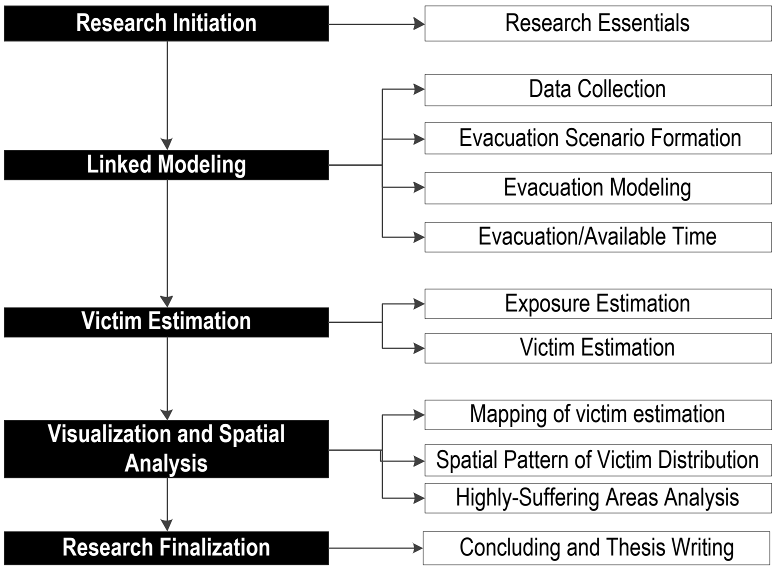

Figure 1-5 General Research Phasing

1.6.2. Data Collection Scheme

Types of data needed, data properties and collection methods following the research framework are specified in Table 1-1. Further data organization and processing are elaborated in Chapter 4: Data collection and processing.

Table 1-1 Necessary Data and Collection Methods

Analysis	Dataset	Data	Format	Resolution	Collection Methods
Generic	Study Area	Administrative boundary at neighbourhood (Dutch: Buurt) level in Land van Maas en Waal	V	Neighbourhood (Buurt), XY coordinates	Already in hand

Flood Modelling	Flooding Scenario Profiles	Proposed Breach location and hydrological conditions, etc.	Doc[4]	N/A	Provided by key contacts[5]
	Water characteristics (dynamic)	Water Depth (t) Velocity (t) Rising Rate (t) Impulse (t)	V/R[6]	Maximum grid size of raster dataset (75m * 75m) Temporal: hour	Provided by key contacts
	Water characteristics (maximum)	Water Depth (max) Velocity (max) Rising Rate (max) Impulse (max)	R		
		Time to flooding	R		
Evacuation Modelling	Demographic	Population	T[7]	Neighbourhood	Retrieved from CBS database (2007)
		Average Family Size			
		Age structure of population			
	Transportation	Road Network (Road Types, Free Driving Speed, Driving Directions, etc.)	V	XY coordinates From Highways to residential and countryside roads	Retrieved from open-sourced data (Open street Map)
					Verified by comparing to Google Street View and Dutch conventions

1.6.3. Research Methods

1.6.3.1. Scenario Development

Expert consulting and literature study are the major methods to be applied to formulate evacuation scenarios. These methods were also ever employed in FLORIS (Rijkswaterstaat, 2006) project and related studies in dike-ring areas in the Netherlands (S. N. Jonkman, Kok, et al., 2008; Maaskant, et al., 2009). Given limited knowledge and empirical data about evacuation events, in addition to extensive literature review, experts in transportation modelling and urban management (e.g. ITC staff in UPM) would be supposedly consulted to provide insights in human behaviour under flooding situations.

1.6.3.2. Representation of Flooding Process

To represent the dynamics of flooding process, both static and dynamic approaches are used. First, since the datasets of water characteristics listed in Table 1-1 are directly adopted as outputs of existing flood simulation, these datasets are visualized by regular thematic maps in GIS. Second, for describing the dynamic process of flooding over time, hourly datasets of prevailing water characteristics are organized in Geodatabase as "Raster Catalog" linked with time properties upon which animations showing the dynamic flood processes over time could be visualized using temporal GIS technologies.

[4] Doc: Documentations of flood simulation, in forms of PDF files or web pages.
[5] Key contacts would be water management experts like staff at water management department, ITC.
[6] V: Vector format (ESRI Shape or Geodatabase features.); R: Raster format (*.img, *.asc, etc.). All Geo-information data used in this study is projected by the Dutch national projection system: RD-New (GCS: Amersfoort).
[7] T: tabular dataset (MS Excel files or SPSS data files).

1.6.3.3. Evacuation Modelling

Given water characteristics of simulated floods as results of modelling, integrated **GIS spatial analysis** and a **GIS-based evacuation model** is applied to simulate people's responses under certain flooding situations. Specifically, typical geoprocessing tools like overlay and intersection are used to integrate outputs of flood model (water depth) with demographic and road network data to prepare basic inputs for evacuation modelling (population at risk, network available, exit choices, etc.). A GIS-based evacuation model would take advantages of Network Analyst Toolbox of ArcGIS and related routing optimization algorithms (CCRP and CASPER) which aims at enhancing evacuation modelling with optimality, applicability, scalability and enforceability (Shahabi, 2012).

Various data and information are required to perform evacuation simulation. First, dynamic evacuation demand is derived out of both spatial distribution of people who are affected by proposed floods and departure of evacuees over time. This information would be generated by one module of the evacuation model, the **evacuation demand module**. Second, road network and exits available for evacuation would be influenced dynamically by expanding inundation; hence its changing properties, particularly their availabilities are generated with relation to expansion of floods in **evacuation supply module**. Third, evacuation routing algorithms are specified according to scenario profiles using third-party ArcGIS extension, ArcCASPER (Shahabi, 2012), then routing algorithms are utilized by network analysis of ArcGIS to generate evacuation routes and times (as travel cost) from departure places (usually assumed as residential areas) to destinations (exists).

Important assumptions about human behaviour and road traffic behaviour are made before setting up the model. Assumptions of human behaviour include logistic-form departure pattern, solo travel mode and exit choices, shortest routing and awareness of road congestions. All assumptions are derived from literature review or expert consultancy. What needs to be noticed is that high level of uncertainty about evacuation processes (e.g. level of organization) needs to be engaged in scenario profiles with which a conditional probability of occurrence of the scenario based on studies of similar cases is attached. Further, assumptions of traffic behaviour include ignorance of delays at crossing, discontinuous road conditions over time periods are made.

1.6.3.4. Exposure and Victim Estimation

In order to estimate the population exposed on evacuation routes, namely "En-route exposure", different from existing methods applied that imply assumptions that proportion of population exposed in flood is linearly correlated to the difference between time available and time needed for evacuation, this study innovate a new algorithm to interactively inspect the temporal-spatial relations between moving evacuees and advancing floods and then identify potential location and time of en-route exposure. To implement this algorithm, a new spatial-temporal enabled data structure called: Evacuation Milepost Series (EMS) is constructed based upon outputs of evacuation model. This approach is carried out by coupled modelling between GIS and MatLab. In addition, optionally, effects of sheltering and rescuing in exposure estimation could be considered.

Referred to existing works (S. N. Jonkman, Lentz, & Vrijling, 2010; S. N. Jonkman, van Gelder, & Vrijling, 2003), victims of floods are estimated by **multiplying people exposed with mortality rate which is modelled as a function of water characteristics** (water depth, velocity, rising rate, etc.) calibrated by history data. Given no field data collection, mortality function adopted in this study would be specified by literature review.

1.7. Structure of Thesis

Chapter 1: Research proposal
This chapter gives a brief introduction over essential issues of the study, including background introduction, research problems, objectives, questions, anticipated results and general design of research (framework, data and methods).

Chapter 2: Literature review
A thorough study of existing literatures in three related fields: victim estimation and evacuation modelling. The evolution of major methods and modelling approaches, their pros and cons are reviewed. By the end of this chapter, concluding remarks are drawn based on literature evaluations. These remarks provide insights and hints for methodology development in Chapter 3.

Chapter 3: Methodology
Including general introduction of the modelling framework, organization of major modelling components (modules) and detailed descriptions about each module including assumptions, input/output relations, definitions of important variables and parameters, schematic or mathematical description of essential methods or algorithms (e.g. CASPER routing, EMS and En-route exposure simulation). By the end of this chapter, definitions and specifications of 4 scenarios are clarified showing assumptions about human behaviours in different situations.

Chapter 4: Data collection and processing
Types of data required in this study (Data of flooding simulation, transportation data and demographic data) are listed and described. The workflows for data processing and ways in which datasets are organized (Geodatabase) are explained.

Chapter 5: Linked Flooding-Evacuation Modelling
This chapter demonstrates the implementation of the designed modelling modules (evacuation supply, demand and routing) from Chapter 3 in the case study area. Results of modelling and analyses, including dynamic network and exits availability, population composition in evacuation participation and departure, departure pattern in time, evacuation performance analyses are demonstrated by tables, charts and maps. At the end of the chapter, there are conclusions about evacuation modelling in study area and discussions about model applications.

Chapter 6: Exposure and victim estimation
This chapter exhibits how to generate the primary results of this study: exposed population (home-based and en-route) and victims. Estimation results are displayed in forms of charts, tables and maps. Then spatial patterns of victim distribution are explored using spatial statistics. Similar with the previous chapter, at the end conclusions and discussions are stated.

Chapter 7: Conclusion and discussion
The final chapter gives a summary for the whole study, including important conclusions from the case study, and detailed discussions of methodology development (review of the objective "comprehensibility", model evaluation, model functions, limitations and future improvements).

Appendix
The appendix includes repository of modelling documentations, including geoprocessing model, snapshots of data organizations, MatLab script codes.

2. LITERATURE REVIEW

According to research scope and objectives, this chapter is organized in the following structure. First, the central issue of this research, methods for victim estimation in a flood is reviewed, primarily based on the work of Jonkman et al. (2008). Third, as a strategic linked flood simulation – evacuation modeling framework being the main objective of the study, an extensive review of the models and methods applied in evacuation modeling, specifically in emergency and hazard settings, from the early ones firstly developed in 1980s up to the latest, is carried out. General framework of evacuation modeling, and the major three modeling phases: travel demand, trip generation and traffic assignment that are derived from the classical framework of transportation modeling, are carefully discussed. In addition, discussions about pros and cons of different methods and models in each of these phases are included. Finally, remarks summarized to indicate possible insights from literature studies for this MSc study are presented in the conclusion section.

2.1. Victim Estimation

Since estimation of victims in floods is the central topic of this MSc study, it is necessary to take review of existing studies in this field, particularly about the methods used in the victim estimation in coastal/river floods which is typical with the Dutch cases.

2.1.1. Methods developed for coastal/river floods

2.1.1.1. General Approach

It is concluded by Jonkman and Vrijling(2008) that from 1980s, several studies have been conducted for the coastal/river induced floods which are relatively more likely to happen in the Netherlands. Most of these studies have adopted an empirical inductive approach, by primarily relying on fatality data recorded in historical flood events. For example, several studies have used the fatality data of 1953 North Sea storm surge flood that severely hit South-western Netherlands for developing methods of victim estimation (Duiser, 1989; S. Jonkman, 2001; Vrouwenvelder & Steenhuis, 1997; Waarts, 1992a). Zhai et al. (2007) used the data of historical floods in Japan for coastal/river flood risk evaluation. Since number of victims in floods is a component of flood risk, it is related to both hazard level and vulnerability of people at risk. Existing studies have included both hazard factors, the most typical of which is flood characteristics (e.g. water depth, velocity, rising rate, etc.), some other indirect hazard impacts like building collapsing. The side of vulnerability, aspects including people's instability, chances to be sheltered or to be evacuated, have been considered (S. N. Jonkman, Vrijling, et al., 2008).

2.1.1.2. Existing Studies

Duiser (1989) was the first one taking advantage of the data the 1953 flood. In order to estimate the number of victims in a coastal/river flood, Duiser proposed a model which described the victim amount as a function of water depth. Later, Waarts (1992a) used the same set of historical data and improved Duiser's model by adding more data. Another remark of Waarts's work (Waarts, 1992b) was specified estimation based on three categorized flooding zones: 1) Rapidly Rising Waters; 2) High flow velocities; 3) Remaining Zone. From statistics about the number of victims in three zones, it was discovered by Waarts(Waarts, 1992b) that fast rising water has much significant influence for loss of life in floods. Later, similar zonal estimation approach was developed based on Waarts's findings (S. N. Jonkman, Vrijling, et al., 2008).

Duiser (1989) and Waarts (1992a) only included one characteristic of the flood: water depth in the general model, which cannot reflect the importance of other flood attributes on conditions that rapid rising water has been statistically proved as crucial for hazardous consequences. Therefore, later Vrouwenvelder and Steenhuis (1997), also Jonkman (2008), further extended the general model by incorporating the water rising rate variable. Besides the mortality-function mainly considering hazard side, Vrouwenvelder and Steenhuis for the first time take wider range of aspects, including fraction of building collapsed, extreme high death rate caused at the breach area, positive effects of evacuation and other factors. Obviously, comparing to Duiser's and Waarts's simplified hydrologic-based model, Vrouwenvelder and Steenhuis's extended model has been more comprehensive. However, for the new variables added, for example, effects of evacuation and collapsed houses, there was basically no relative data ever being recorded. So, parameters about these factors were derived from expert knowledge rather than historical data.

Then, based on previous work, Jonkman (2001) proposed a model for coastal/river flood in the Netherlands. It described the number of victims as a function of water depth, velocity and effects of evacuation. However, different from previous studies for merging effects of different flood characteristics, Jonkman considered effects of water depth and water velocity upon mortality separately. Therefore, two mortality functions were applied for victim estimation (S. Jonkman, 2001). For velocity-induced mortality, the function relied on existing studies about people's instability in fast-flowing water while the effects of water depth for mortality was still described by the general model of Duiser (1989). Also, in this model (S. Jonkman, 2001), the probability of evacuation was applied for reducing population at risk, which could be seen as inherited from Vrouwenvelder and Steenhuis's model (Vrouwenvelder & Steenhuis, 1997).

There were several studies dedicated of floods in other places that were reviewed. Somehow they have adopted different methods for victim estimation in coastal/river floods from those adopted in the Netherlands. For instance, Zhai et al. (2007) built a relation between number of victims and the number of house inundated, by analysing flood data in Japan. However, Zhai's method was criticized (S. N. Jonkman, Vrijling, et al., 2008) for its lack of engagement of other possibly important determinants of fatalities (flood characteristics, warning, evacuation and houses collapsed instead of inundated), hence resulting in a less robust estimation.

All the studies discussed above were directly or indirectly based on analysis of historical records. As a result, these approaches, particularly selection of variables may be restricted by availability of empirical data. Some new studies for UK cases (Ramsbottom, Floyd, & Penning-Rowsell, 2003; Ramsbottom et al., 2004) , summarized by Jonkman (2008), adopted new methods for modeling, including expert consulting and laboratory experiments on human instability and the effects of debris.

2.1.1.3. Modeling Characteristics, Merits and Limitations

The main characteristics of existing models reviewed are summarized in Table 2-1.

Table 2-1 Overview of Existing Models for Victim Estimation (Coastal/River Floods)[8]

Models	Data basis	Factors engaged in models					
		Water Depth	Velocity	Rate of rising	Warning & Evacuation	Building Collapsing	Others
Duiser (1989)	River/Coastal	■					

[8] Source: Jonkman, 2008.

Waarts (1992a)	Floods in the Netherlands (1953, etc.)	■	■	■	■	■	
Vrouwenvelder and Steenhuis (1997)		■		■			
Jonkman (2001)		■	■		■		
Zhai et al. (2007)	Floods in Japan					■	
Ramsbottom et al. (2003; 2004)	Experiment over instability, Expert knowledge	■	■	■	■	■	Population vulnerability (Instability)

From the table above, it is obvious that most of existing models still based on historical data analysis. Concerning for factors being taken into account, water depth is the most popular one possibly because it has been always recorded in historical data. For some studies (Ramsbottom, et al., 2003; Ramsbottom, et al., 2004; Waarts, 1992a) in which extensive factors are engaged, some level of qualitative methods, like expert consulting may be needed. However, this increased modeling complexity on another side might reduce the reliability of estimation results since the results might be in large variation, particularly while an agreement of experts on parameter settings is difficult to reach.

Jonkman (2008) pointed out several limitations of existing methods and models for victim estimation:

- Due to strong dependence on historical data, many existing methods are quite specific for certain type of flood or region, which makes it less appealing for application in other areas.
- Limited factors have been involved.
- In some models, verification and calibration largely depend on expert knowledge which may lack a sufficient empirical basis.

The estimation results by existing methods seem not to be robust because results for the same area and flood event are not comparable. By performing an evaluation over several methods with an identical set of data, large variation in estimation results[9] (S. Jonkman, Van Gelder, & Vrijling, 2002).

2.1.2. A New Method (Jonkman, 2008)

A new method for victim estimation was proposed by Jonkman (2008) for victim estimation in a more generic way. This method has inherited merits from the existing methods proposed beforehand, particularly those within a Dutch context (Duiser, 1989; S. Jonkman, 2001; Vrouwenvelder & Steenhuis, 1997; Waarts, 1992a). It includes a comprehensive set of determinants for victim estimation based on wide-ranging literature review, and then proposed a process-based framework for modeling which was acclaimed to be adaptive for extended types of floods (S. N. Jonkman, Vrijling, et al., 2008). In this new method, Jonkman (2008) still adopted a classical reductionism method based on historical data analysis. The major two components for victim estimation: total population exposed in flood and mortality rate[10] are estimated respectively. Jonkman (2008) explained that the first component is calculated by a dedicated analysis of processes like evacuation, sheltering and rescue. A dynamic evacuation model (van Zuilekom & Zuidgeest, 2008) was incorporated to calculate effects of evacuation. For the essential mortality rate, Waarts's zonal estimation (Waarts, 1992a) was used and adapted with an extensive pool of historical flood event data set collected from either official records or literature studies. As a result, mortality functions for

[9] For example, estimation for a case study in the Netherlands ranges from 72 to 88,000 victims.
[10] Mortality rate refers the share of total population being exposed in flood that is likely to die in a flood event. It is usually estimated based on probability approach (e.g. a probabilistic mortality rate function).

each of the three categorized flooding zones (breach zones, zones with rapidly rising water, remaining zones) were specified and calibrated.

Since this new method was more adaptive and flexible for different regions and flooding scenarios, it has been applied in different case studies and proved as effective for victim estimation (S. N. Jonkman, et al., 2011; S. N. Jonkman, Kok, et al., 2008; S. N. Jonkman, et al., 2010; S. N. Jonkman, Vrijling, et al., 2008; Maaskant, et al., 2009; Rijkswaterstaat, 2006). Therefore, it has been adopted as the primary method to be developed and applied in this MSc study. In the following sub-sections, essence of this method, including general framework, methods used and major modeling procedures are explained. More detailed discussion would be followed in the next chapter "Methodology".

2.1.2.1. Determinants for Victim Estimation

It is necessary to identify important determinants for victim estimation prior to actual modeling. A review about relative studies about determine factors in victim estimation was done to gain insights into factor selection of the new method (S.N. Jonkman, 2007). As a result, some commonly used determinants are identified:

- Possibility of prediction and early warning.
- Availability and performance of evacuation.
- Possibility for sheltering.
- Collapse of buildings.
- Water depth (the major hydrological factor considered in most studies, it is even more crucial for low-lying areas like the Netherlands)
- Combination of large water depth and rapid rising water has been proved hazardous by different studies.
- High flow velocity (leading to possible building collapse and instability of people, hence lowering possibilities of sheltering and evacuation).
- Demographic vulnerability of population (mainly for children, elderly and disabled people).

2.1.2.2. Proposed Modeling Framework

On the basis of factors identified Jonkman and Vrijling (2008) proposed a general framework for victim estimation which is schematically presented in Figure 2-1.

This framework, as illustrated, could be divided into three major steps:

1) **Flood simulation** including analysis of water characteristics (depth, velocity, rising rate, time of arrival, etc.)
2) **Exposure estimation**. In this step, number of people exposed in flood is estimated by considering effects of warning, evacuation and sheltering[11].
3) **Victim estimation**. Based on the exposed people calculated in step 2 and the mortality function which could be characterized by flood attributes and effects of collapsed houses.

In short, the essence of the general framework could be represented by the formula below (S. N. Jonkman, Vrijling, et al., 2008).

[11] It is noted that in Jonkman and Vrijling's proposal (2008), the exposed population is taken as a whole entity as shown in formula(2.1.1). There is no evidence indicating a distinction between home-based exposure and en-route exposure.

$$N = F_D N_{\exp} \tag{2.1.1}$$

In formula(2.1.1), N is the number of victims estimated for the study area, F_D is the mortality rate which is defined as the proportion of people at risk died in floods. The variable $N_{\exp}$ is the number of people estimated being exposed to flood.

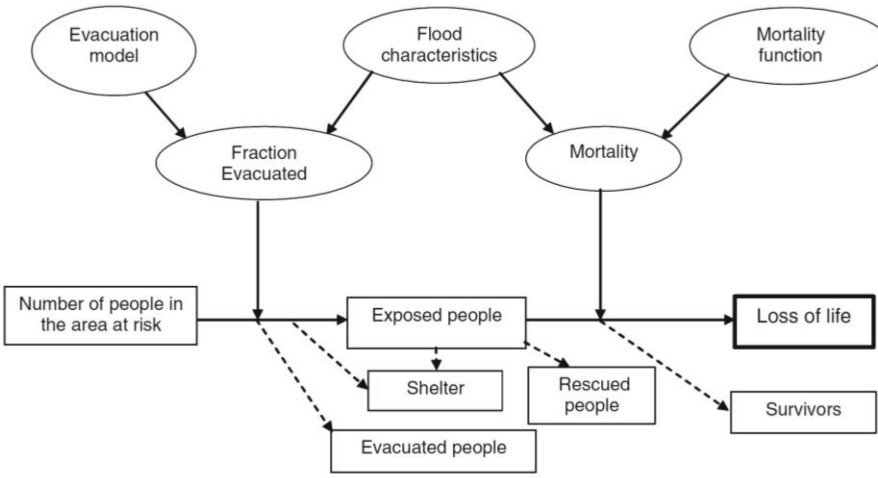

Figure 2-1 General framework for victim estimation in floods[12]

2.1.2.3. Exposure Analysis

To estimate the people exposed to flood, a process-based approach has been developed. As shown the general framework in the figure above, the people exposed to flood are supposed to be the remnant of people considered at risk after subtracting population evacuated, sheltered and rescued, which is described by the formula below (S. N. Jonkman, Vrijling, et al., 2008).

$$N_{\exp} = N_{PAR} \cdot (1 - F_E) \cdot (1 - F_S) - N_{res} \tag{2.1.2}$$

In Formula(2.1.2), number of people at risk N_{PAR} is estimated as all population registered in the area that would be flooded. Fraction of people evacuated (F_E) is estimated by applying a dynamic evacuation model (van Zuilekom & Zuidgeest, 2008) in which the time available for evacuation and the time needed to evacuate a region is compared. Fraction F_E is assumed as proportionate to the difference of the two time variables. For sheltering factor, it is assumed for the Dutch context that fraction of people not evacuated who can managed to find a shelter is ranging between 0 in rural areas and 0.2 in urban areas (S. N. Jonkman, Kok, et al., 2008; S. N. Jonkman, Vrijling, et al., 2008). For the effects of rescue (N_{res}), the detailed method for estimation wasn't clearly explained.

2.1.2.4. Mortality Estimation

The other important aspect of victim estimation, as suggested in the general framework, is the estimation of mortality function. Mainly based on Waarts's study (Waarts, 1992a) about zonal specification for mortality function, Jonkman et al. (2008) proposed an approach for specified mortality function estimation based on mainly water characteristics by derivation from historical data.

Three flooding zone types with mortality functions are specified as:

---

[12] Source: Jonkman et al. 2008.

1) **Breach zones:** zones near the breach (real or proposed) with high flow velocity that will cause high possibility of house collapsing and human instability (S. N. Jonkman, Vrijling, et al., 2008). Based on prior study about relation between house collapsing and flow conditions (Clausen, 1989, referred by Jonkan et al. 2008), Jonkman et al. (2008) adopted the criterion below to define the breach zones. By assuming that people within breach zones have no time for evacuation or finding a shelter, as they are all supposed to stay indoor while the house collapsed. So the mortality function is set as below.

$$hv \geq 7 \text{ m}^2/\text{s} \quad \text{and} \quad v \geq 2 \text{ m/s} \tag{2.1.3}$$

$$F_D = 1 \tag{2.1.4}$$

2) **Zones with rapid rising water**: based on victim data available for the flood in the Netherlands in 1953 (12 locations) and the flood in UK in 1953 (1 location), the criterion for zone with rapid water rising definition and the mortality function estimated[13] are shown below. It is declared that this function has a good fitting with the historical data in the Netherlands and the UK ($R^2 = 0.76$) (S. N. Jonkman, Vrijling, et al., 2008).

$$rr \geq 0.5 \text{ m/h} \ \ (rr: \text{ rising rate}) \tag{2.1.5}$$

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \tag{2.1.6}$$

$$\mu_N = 1.46 \quad \sigma_N = 0.28$$

3) **Remaining zones**: remaining zones is distinguished as the area outside breach zone and zones with rapid water rising (S. N. Jonkman, Vrijling, et al., 2008). Jonkman listed possible reasons for fatalities in this slow-flowing area, including no sheltering or those death from health conditions triggered by extended stay in sheltering (S. N. Jonkman, Vrijling, et al., 2008). Based on historical data in Japan, the Netherlands, UK and the US, a mortality function with the same log-normal distribution (LND) assumption as the previous one was estimated, with weak fitting to observed data[14].

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \tag{2.1.7}$$

$$\mu_N = 7.6 \quad \sigma_N = 2.75$$

2.2. Evacuation Modeling

First of all, as Jonkman (2010) highlighted, effects of evacuation, sheltering and rescue need to be taken into account for estimating people exposed at risk (exposure estimation) which is generally considered as the essential component for victim estimation in a flood. It is therefore necessary to conduct an intensive review about the evacuation studies, concerning both models and approaches already developed and applied. Second, as existing review studies (S. N. Jonkman, et al., 2010; S. N. Jonkman, et al., 2003; S. N. Jonkman, Vrijling, et al., 2008) about the victim estimation and risk assessment have not yet gone through an intensive review about existing evacuation modeling field for its extensiveness, there is less discussion

[13] It is assumed that the differential of mortality follow a log-normal distribution over water depth in the zones with rapid rising water. Thus, the mortality could be calculated by the cumulative distribution function (CDF) of normal distribution, with logarithm of water depth (h) as the independent variable.

[14] The weak correlation might be caused by outliers in the extended dataset (Jonkman, et al. 2008).

and insights about how to adapt existing modeling approaches into a specific framework for victim estimation in a flood. In addition to that, guided by the objective of this study, a review of evacuation modeling would also provide valuable insights into design of a strategic modeling framework linking flood simulation and evacuation modeling together.

2.2.1. General Framework of Evacuation Modelling

Facing with all kinds of natural and man-made hazards, human society is taking actions. Mass-scale evacuation has ever been a major strategy and it seems to be more and more challenging to achieve a nice evacuation since the rapid social-economic growth over the relatively lagged infrastructure development and public services provision, particularly at urbanized areas (Adam J. Pel, Bliemer, & Hoogendoorn, 2012).

The value of a successful evacuation in decreasing hazard risk to the largest extent is obvious. Therefore, the performance of an evacuation needs to be evaluated. To evaluate the performance of an evacuation, important determine factors are identified (Dash & Gladwin, 2007; Lindell & Prater, 2007), including time for warning process, response time, information for evacuees, instruction delivering procedures, evacuation exits/destination assignment, evacuation routes, traffic control measures, etc. All different factors collectively formulate a complex image which in result entails an exquisite “glass”, as tool for exploration. In realm of evacuation studies, this magic glass could be improved modeling tools and methods. This requirement for better models has triggered different studies (Barrett, Ran, & Pillai, 2000; Hardy, 2010). And as result, these efforts lead to a consistent road to a general framework for evacuation modeling.

By a thorough review of developed evacuation models, Pel et al. (2012) proposes a typical framework for dynamic evacuation modeling which is comparable to classical four-step transportation models, as shown in Figure 2-2.

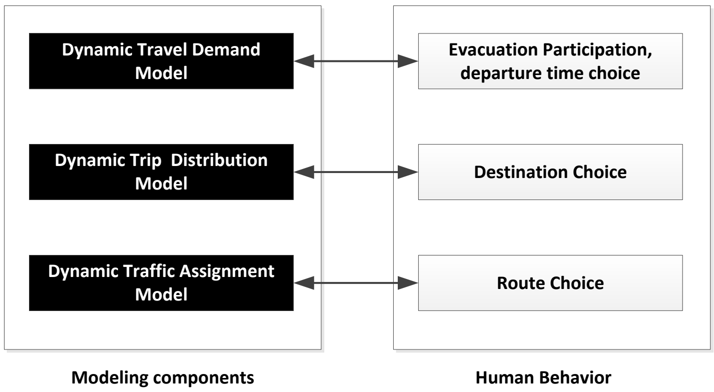

Figure 2-2 General Framework for Dynamic Evacuation Modeling[15]

This framework consists of two counterparts: modeling components and corresponding human behaviours. It is organized in a sequential way. First, to simulate people’s participation into the process of evacuation and their departure temporal pattern, a dynamic travel demand model is set up basically to answer the question: how many people will depart and start evacuating at what time. Second, once departed from their original places, evacuees choose the destination by location types and evacuees’ preferences. Accordingly, a trip distribution is performed to simulate people’s destination choice and propagate an origin-destination matrix (OD Matrix). Typically, a gravity model is applied. However, it should be noted that not in all cases a trip distribution model is indispensable (Adam J. Pel, et al., 2012).

[15] Source: Pel et al., 2012, re-drawn by the author.

Exemptions will be discussed below. Third, it is up to the evacuees who would choose the optimal route getting themselves out of the danger. A traffic assignment model is performed to distribute traffic volume along the network. Then important indicators concerning the traffic conditions are generated, such as Volume-Capacity Ratio, congestion level, clearance time, etc. and the assignment algorithm is usually manipulated in an iterative or incremental way so as to achieve certain optimization objectives, e.g. user equilibrium or system optimum.

The following review of existing evacuation studies follows the modeling framework, by firstly taking an overview of models and applications ever being developed for evacuation planning or simulation, then elaborating on these three phases shown in Figure 2-2 basically upon which most of the existing models have been established.

2.2.2. Overview of Existing Models and Applications

2.2.2.1. Model Developing Trends

The development of evacuation modeling is intertwined with social trends. That is, the modelling work have being always following the urgent social needs in different periods, from evacuation out of nuclear accident affected areas in Cold War Era, hurricane threats frequently hit in 1990s to terrorist attacks after September 11th, 2001. In the Netherlands, as increasingly threatened by rising sea level and inner flooding, more studies focus on fooling evacuation and risk assessment, like the studies discussed in the previous sections.

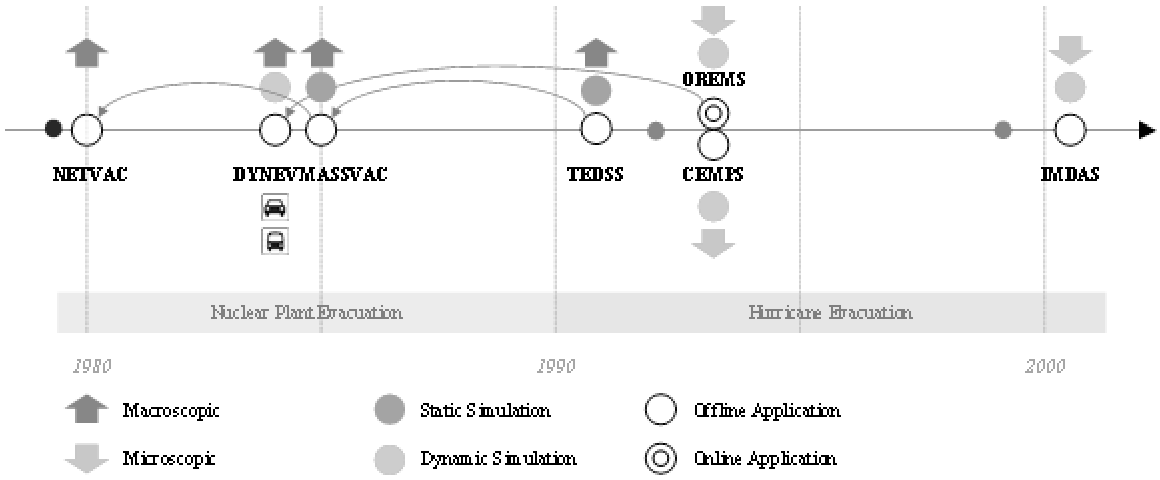

Figure 2-3 Characteristics of Modeling Development in 1980s and 1990s[16]

2.2.2.2. Characteristics of Existing Models

The main characteristics of existing evacuation modeling studies could be summarized following the general framework (Adam J. Pel, et al., 2012) in the previous section. They are listed as below:

- **Travel demand modeling**: either prescribed departure timing scheme or simulated departure curve was popular for estimation of dynamic travel demand.
- **Trip distribution modeling**: besides a predefined OD trip matrix directly from real data, probably the most frequently used model is still the classical gravity model, sometimes enhanced by traveller preference approaches.

[16] The figure is drawn by the author, based on comprehension and summary from Pel et al. 2012.

- **Traffic assignment modeling**: basically two ways of assignment are regularly adopted. For studies aiming at existing evacuation plan/measure evaluation, prescribed evacuation routes are accepted as inputs (Hobeika & Jamei, 1985; Rathi & Solanki, 1993), while in other optimization studies, route switching is enabled usually by dynamic traffic assignment algorithm under user equilibrium assumptions (Mitchell & Radwan, 2006; P. Murray-Tuite, 2007).
- **Network Conditions**: many studies have simplified the network conditions in the course of evacuation as being static; while remarkably as approximating towards reality, also some studies (Hobeika & Jamei, 1985) regard the network properties as dynamically being affected by moving of hazards, e.g. path of hurricane.

In the following sections, these major phases of modeling are further discussed, by elaborating primarily on the pros and cons of methods/approaches ever being adopted in existing studies.

2.2.3. Travel Demand Modelling

2.2.3.1. Demand Components and Estimation Approaches

Although, being the most studied part in evacuation modeling, the efforts about travel demand modeling are considerable, a simplified paradigm still could be figured out (Adam J. Pel, et al., 2012). The figure below shows the major model outputs and frequently applied two models, **Sequential Model** and **Simultaneous Model**. Primary components of demand modeling include the ratio of evacuees out of total residents (namely as evacuation participation share), and the departure pattern as the result of individual or household departure time choice. It should be noted that these two components are grounded upon basic assumptions about human behaviour under emergencies settings. First, due to a variety of reasons, it is not likely that all residents at risk of hazards will participate in evacuation. Hence the fraction of population participating in the progress should be estimated properly. Second, after making evacuation decision, not all evacuees depart from their homes, working places or any other origins. Instead, by constantly perceiving surrounded environments and evaluating leave/depart choices according their own household preferences, conditions and social interactions, evacuees make decisions of either instant departure or a postponed one. Therefore, it can be concluded that the travel demand model essentially answers the question: At each moment in the overall course of evacuation, how many people actually depart and start to evacuate to their destinations.

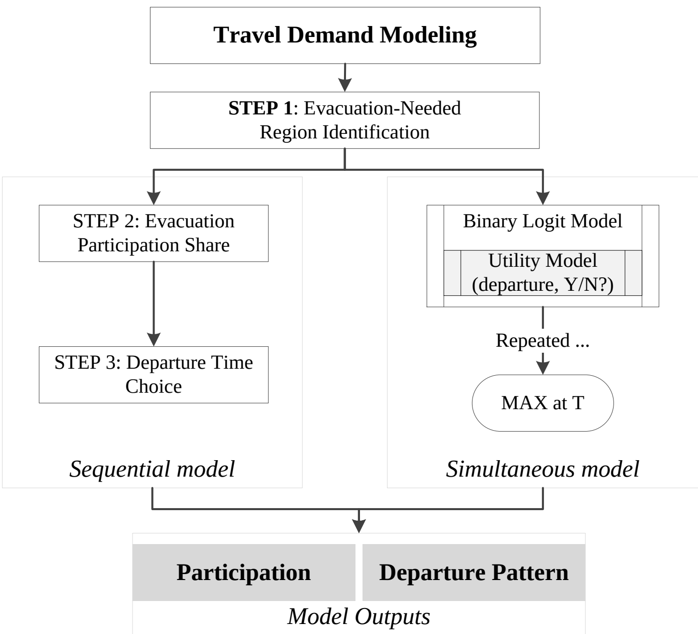

Figure 2-4 Modeling Approaches for Evacuation Travel Demand

First of all, it is usually the initial step of demand modeling that evacuation-needed regions are identified. Obviously, the regions to be evacuated are spatially determined by intensity of hazards effects. Therefore, simulated or observed characteristics of hazards (hurricane, floods, etc.) are adapted for evacuation-needed region identification. In order to develop methodology for evacuation zones delineation in hurricanes, Wilmot et al. (2005) used various hurricane attributes (size, velocity, tracks, etc.) to generate a synthesized flooding risk with varied levels to be assigned to each analytic zone. Then, different zones could be selected and engaged into demand estimation by setting cut-off values corresponding to specific scenarios. Usually, it is not technically difficult to perform region identification once the hazard dynamics is explicitly represented, since the spatial relation is relatively straightforward and easy to be modelled by GIS. However, Durham's study (2007) has suggested this seemingly simple causality might be more complicated than ever perceived, particularly if the so-called "shadow evacuation", the actual evacuation of regions at lower risk just because of misinterpretation or overestimation of threat level, is concerned. Durham argued the side effects of shadow evacuation need to be noticed as it might cause higher demand and overloaded traffic thus hindered those in need to evacuate (Durham, 2007). It is also discovered that shadow evacuation is more likely to take place in mass-evacuation. So evacuation plans containing large, densely populated areas may need to take this issue into account.

As stated, the major outputs in demand modeling include both demand components of participation share and departure pattern. There are usually two approaches: **sequential model** and **simultaneous model**, summarized by Pel et al. (2012) As the names of models suggest, the technical difference between the two models lies in modeling procedures, that is, whether estimations for two demand components are realized in a sequential order by two separated steps or are integrated by one model. Further, it can be argued that the two approaches are essentially different because the sequential method is based on inductive manner and an exogenous departure curve while the other one managed to incorporate the critical human behavioural factors to formulate an endogenous model with deductive philosophy. This point is further explained by following discussion of each approach.

2.2.3.2. Sequential Model

As mentioned above, sequential model addresses the issues of participation share and departure pattern separately. It is composed by two major sub-steps in sequence: 1) evacuation participation share estimation and 2) departure time choice simulation.

Baker (1991) first proposed five major determine factors for people's participation into evacuation after analysing real hurricane data set:

- Level of risk (objective)
- Actions taken by public authorities
- Type of Housing
- Prior perception of personal risk (subjective)
- Storm-specific threat factors

Although seems to be quite simple, Baker's factor set was quite influential for succeeding studies as it could be seen being repeated referred to and adopted for later modeling framework (PBS&J, 2000). Unfortunately, Baker did not build up a quantitative model facilitating participation estimation. Also, Baker's factor set was criticised because some correlated factors which in traditional reductionism modeling paradigm might undermine reliability of model parameters. Later the planning agency PBS&J (2000, referred by Pel et al. 2012) took efforts in developing a behaviour-based model backed by cross-classification trip generation in which four aspects of factors were engaged: hurricane type, hurricane speed, tourist-occupancy and housing typology. PBS&J's factors were more simplified, explicit and less overlapped with each other. Later Wilmot and Mei (2004) used the data collected at south-eastern Louisiana during hurricane Andrew to develop and calibrate a logistic regression model to estimate household's probability of evacuation. In addition, different types of neural network models, including feed-forward back-propagation network, probabilistic neural network (PNN) and learning vector quantizer (LVQ) were tested and compared in the same study for their capabilities of reproducing participating pattern. Wilmot and Mei's study (2004) showed these complex and data-intensive models were capable of fitting existing demand data pattern. These models were also criticized for their less comprehensibility, data-demanding calibration and less insights into evacuees' behaviours (Adam J. Pel, et al., 2012). Comparatively, the much simpler cross-classification model by PBS&J seems to be easier understood and more feasible especially for areas with less data available.

The objective of the final step of sequential model is to temporarily distribute evacuees in the course of evacuation, i.e. the departure pattern which is usually in sequential model characterized by a departure/response curve. Similar to participation estimation, Pel et al. (2012) argued the departure curve should be specific for zones in varied sequence being exposed to hazards. In terms of mathematical and geometric properties of the departure curve, different distributions, both linear and non-linear, have been used. Some studies (Chen & Zhan, 2008; Chiu, Villalobos, Gautam, & Zheng, 2006; Liu, Lai, & Chang, 2006) assumed the most simplified instant departure which implies all evacuees rush into the network at the very beginning of evacuation. This assumption might be the strictest one for departure pattern. Once it was made, there should be sufficient evidence to justify the rush at time 0. Yuan et al. (2006) then relaxed the rigid assumption of instant departure by a linear departure assumption. However, linear assumption is still often inconsistent with non-linear patterns observed in reality. Hence, it is further relaxed and several non-linear distribution were adopted by different studies, including Rayleigh distribution (Tweedie, Rowland, Walsh, Rhoten, & Hagle, 1986), Poisson distribution (Cova & Johnson, 2002) and Weibull distribution (S.N. Jonkman, 2007; Lindell, 2008). Despite of their better fitting with realistic pattern, these distributions still suffer less interpretability as the meanings of parameters of cumulative distribution function (CDF) are obscure and hard to be explained.

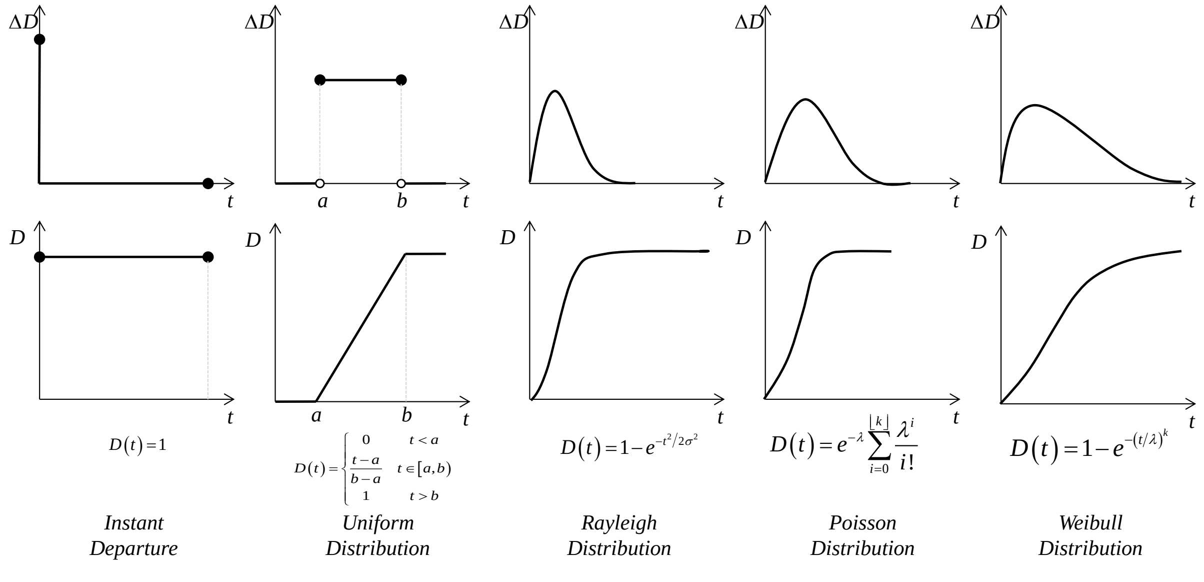

Figure 2-5 Frequently Used Distributions for Simulating Departure Curve

Probably the most favourable distribution used in demand modeling would be the Sigmoid Function or more known as logistic curve with an "S" shape which is defined by:

$$D(t)=\left(1+\exp\left[-\alpha(t-h)\right]\right)^{-1} \tag{2.2.1}$$

Where $D(t)$ is the cumulated departure percentage of evacuees at time instant t, α and h are major parameters to be calibrated, respectively named as response rate and half-loading time. It can be inferred the model is exogenous as no variables of human behaviour, hazards attributes or policy measures is ever involved.

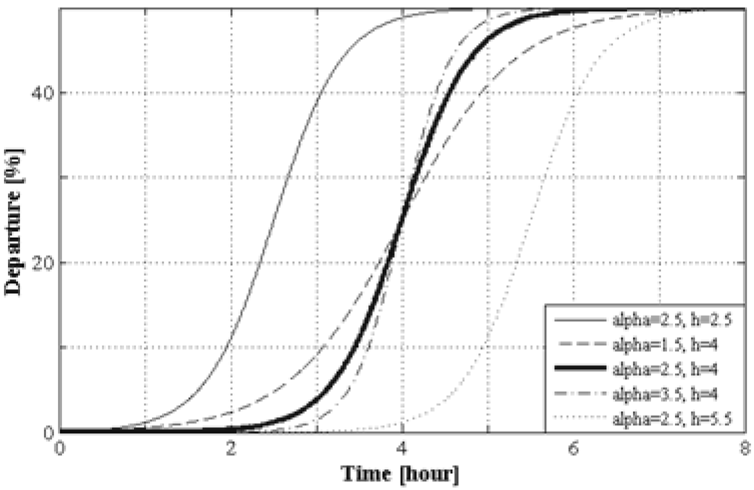

Figure 2-6 Logistic Curve with different Values of Parameters[17]

Different from other non-linear distributions, the two parameters in logistic curve, α and *h* have explicit practical meanings. By comparing shapes of curves with different values of α and *h*, it can be seen that a larger value for parameter α steepens the curve while increasing value of *h* shift the curve in parallel to the right. In fact, α or *h* respectively represents the response rate of people for departure, and the half-loading time by which 50% of participants would have departed and entered the evacuation network. The explicitness and simplicity of logistic curve have made it favourable for a number of applications (Kalafatas & Peeta, 2009; van Zuilekom & Zuidgeest, 2008; Xie, Lin, & Waller, 2010). However, even the two parameters need to be calibrated with caution as small change of response rate or half-loading time might cause considerable deviation in modeling results. Ozbay and Yazici (2006) conduct an intensive study to explore the effects of different response curves on evacuation modeling results, by simulating sensitivity analysis with a simplified version of Cape May County network, in New Jersey. They found out that changed response curve could lead to non-linear change in network performances. For example, given response rate unchanged, shorter or longer half-loading time may only change total clearance time, leaving average traveling time keeping the same. However, if the curve is "rotated" by an altered response rate, network performance may be non-linearly deteriorated by a positive feedback loop (high travel demand within short time → overburden roads far beyond capacity → lowering network performance). In conclusion, Ozbay and Yazici (2006) argued the use of response curve should not be taken as an assumption, but carefully verified, calibrated and validated.

Ozbay and Yazici (2006) also tried to explain the popularity of response curve in travel demand generation with some obvious reasons (Pros) listed below:

- Mathematical simplicity and explicitness
- Proved as capable to reproduce evacuation behaviour (Not by large-scale survey as Simultaneous model but with previous observation)
- Less data requirements
- Extensively mentioned in literature
- Official study endorsements

[17] Source: Pel et al. Pel, A. J., et al. (2012). A review on travel behaviour modelling in dynamic traffic simulation models for evacuations. *Transportation, 39*(1), 97-123., redrawn by the author.

On another hand, noticeable limitations also have stated for response curve (Fu & Wilmot, 2004; Ozbay & Yazici, 2006):

- It's not suitable for longer evacuation which might be lasting for days
- There is no possibility yet to model day-night variations
- As the lack of endogenous variable, response curve is not compatible for testing evacuation orders which might have significant influence on travel demand.
- As the response curve only estimates the proportion of departure, so prior to that, the total travel demand has to be modelled.
- Usually, as a typical top-down process, the design of response curve is largely based on expert knowledge, which is believed less incorporative for local knowledge.
- Being an exogenous model, response curve can't directly take hazard attributes into account (might get limited support from specification for different hazard affected zones, but need much more calibration efforts).

Therefore, for attempts to apply response curve in sequential model, those limitations mentioned above and the settings of the real case need to be carefully examined, to guarantee the validity of response curve.

2.2.3.3. Simultaneous Model

To address the limitations of the response curve, there have been quite a few efforts in an integrated modeling with an aim of estimating both demand components: participation share and departure time pattern at the same time, denoted by Simultaneous Model by Pel et al. (2012). This recently developed model basically consider the process prior to actual start of evacuation as a series of repeated binary decision-makings at each time instant: whether to depart and evacuate, or rather keep staying at where it is. The conceptual framework is illustrated by Pel et al. (2012) as shown in Figure 2-7.

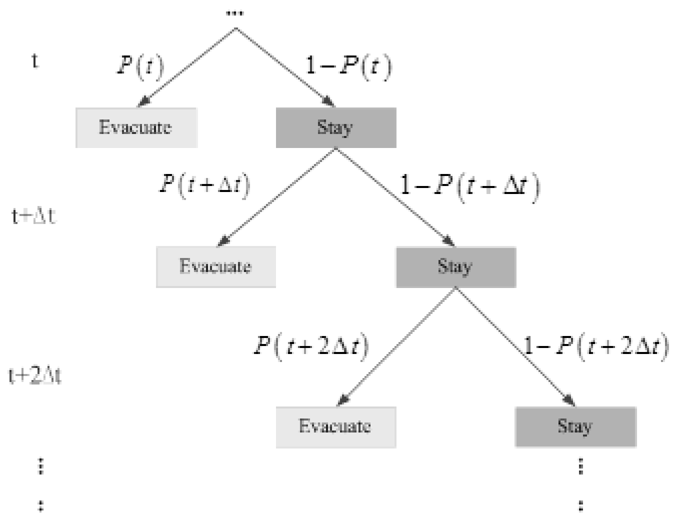

Figure 2-7 General Framework for repeated binary logit model[18]

In Figure 2-7, it is obvious to see that first, horizontally, at each time instant, decisions of either evacuation or further stay are exclusive events; second, vertically, it is assumed that decision between time instants are independent and also, the single-sided and one-directional connections between instants imply that once the decision of evacuation has been made, it cannot be reverted. A person deciding to evacuate at instant t must have been staying so far from the beginning.

[18] Source: Pel et al. 2012, re-drawn by the author.

A detailed description of simultaneous model is explained in Appendix A1: **Description of Simultaneous Evacuation Demand Model**.

Pel et al. (2012) pointed out some new insights into travel demand modeling for evacuation studies. First, in simulation of human-behaviour, most current approaches and models still maintained a rather static fashion which is deeply rooted in rationalism. It is always the prevailing conditions that served as the basis of utility evaluation and decision-making. It is argued that there is no good reason for people only considering current situations, without making decisions based on their observation, perception and estimation of instant, changing hazard conditions. Second, even in dynamic binary logit models which are dedicated for human mental process, it is still assumed that households or individuals are mutually independent. Though this assumption might be necessary for the estimation of repeated choice model with underlying independence requirements, it is not consistent with reality. Recent studies have confirmed this point. For instance, factors to be considered in utility modeling (Carnegie & Deka, 2010) also include the evacuation conditions of neighbours, which has suggested possibly significant interaction among neighbourhoods may to some extent affect household decisions process. Murray-Tuite and Mahmassani (P. M. Murray-Tuite & Mahmassani, 2003) put forward an evacuation simulation in which trip-chaining due to social interaction was explored. They suggest that incorporating social connections, e.g. social communications and information provision and exchange, will not only improve capability of explaining unusual trip pattern but also give rise to enhanced evacuation performance as results of route switching and en-route routing.

2.2.3.4. Model Comparison

Though comparing to the exogenous response curve, the simultaneous model obviously has more strengths. First, it is apparently much more adaptive for modeling the complexity in real world, like the diverse behavioural characteristics, dynamic hazard impacts simulation, evacuation instruction/orders incorporation and even social connections. Second, its excellent adaptability and expandability also make itself much easier to be transplanted to new areas where social, infrastructural, political environments might be totally different from previous cases. Third, random utility approach may leave more space for modeling uncertainties, so as to make model itself less sensitive and more robust.

However, the drawbacks of simultaneous model are also easily to identify. First of all, due to its mathematical complexity, for normal users, the learning curve might be much steeper than its alternative, which may undermine its wide applications. While the other one, with intuitive geometric vision, makes itself easily understood and interpreted. Second, there is no doubt that the simultaneous model is data-intensive, let along its complicated calibration and validation. Finally, there is no reliable evidence yet showing a superior capability of simultaneous model over sequential model in data fitting and predicting travel demand.

In conclusion, the efficiency and effectiveness of both models need to be evaluated according to the specific need of modelling task, and the availability and quality of key resources, e.g. data ever mentioned. For example, simultaneous model might be more suitable for dedicated evacuation simulation while for some integrated studies in which the evacuation model is served as only one module of the whole framework and the compatibility between models are much more crucial, it might be a good option to adopt sequential model to increase the overall comprehensibility and flexibility.

2.2.4. Trip Distribution Modelling

Basically, in trip distribution, evacuees' choice for destination is described. Comparing to travel demand modeling, there are significantly less studies devoting to this area. But, the existing studies generally use a common modeling procedure which consists of two major steps: first, the driving factors that determine the type of destination locations are identified; second, destinations are evaluated, selected and spatially related to origins where evacuation process starts, as a result, usually an OD matrix in which trips are distributed over the space is constructed. To perform the second model, always a gravity-based model is employed to describe the spatial relations between origin and destinations.

2.2.4.1. Factors for Destination Choice

Because from a microscopic perspective, the process of trip distribution could be accounted for an aggregation of many individual choice making processes which primarily rely on personal preferences. Thus, a few existing studies have used data collected by stated preference and revealed preference methods. Studies using post-hurricane data (Brodie, Weltzien, Altman, Blendon, & Benson, 2006; Whitehead et al., 2000) compared people's destination choices with their demographic status, and found out that people's income and education level may affect people's destination choice. Cuellar (2009) studied the people's relocation choices in specific area of US Golf Coast, and found that whether people will evacuate to their relatives other than other places will be determined by the whether family they want to go to belongs to the local dominant racial group. More recently, Deka (2010) performed analysis for the transportation-disadvantaged population in north New Jersey, using data from stated preference survey. Deka's study confirmed the social-demographic variations in the targeted population as the major factors affecting type of destination: either to shelters or non-shelters (friends, relatives, hotels, motels, etc.).

So it can be found from limited studies that social-demographic factors play an important role in destination decision making. However, it should be noted, due to the limited number of empirical studies and the narrow scope of existing ones (often for specific hazard, specific groups and areas), the generalization of the existing findings in other areas might not be appropriate.

2.2.4.2. Destination Choice Model

Once the destinations are selected by criteria which have contained effects of the factors discussed above, the next step is to build an OD matrix by assigning evacuees between their starting locations and chosen destinations.

Early in 1995, US Army Corp. of Engineers (UACE) has completed a manual book containing technical guidelines for hurricane evacuations (1995, referred by Pel et al. 2012). In this book, a gravity-based model was proposed for assign evacuees between origins and destinations. In this model, the amount of evacuees distributed between each pair of origin and destination is positively proportionate to population/participants at the origin, the receiving capacity of the destination, and negatively weighted by a distance function which describe the generalized cost to be encountered to reach the destinations. Most models developed in 1980s and 1990s also used this classical approach.

In a general gravity-based model, there is no distinction between destinations. However, as discussed in the previous sub-section as well, different types of destinations may not have the same attractions for different social-demographic groups. Empirical studies (Brodie, et al., 2006; Whitehead, et al., 2000) have found evidences in real hurricane evacuation cases. Therefore, there is need for location type specification and incorporation of behavioural inferences in destination choice modeling. Cheng (2007, In abstract) calibrated two sub models by differentiating types: friend/relative and hotel/motel. However, there was still no behavioural consideration in this approach. So later in 2008, a developed version was completed in which multinomial logit models were proposed and calibrated using the same set of data as the one ever used in 2007. In both sub-models, not surprisingly, travel distance and the risk of being threatened by hurricane have negative effects while population at the destination and the racial (White) percentage cast positive influences.

2.2.4.3. Discussion about Trip Distribution Modelling

From the literature review, a general framework for trip distribution in evacuation modeling could be summarized and illustrated as the figure below. Major steps include affecting factor identification, destination identification and specification and the gravity-based models which are specified for each destination types.

However, there are still some limits of the application of this framework. First, in the steps of factor identification and gravity model calibration, detailed data about people's preference and destination choices is needed. However, in reality, such kind of data is still quite in scarce. Second, also as mentioned previously, the highly specification of the models, either about preference factors or destination types, can make it less desirable for generalization.

By referred to Cheng et al.'s work (Cheng, Wilmot, & Baker, 2008), Pel et al. (2012) proposed 3 aspects that future modeling could direct on. First, dynamic destination availability could be incorporated since due to both capacity constraints and hazard impacts, some destination might be not available or not accessible in the course of evacuation. Second, as the most prominent factor for destination choice, distance or generalized travel cost, is often described by travel time based on pre-disaster evacuation estimation, which might not be realistic. It may be a better option to use prevailing travel time in trip distribution, which however, might be quite challenging as it means an integration of trip distribution and traffic assignment. Third, rather than average impacts from hazard (Cheng, et al., 2008), prevailing threats of hazard to destination should be considered.

Another important remark is that for special cases like no-notice or short-notice evacuation[19], evacuees may not choose their destination at departure, but try to find the optimal route to lead themselves out of the area at risk (Adam J. Pel, et al., 2012). Under such assumption, trip distribution may be not indispensable or could be integrated with route choice modeling. Both Pel et al.'s (2008) and Peeta and Hsu's works had less focus on trip distribution, instead on route optimization which is more crucial for no-notice/short-notice evacuations.

2.2.5. Traffic Assignment Modelling

Generally speaking traffic assignment model is to assign trips or travellers onto routes, by modeling people's route choice behaviour. Pel et al. (2012) induced three major models ever developed and applied for traffic assignment: Pre-trip routing model, En-route routing model, Hybrid routing model. In most models, route is assigned by either user equilibrium assumption or system optimum objectives.

2.2.5.1. Pre-trip routing model

In pre-trip routing model, it is assumed that evacuees choose their evacuation route at departure and are not allowed to change route during the trips. Thus, this requires a careful evaluation of all possible route choices at the departure. Also, the basic assumption implies a full compliance of initial route plan.

There are primarily two different approaches for pre-trip routing: user-equilibrium approach and system optimum approach which are distinct basically at their objective.

[19] Based on the availability of lead-time in the predictability of a disaster's occurrence, the evacuation problem can be categorized into short-notice and no-notice evacuations. Short-notice disasters, such as hurricane and flooding, provide a lead-time of between 24-72 hours. A no-notice evacuation takes place immediately after the unexpected occurrence of a disaster. Examples of such disasters include earthquake, terror attack, and hazardous material release (Peeta, S., & Hsu, Y.-T. (2009). *Behavior modeling for dynamic routing under no-notice mass evacuation*. Paper presented at the the 12th International Conference on Travel Behaviour Research, Jaipur, India.).

In user equilibrium, or known as Wardrop's equilibrium (Wardrop, 1952), no single driver could be better off by solely switching to any new route, so it is based on hypothesis of individual utility maximization. There could be different ways to achieve user equilibrium assignment. Many studies (Lin, Eluru, Waller, & Bhat, 2009; Song et al., 2009) have adopted an iterative approach which is supposed to lead the traffic to equilibrium by iteratively re-routing and re-calculation of route utility. The essential assumption of this approach is that experience in the past could contribute to reasonable expectation of traffic conditions in the future. However, Pel et al. (2012) pointed out this assumption may be only valid for longer-term applications, whereas for abnormal event like evacuation under hazards, in which traveller's behaviour, demand and road conditions are quite far too sophisticated and dynamic to be predicted with acceptable accuracy, this assumption may not hold as true. To avoid problems by making such assumptions, other studies (Brown, White, van Slyke, & Benson, 2009; Shahabi, 2012; Song, et al., 2009) adopted another approach: incremental assignment. It is performed by sequential route choices and step-wise assignment. In incremental assignment, only a small fraction of evacuees are assigned each step, and priority of being assigned to most attractive routes (with lower travel cost) is attributed to specific group of evacuees. Also, route travel costs are prevailingly updated after each step's assignment. At last, when all evacuees are assigned, user equilibrium is supposed to be reached.

Different from user equilibrium in which individual optimal route is selected, for system optimum approach, the objective is obviously to minimize total travel cost (Kalafatas & Peeta, 2009) and hence achieve system optimization. The system status could be monitored by system performance indicators and evacuation clearance time is the one most frequently used.

The main limitation of pre-trip routing lies in its strict assumption: it's not possible for people to deviate from the route assigned at the departure, meaning a complete compliance of evacuees. Pel et al. (2012) argued this assumption is too strict to fit for real situation, and in order to address the problem, more flexible en-route routing may be more desirable.

2.2.5.2. En-route routing model

Different from the rigid setting, in en-route routing, the basic assumption is relaxed, which means travellers can deviate prescribed evacuation routes during a trip. It assumes that travellers don't make route choices at the beginning, rather on the way by observing prevailing traffic conditions and continuously making route choices accordingly (Adam J. Pel, et al., 2012).

According to Pel et al (2012), two issues need to be solved in order to realize en-route routing. First, prevailing traffic conditions are estimated dynamically. Second, dynamic decision making needs to be modelled. For the first issue, traffic volume along all links are computed at intersection nodes, and for a downstream link, traffic volume is computed by probability that if any route is taking this link, that route could enjoy lowest travel cost. Thus, it could be seen that en-route routing is highly complicated and its calibration might be much challenging because of the data availability issue. Also, by adopting en-route routing, prescribed evacuation routes which usually appear in many evacuation plans are basically not possible, which could really let the evacuation modellers down. This complexity may have hindered application of this model, as there are much less studies (Mitchell & Radwan, 2006) in evacuation modeling field applying it comparing to pre-trip routing model.

2.2.5.3. Hybrid routing model

Hybrid routing model is not simply a combination of the first two models, but with a different fundamental assumption that people may have a prescribed route or choose a route at departure, and afterwards during their trip they adapt to the prompt traffic conditions by route switching if the new route can really (or just believed) make themselves better off. So differed from seemingly quite strict assumptions of both pre-trip and en-route modeling, the hybrid routing has taken a middle way to make it more adaptive to the special need of evacuation modeling (prescribed routes) meanwhile more flexible in evacuees' behaviour simulation (partial compliance). Different models have adopted hybrid routing as their assignment method. These models include DYNASMART model (Mahmassani, 2001, referred by Pel et al. 2012) at micro scale and macro-scale EVAQ model (A. J. Pel, et al., 2008) which was developed for flooding evacuation in Zeeland, the Netherlands.

2.3. Concluding Remarks

Several important remarks are concluded from the extensive literature review in this chapter.

First, as one essential component of flood risk, the estimation of victims due to flood should follow the fundamental definition of risk which covers both sides of hazard and vulnerability. This requires both flooding hazard and responses of human society should be taken into account.

Jonkman (S. N. Jonkman, Vrijling, et al., 2008) developed a complete framework from existing approaches and empirical research of historical flood events. Jonkman's framework engages more impact factors and highlights effects of evacuation which is seen as positive action to reduce "vulnerability". Also a zonal classification approach is applied to comprehensively evaluate the overall hazard level of flood. The flood zone types are also utilized to specified different mortality functions calibrated by historical event data. Despite of its completeness and explicitness of model design, Jonkman's framework still has several limitations. First, this model may be dedicated to macro scale analysis so that there are no distinctions between home-based victims and en-route ones (casualties on evacuation routes) which may reveal significant spatial pattern only in meso/microscopic regions. Second, this framework directly adopts a dynamic evacuation simulation model (van Zuilekom & Zuidgeest, 2008)that is dedicated for pre-disaster evacuation. For large, populous region like South Holland, application of pre-disaster evacuation model may be acceptable for exposed population and victim estimation, because the clearance time of evacuating such a mega-region may be as long as dozens of hours, leaving some late departing and evacuating evacuees being caught by flood. But for much smaller dike-ring area as Land van Maas en Waal, pre-disaster evacuation model may not be suitable. Furthermore, since the evacuation model used in Jonkman's framework is not fully explained, the relations between flooding and evacuation processes, in terms of flood's impact in demand generation, trip distribution and routing are not clarified. Therefore, in order to build a strategic modeling framework and procedure sets for victim estimation, an evacuation model for simulating acute evacuation in smaller dike-ring area (Land van Maas en Waal) needs to be established. Apparently, relations between evacuation processes (trip generation, distribution, routing) and flooding process should be clarified.

The extensive review about evacuation modeling within a classical framework (comparing to 4-step transport modelling) provides good reference or evacuation model design in this study.

First, with regard to evacuation demand (evacuation participation, departure time choice), both sequential and simultaneous models have pros and cons which have been discussed in sub-section "Model Comparison". Since the "comprehensibility" objective of this study, sequential model can be adopted due to its mathematical simplicity and sufficient adaptability to different departure pattern.

Second, from literature review, it is the classical gravity-based model that has been applied in most studies. However, as discussed in sub-section "Discussion about Trip Distribution Modelling", in short-notice or no-notice evacuation, multi-destination choice may be no longer important for evacuation modelling. Since the essential objective in such situation is to get evacuees out the area via optimal routes. Therefore with similar evacuation situation (acute evacuation in flood), trip distribution module will also be integrated into evacuation routing module.

Third, in traffic assignment modelling or evacuation routing, pre-trip routing has posed too strict assumption that evacuees fully comply with prescribed routes. This assumption may cause the routes choices deviating from reality where people are free to alternate predefined routes by inspecting prevailing road conditions and hazard level. Therefore, en-route routing and hybrid routing models are developed. However, considering technical difficulties of the two advanced routing models and time limits for MSc study, the pre-trip model is adopted for evacuation routing. In addition to the usual functions like route optimization and network performance calculation, the evacuation routing module designed in this study should be capable of generating detailed evacuation routes and road travel cost statistics both of which are used for en-route exposure and victim simulation.

Finally, through the literature review of evacuation modelling, it is discovered in existing studies, there is rarely any discussion about the impacts of hazard upon transport infrastructure (e.g. roads being gradually flooded, or exits are disabled or closed due to its proximity to flood). However, in acute evacuation in flood, dynamic interaction between road infrastructure and advancing flood does exist. It may have big influences in route choice, performance of evacuation and en-route casualties (people being stuck in water during their journey to the exits). Hence, different from traditional evacuation models, a new module dealing with changing availability of road network with relation to flood dynamics (evacuation supply module) should be designed and integrated with other parts (demand and routing) of evacuation model.

3. METHODOLOGY

3.1. General Approaches and Methods

According to the settled research objectives and review for existing studies, a linked modeling approach would be applied with adoption and conjunction of multi-modeling approaches. Based on review of existing studies in flood risk assessment and victim assessment, there is a trend in research methodology to combine and link both sides of hazard and vulnerability analyses, by carefully considering the impacts of flood process and people's reaction to it. Jonkman (2008) proposed a rather complete and applicable modeling framework for victim estimation on basis of extensive literature review and methods comparison, which has been reviewed in the previous chapter. Jonkman's framework has been applied in similar cases with geographical characteristics of low-lying areas usually protected by water systems and proved as effective in victim estimation and risk assessment (S.N. Jonkman, 2007; S. N. Jonkman, et al., 2011; S. N. Jonkman, Kok, et al., 2008; S. N. Jonkman, et al., 2010; Maaskant, et al., 2009; Rijkswaterstaat, 2006). Therefore, it is possible to apply the ideas of Jonkman's modeling framework in the case of Land van Maas en Waal. However, as highlighted in the concluding remarks of literature review, essentially due to the unclear relations between flood simulation and evacuation modeling, and the limitations in evacuation model (van Zuilekom & Zuidgeest, 2008) adopted in the framework. Therefore, in order to achieve the main goal of this MSc study: a strategic modeling framework for victim estimation in flood, it is necessary to develop a new linked flood-evacuation modeling framework on the basis of Jonkman's proposed model (2008), by elaborating on the relation between dynamic flooding characteristics and simulation of evacuation (in each step of evacuation modeling: travel demand, trip distribution and routing). Also, to support the "strategic modeling" objective, a new evacuation model which is adaptive for acute (short-response) evacuation is proposed in this chapter, by selectively adopting appropriate methods and approaches reviewed in the previous chapter.

Based on Jonkman's framework, a conceptual model for the linked-modeling approach of victim estimation is proposed below. The model framework includes six major components by consideration of major flooding-evacuation process and major factors in victim estimation (S. N. Jonkman, Vrijling, et al., 2008).

1) Representation Of Flood Characteristics
2) Flood Zone Classification (S. N. Jonkman, Vrijling, et al., 2008; Waarts, 1992a)
3) Evacuation Modeling (Simulation of travel demand, supply of infrastructure, routing)
4) Exposure Estimation (Home-based exposure and en-route exposure)
5) Victim Estimation
6) Spatial Pattern Analysis of Victim Distribution

First of all, dynamic flood characteristics (water depth, rising rate, time to flood, etc.) as the result of flood modeling are represented in GIS to gain understanding of the flooding process. Also because it has been widely confirmed (Clausen, 1989; Duiser, 1989; S. Jonkman, 2001; S. Jonkman, et al., 2002; S. N. Jonkman, Vrijling, et al., 2008; Ramsbottom, et al., 2003; Ramsbottom, et al., 2004; Vrouwenvelder & Steenhuis, 1997; Waarts, 1992a) that the intensity of flood hazard could be represented by water characteristics, the proper GIS-presentation of dynamic flood characteristics provides basis for later analysis of flood zones and impacts of floods on evacuation process. Second, different flood zones, denoted as breach zones, zones with rapid rising water and remaining zones are identified by classification of water characteristics.

As both Waarts (1992a) and Jonkman et al. (2008) have confirmed the significant variation of flood zones, the MSc study also adopts this zonal approach which would affect both evacuation demand and estimation of mortality function. Third, differentiated by evacuation scenarios, fraction of people at risk would be estimated by evacuation model, which would then be considered in estimation of people exposed to flood by sequentially engaging the effects of sheltering (S. N. Jonkman, Vrijling, et al., 2008). Forth, number of victims in one flood scenario would be estimated for each evacuation scenario and flooding zone, by multiplying mortality rate and exposed population. Finally since the numbers of victims have been estimated, spatial pattern of victim distribution would be analysed by GIS and geo-statistics methods.

In the following part the first section, essence of each modeling component and the main methods and approaches are described. In the second section of this chapter "Design of Modeling Framework", more elaborated modeling issues, including adopted methods and relation with literature, major assumptions and mathematical description are present.

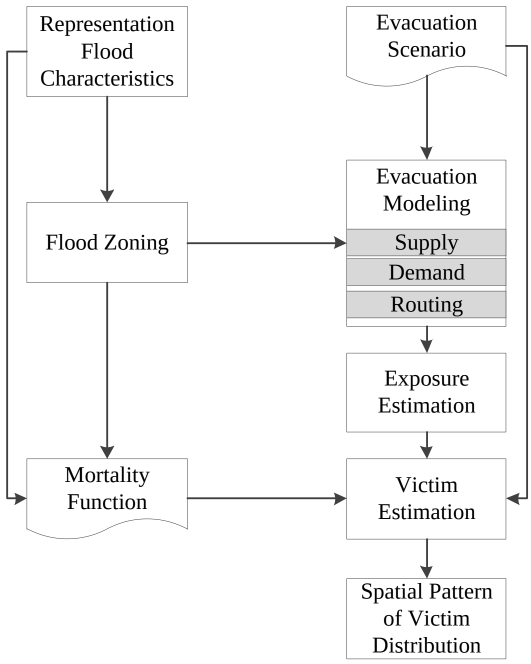

Figure 3-1 Conceptual Model of a Linked-Modeling Approach

3.1.1. Representation of Flood Propagation

Due to time and resource limitations of the MSc, results of flood propagation, the dynamic flood characteristics are directly adopted as the basic inputs of linked modeling. Flooding characteristics are fundamental for victim estimation as it is the major representative of hazard impacts. In the proposed modeling framework, flood characteristics are presented not only for understanding the dynamics of floods, also they are served as the most important factors affecting mortality rate, prevailing availability of road network and evacuation exits, people's departure participation and departure.

For the sake of simplicity in modeling, not all water characteristics modelled by flood propagation are involved. But only those proved by existing studies (Duiser, 1989; S. Jonkman, 2001; S. Jonkman, et al., 2002; S. N. Jonkman, Vrijling, et al., 2008; Ramsbottom, et al., 2003; Ramsbottom, et al., 2004; Vrouwenvelder & Steenhuis, 1997; Waarts, 1992a) as relevant and crucial for victim estimation are selected for this study. The water characteristics selected include:

- Water depth (h)

- Flow velocity (v)
- Rising rate of water (rr)
- Time to flooding (ttf)

All of the water characteristics involved above has been generated by existed flood model in raster base. Thus, it is proper to use GIS package like ArcGIS for spatial representation.

3.1.2. Zonal Simulation

Studies have argued (S. N. Jonkman, Vrijling, et al., 2008; Waarts, 1992a) that for zones with different water characteristics could have significantly different impacts for people's actions like evacuation, sheltering, instability and drowning. Hence, it is reasonable to identify different flooding zones by applying classification based on thresholds of different water characteristics which has been discussed in Chapter 2 (S. N. Jonkman, Vrijling, et al., 2008). The main purpose of flood zone classification is to perform the evacuation modeling and victim estimation based on distinction of flooding zones.

Jonkman et al. (2008) proposed a classification method for three different types of flooding zones: breach zones, zones with rapid rising water and remaining zones, by considering different thresholds of different flood characteristics for each zone type (for detailed description of this method, see discussion in Chapter 2). This method is adopted in the model design of the MSc study, while it might be necessary to adjust the thresholds for the specific case study area (Land Maas en Waal). Since water characteristics have been prepared in ArcGIS, classification of flood zones could be performed by raster reclassification and combination in ArcGIS.

3.1.3. Evacuation Modelling

The role of evacuation modeling in victim estimation framework is to estimate the fraction of people evacuated out of the total population under risk of flood, which is believed as one essential step prior to estimation of population exposed to floods. As discussed in Chapter 2, in Jonkman et al.'s modeling framework (2008), evacuation has been engaged as one important factor for victim estimation. However, a model (van Zuilekom & Zuidgeest, 2008) based on dynamic traffic assignment was adopted, which is not fully consistent with the short-notice or no-notice evacuation scenarios (Peeta & Hsu, 2009; Adam J. Pel, et al., 2012) set for this MSc study. Also, the evacuation model applied has limitations like lack of spatial difference speculation, less clarified relation between flooding dynamics and travel demand, trip distribution and routing, which has been in particular reported as important in evacuation modeling (C. G. Wilmot, et al., 2005).

Therefore, in order to relax the limitations of Jonkman's framework, a new evacuation model aiming for adaptability and comprehensibility is proposed in this MSc study. It is based on the general framework proposed by Pel et al. (2012) consisting of sequential steps: travel demand modeling, trip distribution modeling and traffic assignment modeling supported by a ArcGIS-based evacuation routing algorithm: ArcCASPER (Shahabi, 2012). Specifically, to make the proposed evacuation model more adaptive to the situation of evacuation in flood, more hazard impacts are considered and linked into the design of evacuation model, that is, the relation between dynamic flood characteristics and travel demand, trip distribution and evacuation routing are clarified in both mathematical and geographical fashion.

In situations of long-notice (pre-disaster) evacuation, there are usually several days ahead of the actual flooding, hence it is rare to see victims in this case, because there are sufficient time for evacuating the whole area (particularly for relatively smaller area like Land Maas en Waal). However, for flooding happened unexpectedly with much lower probability of prediction and early warning, considerable casualties could be caused by rapid coming water. In this case, based on behavioural assumptions, studies (Peeta & Hsu, 2009) (Adam J. Pel, et al., 2012) have argued the first priority is to get the people out of the area at risk as quick as possible, which leads to less emphasis on complex trip distribution pattern typically modelled by gravity-based model (Brodie, et al., 2006; US-Army-Corps-of-Engineers, 1995; van Zuilekom & Zuidgeest, 2008; Whitehead, et al., 2000). Instead, shortest path routing with destination (evacuation exits) choice dynamically affected by flooding could be adopted for evacuation modeling under this situation (A. J. Pel, et al., 2008). Therefore, in this study, the deterministic gravity-based trip distribution model is replaced by a more comprehensive evacuation supply model with prevailing availability of road network and exits affected by proceeding floods.

Hence, the evacuation model consists of three major modules: evacuation supply, evacuation demand and routing, which are schematically presented as below. In this framework, supply module considers the availability of both network and exits which are served as the basic infrastructure for evacuation. Demand model adopts the sequential modeling approach which has been intensively discussed in Chapter 2. Sequentially, it estimates the area and total population at risk (N_{PAR}), share of population participated in evacuation and the spatial-temporal pattern of departure. Routing module takes the outputs of both supply and demand modules to perform the routing optimization for different routing principles. As the result of evacuation modeling, people staying at home who are supposed to be exposed to floods, time needed for evacuation for each parcel of evacuees of each neighbourhood and the related route information are exported to be the inputs for exposure model.

The evacuation model is closely linked with flood dynamics. Both supply and demand module are taking flood characteristics as impacting factors. For example, on one hand, water depth would obviously affect availability of road network, the risk level of evacuating to certain exit would be affected by distance between the flood and the exit; on the other hand, population at risk would be identified by the spatial intersection with flooding extension. People's departure pattern could be varied by different flooding zones and time to flooding.

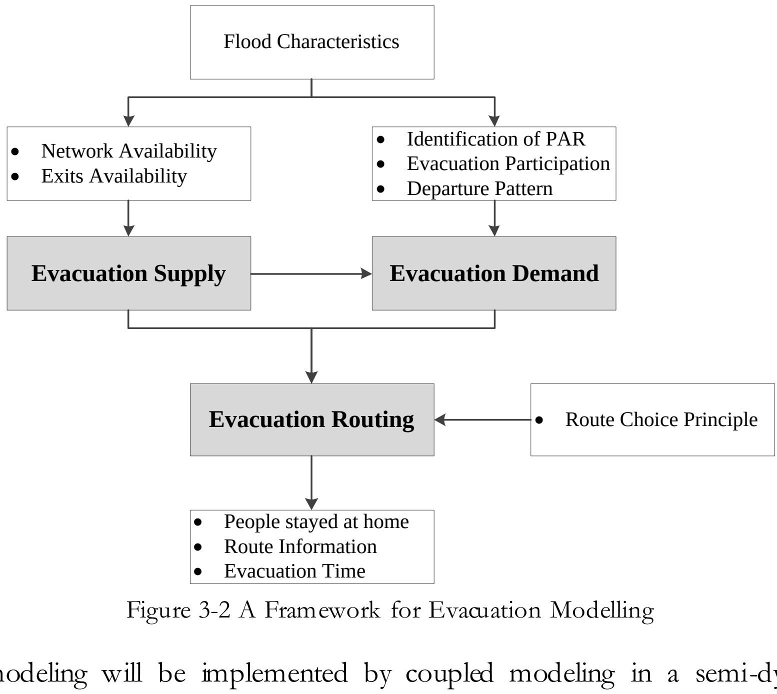

Figure 3-2 A Framework for Evacuation Modelling

The evacuation modeling will be implemented by coupled modeling in a semi-dynamic fashion, by repeated simulation for supply, demand generation and routing in equal time instants (1 step per hour).

For evacuation supply, two sub-models will be established in ArcGIS with primarily Euclidean Distance and Overlay Analyses.

For demand module, first, population at risk which is considered as the base for evacuation demand would be determined by simply looking at spatial relation between residential location and flooding extension. Second, share of participation could be estimated by adopting the simple cross-classification method proposed in the evacuation modeling study for Hurricanes in South-western Louisiana, the US (PBS&J, 2000). Third, for simulation of departure pattern which describes the how many participants (evacuees) would depart their homes at each time instant. Departure curve approach(Kalafatas & Peeta, 2009; Xie, et al., 2010)is applied with adjusted parameter values which are supported by literature studies.

For evacuation routing, a third-party ArcGIS extension called ArcCASPER (Shahabi, 2012) which uses a heuristic approach for route optimization in evacuation by considering the constraints of road capacity and congestion will be applied in the environment of ArcGIS.

3.1.4. Exposure Estimation

After evacuation modeling, fraction of total population at risk (PAR) exposed to flood will be estimated, by considering effects of evacuation and sheltering. Different from Jonkman's approach which takes the people's exposure by no difference, the approach proposed in this study distinguish the people exposed at home (home-based exposure) and the ones exposed on their routes of evacuation (en-route exposure). For the first one, it is directly derived from the participation and departure simulation of evacuation demand module, adjusted by considering the effects of sheltered people. For en-route exposed population, improved from existing methods (S. N. Jonkman, Kok, et al., 2008; S. N. Jonkman, Vrijling, et al., 2008), a dynamic exposure identification model is created and performed based on a new data structure: Evacuation Milepost Series (EMS).

To implement the estimation of exposed population, spatial join methods in ArcGIS could be used to aggregate the specified population not participating in evacuation and the ones not departing from their houses; while for en-route exposure identification and estimation, an iterative scanning algorithm is carried out by linking workflows of ArcGIS (building EMS structure) and MatLab (identify exposure location and time). Procedures of EMS creation and the scanning algorithm are further explained later in the sub-section "Exposure Estimation".

3.1.5. Victim Estimation

As the final step, victim estimation for each neighbourhood is performed by simply multiplying the exposed population, either at home or on the routes, with the mortality rate estimated by functions specified by each flooding zone type. For different evacuation scenarios, number of victims are respectively estimated and then aggregated with probabilities for each scenario.

3.1.6. Spatial Pattern Analysis

After the estimation of victims at neighbourhood level, it is possible to conduct a spatial pattern analysis for the distribution of victims in the study area, which might provide insights into the specific reasons of higher flood risk and corresponding risk-alleviation measures.

3.2. Design of Modeling Framework

The following figure schematically illustrates the design of the modeling framework for victim estimation. In this framework, six major modeling components (flood zone classification, evacuation demand, evacuation supply, evacuation routing, exposure estimation and victim estimation) are organized by the logic of conceptual model which was discussed in the previous section. Also, primary inputs/outputs variables, modeling parameters and interaction of modeling components are also presented.

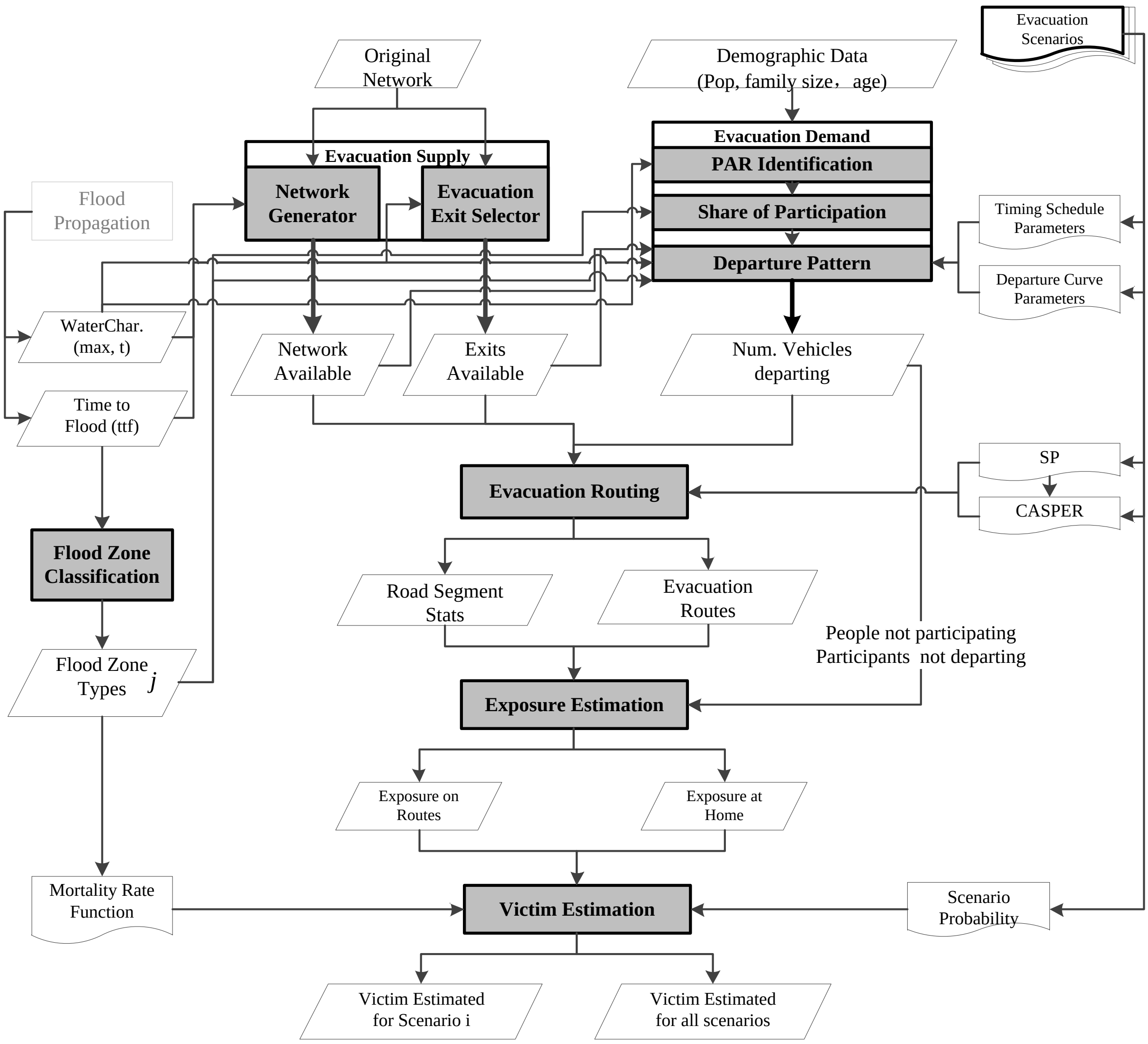

Figure 3-3 Design of Modeling Framework for Victim Estimation

In the following sessions, based on the design of the holistic framework as shown in the Figure 3-3, basic assumptions, I/O (Input/Output) relations and mathematical descriptions of the models which could be translated in modeling environments like ArcGIS and MatLab into practical modeling procedures or computational programs are discussed in detail for each of the modeling components plus the important external profiles for evacuation modeling: settings of evacuation scenarios.

The following discussion of modeling components is organized in a problem-oriented way. That is, the shadowed components in Figure 3-3 are organized in a bottom-up fashion so that the logic for solving the problem of victim estimation is demonstrated in a more explicit way.

3.2.1. Flood Zones Classification

Based on Jonkman et al.'s approach (2008), for classification of flood zone types, flood characteristics are taken as the basic inputs and three types of flood zones are generated as outputs.

3.2.1.1. Assumptions

- There are uniform/homogeneous hydrological attributes and impacts of floods within each type of flood zones, and there are significant variations between flood zones types.

- For different flood zone types, determine factors may different (Waarts, 1992a).

3.2.1.2. I/O Relations

Inputs (from Representation of Flood Propagation):

- Water characteristics: water depth ($h_{\max}$), velocity ($v_{\max}$), water rising rate ($rr_{\max}$).

Outputs (To: Evacuation Demand: Share of Participation Estimation, Departure Pattern Simulation; Victim Estimation):

- Boundary of Breach Zones ($brcZone$)
- Boundary of Zones with Rapid Rising Water ($rapRisZone$)
- Boundary of Remaining Zones ($remZone$)

3.2.1.3. Mathematical Description

The classification of three types of zones is based on Jonkman et al.'s proposed criterion (2008) which has referred to early studies about the breach zones (Clausen, 1989). In principle, as the previous method was also based in Dutch cases, it may be directly adopted. However, the thresholds of water characteristics could be adjusted for the specific case of Land Maas en Waal.

Breach zones are areas near the breach of water structure. It is characterized by high impulse of water and high flow velocity which could lead to collapse of buildings and instability of people. Zones with rapid rising water are namely categorized by higher rising rate of inundation and the third type: remaining zones are therefore the areas left with lower rising rate and kinetic energy of water flow.

$$zone = \begin{cases} brcZone & if: hv \geq hv^{\phi}, v \geq v^{\phi} \\ rapRisZone & if: \left(rr \geq rr^{\phi}, h \geq h^{\phi}\right) \text{ and } \left(hv < hv^{\phi}, v < v^{\phi}\right) \\ remZone & others \end{cases} \tag{3.2.1}$$ [20]

In Formula(3.2.1), hv^{ϕ} is the threshold of kinetic energy for breach zones, v^{ϕ} is the threshold of flow velocity for breach zones, rr^{ϕ} is the threshold for rate of water rising for zones with rapid rising water, h^{ϕ} is the threshold for the water depth for zones with rapid rising water. In existing studies (Clausen, 1989; S. N. Jonkman, Vrijling, et al., 2008), values of thresholds are specified as below:

$$\begin{cases} hv^{\phi} = 7\mathrm{m}^2/\mathrm{s} \\ v^{\phi} = 2\mathrm{m/s} \\ rr^{\phi} = 0.5\mathrm{m/h} \\ h^{\phi} = 2.1\mathrm{m} \end{cases} \tag{3.2.2}$$

Graphic illustrations (S. N. Jonkman, Vrijling, et al., 2008) about the zonal classifications with thresholds in Formula(3.2.2) in variable space are shown below in Figure 3-4.

[20] Source: Jonkman, et al. 2008.

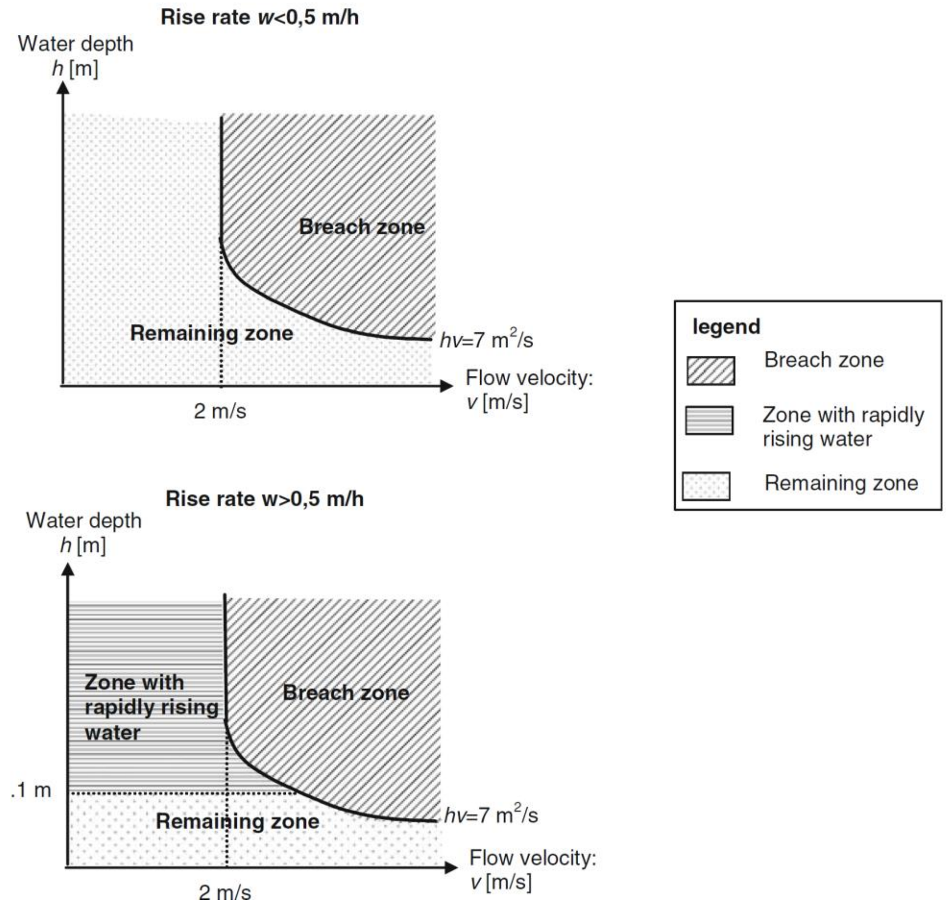

Figure 3-4 Flood Zone Types as a function of water depth, rising rate and flow velocity[21]

3.2.2. Victim Estimation

As shown in Figure 3-3, different evacuation scenarios could be engaged with independent probabilities of occurrence. Different evacuation scenario would lead to varied settings about travel demand and evacuation routing, hence result in different estimation of number of victims. Thus, for one single incident of flood facing with uncertainty of evacuation process, the total estimated victims would be aggregated by summing up estimations for single scenarios weighted by scenario probabilities.

According to Jonkman et al.'s approach (2008), for each evacuation scenario, the number of victims is estimated by multiplying population exposed to flood with mortality. However, what should be noted is that for this MSc study, people exposed to flood are specified as two types: exposure at home and exposure on the routes. Hence, the estimation should be performed for each type respectively since the locations of both types of exposure are different, which means the mortality rate would be different as well.

3.2.2.1. Assumptions

- Different evacuation scenarios are independent, mutually exclusive events which are not possibly happening simultaneously.
- People are exposed to floods either at home or on their routes of evacuation. The two situations cannot happen for the same group of people.

[21] Source: Jonkman, et al. 2008.

- Mortality rates in different flood zones are distinct, within each type of flood zone, mortality is homogeneous and only determined by water depth, and the mortality rate over water depth follows a log-normalized distribution (S. N. Jonkman, Vrijling, et al., 2008).

3.2.2.2. I/O Relations

Inputs (from: Exposure Estimation, Evacuation Scenario):

- Population exposed to flood at home for certain type of flood zone and certain evacuation scenario ($E_{i(H)}^{j}$)
- Population exposed to flood at home for certain type of flood zone and certain evacuation scenario at each time instant. ($E_{i(R)}^{t}$)
- Mortality Rate estimated for each type of flood zones at the water depth level h (F_h^j)
- Probabilities of all evacuation scenarios (P_i)

Outputs (to: Spatial Pattern Analysis):

- Number of victims for each neighbourhood
- Number of total victims for each scenario (V_i)
- Number of total victims for all scenarios (V)

3.2.2.3. Mathematical Description

General Estimation of Victims in ONE flood scenario:

$$V = \sum_i P_i \cdot V_i \tag{3.2.3}$$

P_i: Probability for evacuation scenario i (determined by profiles of Evacuation Scenarios).

For each evacuation scenario i:

$$V_i = F_h^j \cdot E_{i(H)}^{j} + \sum_t F_{h(t)}^{j} \cdot E_{i(R)}^{t} \tag{3.2.4}$$

In Formula(3.2.4), i is the index of evacuation scenarios; j is the index for flood zone types (breach zones, zones with rapid rising water and remaining zones); $E_{i(H)}^{j}$ is the population exposed at home for evacuation scenario i and flood zone type j; similarly, $E_{i(R)}^{j}$ is the population exposed on the routes for evacuation scenario i at time instant t.

$$j = \begin{cases} 1 & brcZone \\ 2 & rapRisZone \\ 3 & remZone \end{cases} \tag{3.2.5}$$

Based on Jonkman et al.'s studies on extensive historical data (2008), mortality functions specified for different types of flood zones are specified by formula(3.2.6).

$$F_h^j = \begin{cases} 1 & j=1 \quad \forall h \\ \Phi_N\left(\dfrac{\ln(h)-\mu_N}{\sigma_N}\right) & j=2 \quad \mu_N = 1.46 \quad \sigma_N = 0.28 \\ \Phi_N\left(\dfrac{\ln(h)-\mu_N}{\sigma_N}\right) & j=3 \quad \mu_N = 7.6 \quad \sigma_N = 2.75 \end{cases} \tag{3.2.6}$$

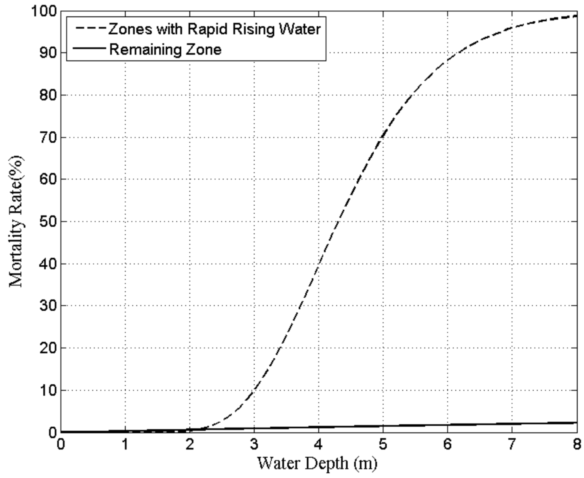

Figure 3-5 Mortality Curves for zones with rapid rising water and remaining zones

3.2.3. Exposure Estimation

The component of exposure estimation gives estimation of population exposed to flood either at home or on the routes of evacuation. For the exposed population at home, it takes the outputs of evacuation demand model including:

- The population at each neighbourhood not participating in evacuation
- The population participating in evacuation but not able to depart because of the coming flood

Considering about the effects of sheltering, it is usually assumed that a small fraction of people exposed at flood are sheltered. According to existing studies in the Netherlands (S. N. Jonkman, Vrijling, et al., 2008; Rijkswaterstaat, 2006), the ratio of sheltered population are estimated as 0.1 at the rural area and 0.2 at the urban area[22]. In the case of Land Maas en Waal, the urban and rural areas are categorized by population density.

For population exposed on the routes, it is more complicated because of the dynamics of both evacuation and flooding process. Ideally, the exposure should be derived from the dynamic analysis about the spatial-temporal relationships between locations of evacuating people and advancing flood. However, due to the highly complex algorithm and demanding computation capability required by this approach, usually an alternative approach (S. N. Jonkman, Kok, et al., 2008; S. N. Jonkman, Vrijling, et al., 2008; Maaskant, et al., 2009; Rijkswaterstaat, 2006) (shown in Figure 3-7) based on Frieser's timeline model (2004) which is shown in Figure 3-6 and is applied by directly comparing the temporal relations of evacuation and flooding processes. Proposed by Jonkman et al. (2008), the fraction of exposure is derived by looking at the relative difference between time needed for evacuation (time of warning, response, delay and clearance

[22] It is assumed by Jonkman et al. (2008) that buildings with more than 3 floors are likely to provide effective shelter for people exposed. And this ratio is estimated respectively for urban and rural areas.

time) and the time available for evacuation (primarily refer to the time to flooding, ttf). By taking the study area as one unit, the clearance time for evacuating the whole area is estimated (time needed for evacuation) and compared with time available for evacuation.

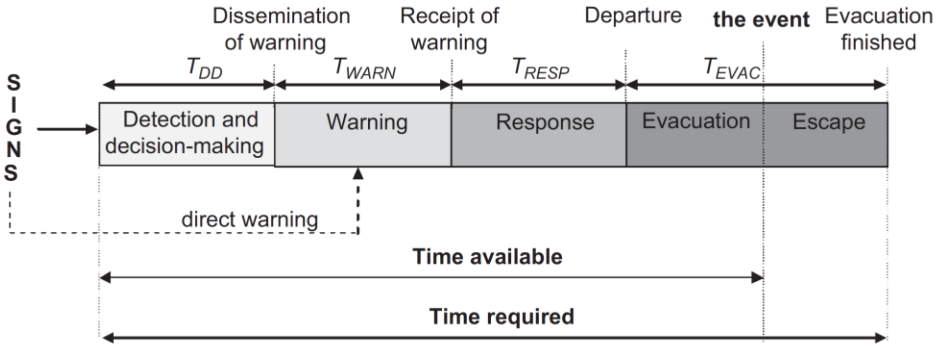

Figure 3-6 General Evacuation Timeline[23]

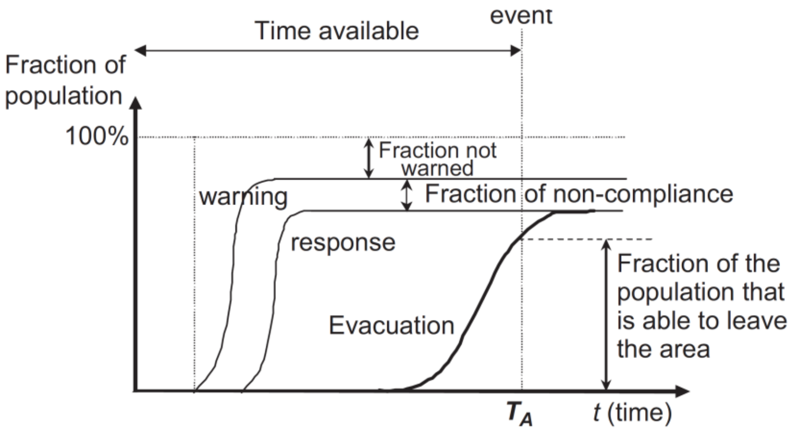

Figure 3-7 Distribution function to time required for evacuation, based on phases of evacuation[24]

However, as shown in Figure 3-7, this approach has applied on the scale of the total population, which provides less insight into the detailed spatial pattern of victim distribution within the study area. Also, there is an obvious paradox in this holistic approach: in the fraction of people who have complied with the evacuation order but not managed to evacuate out of the area at risk, they are exposed on the routes not at their houses. Therefore, it is logically invalid to apply for them the same mortality function as the one who are exposed at home. In order to address this problem, it is necessary to open up the black box of evacuation model, by modeling the evacuation and the exposure estimation on a more disaggregated level (e.g. neighbourhood).

In a disaggregated estimation, the process of evacuation and flooding would be simulated in a more detailed way, in both time and space. By looking at each time instant, the interactive temporal-spatial relation between the evacuation routes (for each neighbourhood unit) and the advancing flood are studied. To support such microscopic simulation, a new data structure: **"evacuation milepost series" which is used for describing the temporal process of evacuation is designed** for the simulation.

[23] Source: Frieser, 2004.
[24] Source: Jonkman, S. N., et al. 2010.

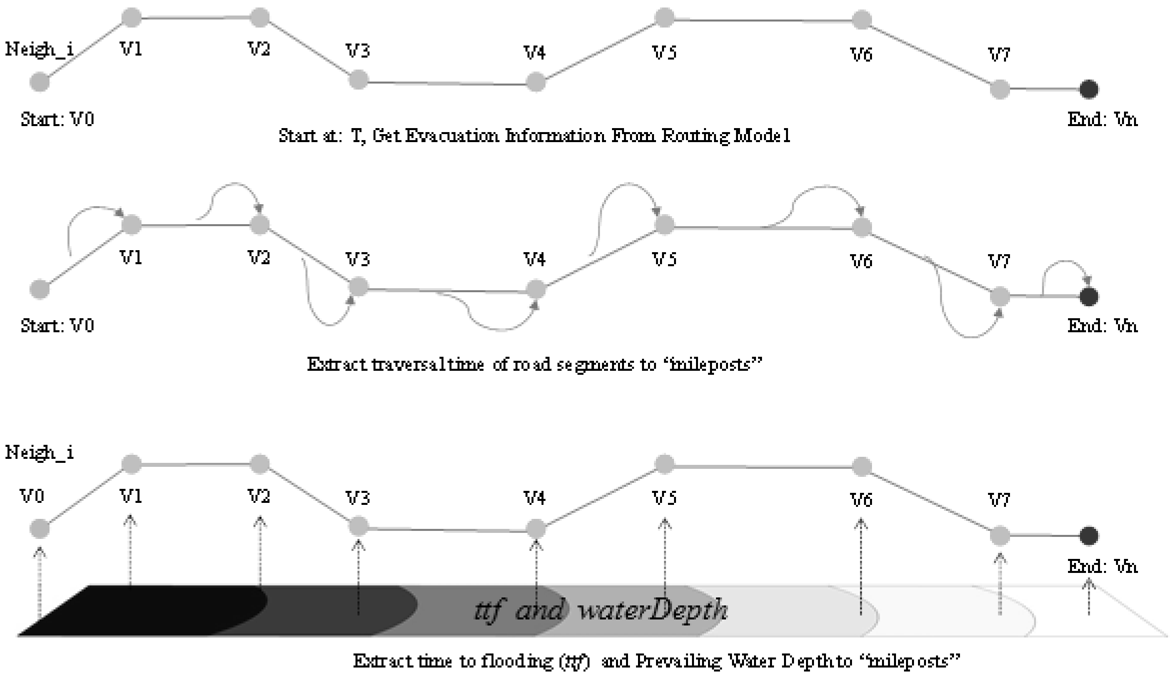

Figure 3-8 Structure of "Evacuation Milepost Series" and Related Procedures

As illustrated at the top of Figure 3-8, an Evacuation Milepost Series (In short: EMS) for one neighbourhood from which a group of people depart and start the evacuation at time T is displayed. Certain amount of evacuees ($N^{p}_{D(t)}$), simulated by Evacuation Routing module, pass through certain number of "mileposts" [25]on their routes and are supposed to reach the exit (ending milepost) with a total estimated evacuation time ($T^{p}_{evac}(t)$). So, **<u>the "Evacuation Milestone Series" (EMS) can be defined as an array of ordered vertexes that belong to the evacuation routes, attached with information including neighbourhood ID, number of evacuees, departing time, cumulative travel time, passing time (at each vertex/milepost), corresponding "time to flooding" and prevailing water depth level on each posts.</u>** It is obvious that in this way, information about both evacuation and flooding dynamics have been integrated into one EMS structure.

By extracting the travel time or congestion information[26] on each road segment next to the mileposts, the traveling time between every two mileposts could be derived from the total evacuation time by weighted averaging (Weighted by travel time or congestion level).

The third step is to extract the time to flooding information (ttf) and water depth (h) from the water characteristics layers to the mileposts. Then data of one *EMS* is illustrated in Figure 3-9.

[25] In ArcGIS environment, the "mileposts" could be seen typologically the vertexes contained by each evacuation routes. The vertexes of routes could be extracted by GIS tools.
[26] Traversal time and congestion level information are the basic outputs of Evacuation Routing (ArcCASPER) on road segment level.

Milepost	Start Time	Travel Time	Passing Time		Time to Flooding	Water Depth(t)	Coordinates	Population
Ni-V0(Start)	T	0	T	<	ttf0	H0	x0,y0	Ni
Ni-V1	T	t1	T+t1	<	ttf1	H1	x1,y1	Ni
Ni-V2	T	t2	T+t2	<	ttf2	H2	x2,y2	Ni
Ni-V3	T	t3	T+t3	>	ttf3	H3<=0.3	x3,y3	Ni
Ni-V4	T	t4	T+t4	>	ttf4	**H4>0.3**	x4,y4	Ni
Ni-V5	T	t5	T+t5		ttf5	H5	x5,y5	Ni
Ni-V6	T	t6	T+t6		ttf6	H6	x6,y6	Ni
Ni-V7	T	t7	T+t7		ttf7	H7	x7,y7	Ni
Ni-Vn(End)	T	t8	T+t8		ttf8	H8	x8,y8	Ni

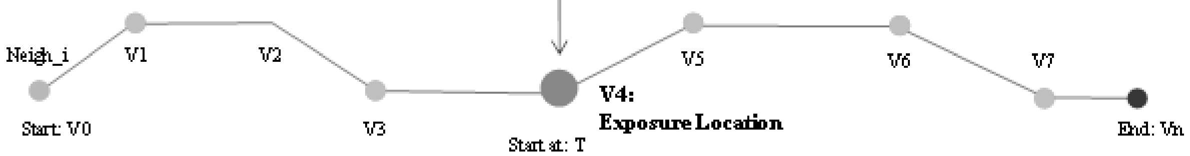

Figure 3-9 Illustration of Exposure Location/Time Identification based on Data Structure of EMS

As illustrated in Figure 3-9, the attribute table of *EMS* is organized in the order of "From (origin) –To (destination)". Hence, it is not difficult to calculate the passing time at each milepost. Then, **from the starting post of the series, all mileposts are sequentially scanned by comparing the essential "Passing Time" and "Time to Flooding"**. Since both passing time and time to flooding are absolute time passed from the initiation of flooding, so at the beginning the "passing time" is prior to (smaller in value) "time to flooding", which means when the evacuees pass the milepost, the flood hasn't reached that location. Also, the water depth at that moment needs to be considered as it is unlikely that a modern vehicle is getting stuck in shallow water (water depth is lower than 0.3m). As long as in the scanning the "passing time" is later than (larger in value) than "time to flooding" and the prevailing water depth is higher than threshold (0.3m), the vehicles of the evacuees cannot pass through that milepost (in Figure 3-9, e.g. the third milepost) as it has been seriously inundated. **So the first milepost in the single *EMS* whose "passing time" is larger than "time to flooding" and the water depth (h) of which is higher than threshold is identified as the location where people departing from neighbourhood i at time T are getting stuck in flood, at the passing time of the corresponding milepost**[27]. This process is iteratively repeated for all neighbourhoods departing at time T and all the modeling time instants. Iterative simulation could be implemented with MatLab scripting by EMS data exchange between ArcGIS Geodatabase and MatLab[28]. In one iteration, the exposure locations and times of all neighbourhoods are identified and exported with the number of evacuees. Identified exposure location and time datasets are taken back into ArcGIS for visualization and further analyses.

By this approach, the limitations of Jonkman et al.'s holistic exposure estimation model are to some extent solved. Through simulation at the microscopic level, profound temporal-spatial interactions between

[27] Or the time of exposure could be approximated by rounding off the passing time to the closest time instant.
[28] Both platforms support ESRI Shapefiles, which could be served as exchange data format.

evacuation and flooding processes could be revealed. In addition to that, high-resolution exposure location and time results also have more potential for aggregation from different perspective.

3.2.3.1. Assumptions

- Once people are exposed in flood, either at home or on the routes, their locations are not going to be changed any more.
- The ratios for people being sheltered at home are estimated respectively for rural and urban areas. In rural areas, the ratio is set at 0.1, while in urban regions it is at higher level of 0.2.

3.2.3.2. I/O Relations

Inputs (From: Evacuation Demand, Evacuation Routing, Representation of Flood Propagation):

- Population not participating in evacuation at each neighbourhood p (N_{NPE}^{p})
- Population participating in evacuation but not departing due to coming flood at each neighbourhood p (N_{ND}^{p})
- Evacuation Routes for all P neighbourhoods ($p=1,\dots,P$) departing at time instant t ($RT_p(t)$), with total travel time along routes ($T_{evac}^{p}(t)$), number of evacuees ($N_{D(t)}^{p}$), real traversal cost on each road segment which topologically belongs to the evacuation route ($Eg_p(t)=(e_1,e_2,\dots,e_j)$, $Eg_p(t).cost$).
- Time to flooding (ttf)
- Water Depth at time instant t ($waterDepth(t)$)

Outputs (To: Victim Estimation):

- Population exposed to flood at home for all neighbourhoods (for evacuation scenario i and flood zone type j)($E_{i(H)}^{j}$)
- Population exposed to flood on the routes for all neighbourhoods at time instant t ($E_{i(R)}^{t}$)
- Locations and Times of exposure for each neighbourhood p and each time instant t

3.2.3.3. Mathematical Description

For exposure at home:

$$E_{i(H)}^{j}=\sum_{p=1}^{P}\left(N_{NPE}^{p}+N_{ND}^{p}\right)\left(1-R_s\right) \tag{3.2.7}$$

In Formula(3.2.7), The ratio R_s is the specified fraction of exposed population being sheltered, for either rural or urban area.

For exposure on the routes (En-route exposure), it primarily contains two steps. First, the EMS data structure is constructed using evacuation routes and road statistics. Second, EMS data is exported to MatLab scripting programs for exposure identification (location of time of exposure). To keep the concision of the thesis, further mathematical descriptions about EMS construction and implementation of dynamic exposure identification are elaborated in Appendix A2: **Mathematical description of EMS data structure and en-route exposure identification**.

3.2.4. Evacuation Routing

3.2.4.1. Assumption

As discussed in the section of "General Approaches and Methods", for the short/no-notice evacuation, it is suggested by literatures (Adam J. Pel, et al., 2012) to focus on the optimal routing for individual evacuee and also for the overall performance of the system. Particularly for the case of flooding, relevant study in the Netherlands about flood hazard (A. J. Pel, et al., 2008) has suggested the first thing to do is evacuating the people as quick as possible. Therefore the very basic assumption of evacuation routing in this study is that **all evacuees of each neighbourhood for each time instant only choose one evacuation exit and one optimal route**. Under this assumption, a state-of-art network algorithm CASPER (Capacity-Aware-Shortest-Path-Evacuation-Routing) and a developed ArcGIS extension (ArcCASPER) are applied for evacuation routing.

Other assumptions about evacuation routing include:

- A pre-trip route choice assumption: the evacuees choose route at departure and cannot deviate from the prescribed routes during their trip (full-compliance assumption).
- Once the traffic flow on roads exceeds critical value (related with road capacity), the performance of system (e.g. traversal speed on roads, congestion level) will decline.
- For disorganized evacuation, selfishness dominates route choice, while every evacuee tries to occupy the optimal (shortest) route to the closest exit, with no consider about others' behaviour. In another word, a simple All-or-Nothing traffic assignment is applied. In this situation, severe congestion and malfunction of network are likely to happen.
- For organized evacuation, optimized routes which are simulated by CASPER algorithm are prescribed for evacuees. It is assumed that people fully comply with the predefined routes during the trips.

For sake of simplification, complex traffic issues, like interactions of traffic between time instants, effects of intersections, etc. are not engaged into this routing model.

3.2.4.2. I/O Relations

Inputs (From: Network Generator, Evacuation Exits Selector, Departure Pattern Simulation, Evacuation Scenarios):

- Network available at each time instant[29] ($availNet(t)$)
- Evacuation exits available at each time instant [30]($evacExits(t)$)
- Number of vehicles departing from neighbourhood p at each time instant[31] (the major results of Evacuation Demand)($veh_p(t)$)
- Family size of each neighbourhood (FS_p)

---

[29] Road available at each time would be affected by flood propagation. As expansion of flood goes, there would be smaller portion of road network available for evacuation.

[30] Locations for exits in different evacuation scenario might be different according to different criteria (e.g. in disorganized evacuation scenario, exits are selected empirically by static evaluation of distance between exits and origin locations, given that evacuees have little information about dynamics of floods; while in organized evacuation scenario, exits are dynamically evaluated and selected by evacuation organizer, and then appointed and informed to evacuees, in order to prevent evacuation towards dangerous zones that is dose to approaching floods.

[31] Numbers of vehides are estimated from population participating in evacuation at neighbourhoods, family size and departure pattern over time.

Outputs (To: Exposure Estimation)

- Evacuation Routes for neighbourhoods at each time instant ($RT_p(t)$), with travel time of routes ($T_{evac}^{p}(t)$) and number of evacuees ($N_{D(t)}^{p}$) as attributes
- Traffic statistics over all road segments engaged in routing (estimated traversal cost, $Eg_p(t).cost$)

3.2.4.3. Route Optimization

The optimal route from origins (neighbourhood) to destinations (evacuation exits) would be determined by different traffic assignment (routing) algorithm, under different scenario settings. Two major routing algorithms are adopted in this study: Shortest Path (SP) and Capacity-Aware-Shortest-Path-Evacuation-Routing (CASPER).

- **Shortest Path (SP)** algorithm is the traditional implemented shortest route algorithm in ArcGIS. The travel cost for each road segment is taken as original and no issue of road capacity/congestion would be considered. To apply this algorithm, it is assumed that people have no or little awareness/information about dynamic road conditions and other people's routing choices.
- **Capacity-Aware-Shortest-Path-Evacuation-Routing (CASPER)** is an heuristic optimization algorithm proposed by Kaveh Shahabi (2012). CASPER takes capacity of road into account and takes a fuzzy approach instead of using hard constraints on traffic volume. According to the review of existing traffic assignment methods in Chapter 2, it could be categorized as the incremental assignment method. The optimization process starts from sorting evacuee groups by their distance to the closest evacuation exit (destination), by performing a shortest path routing without considering effects of congestion. Then it authorizes the priority of the most attractive route for the farthest evacuees (at worst position by shortest-path routing) on the sorted list and assigns the population of evacuee to this route. Then the second-farthest neighbourhood is assigned the second-optimal route and so on. This process is iteratively repeated until there is no evacuee left. During this process, the real cost for road segment is updated by a logarithmic depreciation function based on number of assigned evacuees and road capacity. Different from typical User-Equilibrium methods, CASPER heuristically minimizes global evacuation time without hard constraints. Therefore, instead of individual optimal, throughout the process, system performance is targeted as optimization objective.

A detailed mathematical description about CASPER and dummy demonstration can be referred in Appendix A5: **Mathematical description of CASPER algorithm and a demo model**.

3.2.5. Evacuation Supply

As discussed in Literature review, it has been suggested by existing studies (Adam J. Pel, et al., 2012) that in evacuation modeling, dynamic destination availability with prevailing threat from hazard should be considered. Evacuation supply module functions as a generator for decreasing availability of infrastructure in flood which would be utilized during the whole process of evacuation. This module includes modeling of two major components of infrastructure: **road network** and **evacuation exits**, by considering dynamic flood characteristics as primary impact factors.

3.2.5.1. Network Generator

Sub-module of "road network generator" is set up in ArcGIS as a Geo-processing model to generate the changing availability of road network during flood propagation. Since the roads physically flooded over certain depth (presumably set as **0.3m**) would be regarded as an arbitrary restriction for evacuation, this part of network being inundated at time period t would be subtracted from original network.

Assumptions

- Roads that are inundated by flood water with over 0.3m depth are assumed to be dysfunctional and not available for evacuation
- Once roads are flooded, its availability status cannot be reverted.

I/O Relations

Inputs (From: Representation of Flood Propagation):

- Original road network ($originNet$)
- Dynamic water depth at each time instant ($h(t)$)

Outputs (To: Evacuation Routing, Departure Pattern Simulation[32])

- Network available at each modeling time instant ($availNet(t)$)

Mathematical Description

Mathematical description is presented in Appendix A2: **Mathematical description of dynamic network availability**. Basically, the availability of network over time is determined by the spatial-temporal relations between road infrastructure and the flood. This dynamic relation is illustrated by Figure 3-10.

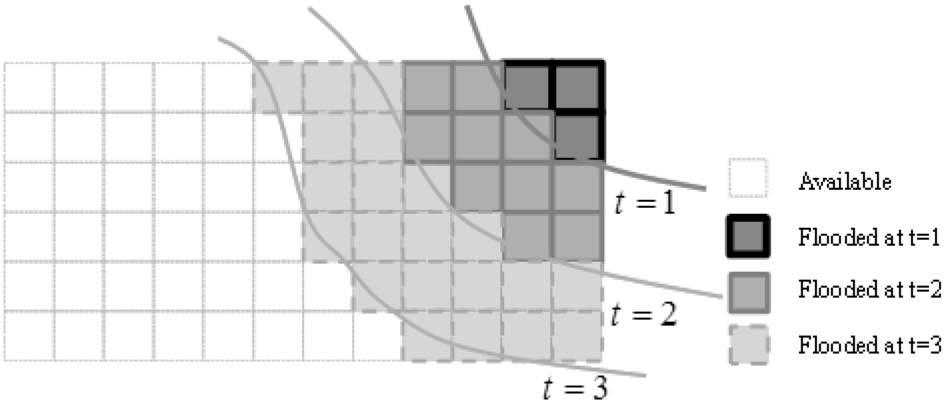

Figure 3-10 Illustration of dynamic network availability

3.2.5.2. Evacuation Exits Selector

Assumptions

- Virtual Super nodes assumption(van Zuilekom & Zuidgeest, 2008): since the essential purpose of evacuation in a short-notice flooding is to get people out of the area as quick as possible, virtual super nodes adaptive to the network data structure are assumed as the exits. Any area not flooded by maximum extension of flood is generally considered safe for evacuees who would use the road network and automobile as the unitary mode of traveling. The intersection points of road network[33] and maximum inundation area then are regarded as exits of evacuation. Once vehicles of evacuees pass through these exits they are considered as not being exposed to floods ever. These "Super nodes" identified are taken as potential exits or safe exits at the beginning. However,

[32] The dynamic network availability is one of the determinants for generating people's departure time window.
[33] Primary roads: including highways and primary roads.

as flood's expansion, some of these exits that are closer to floods may be too dangerous to be evacuated to.

- Under different settings of evacuation scenarios, selection of exits may be different. Selection of exits during the evacuation may be changed due to impacts of floods.
- **In Disorganized Evacuation**: with no or little information of flood expansion, all intersection points of inundation area and network could be served as candidates for exits. Being panic and unaware of flooding process, evacuees tend to be non-sensitive for exits with different threaten level and try to escape out of the area as soon as possible, via the closest exit. Therefore, choices of exits over time are static.
- **In Organized Evacuation**: it is possible and feasible to deliver the latest updated flooding situation by all sorts of warning and notification methods, such as TV, internet, broadcasting, SMS, mobile services, etc. Also, it is practical to perform an instant evaluation over all possible exits and select those that haven't been seriously affected by flood so as to prevent possible consequences that people could be caught up by flood on their way out of disaster (Although selection of exits is still quite deterministic here, in further modeling efforts, more complex decision-making process could be developed by considering hybrid top-down and bottom-up modelling approach, e.g. an integrated departure-destination choice model based on studies about evacuees' preferences). Hence, in an organized evacuation, exits are selected according to iterative evaluations about risk level at each exit (mainly by indicators like water depth and percentage of peripheral area being inundated) by evacuation organizers and delivered to evacuees for destination choice making. Hence, at each time period, exits might be different. However, it is assumed evacuees are still free to choose the nearest exit among those suggested. It is also noted that, trade-off between safety and efficiency has to made by following such exit evaluation-selection process, because while people are redirected to farther and hypothetically safer exits, longer traveling time and more congestion could be expected.

I/O Relations

Inputs (From: Representation of Flood Propagation):

- Original road network ($originNet$)
- Maximum water depth ($h_{\max}$)and dynamic water depth ($h(t)$)

Outputs (To: Evacuation Routing, Departure Pattern Simulation):

- Exits available for evacuation at each time instant ($evacExits(t)$)

Mathematical Description

As demonstrated in Figure 3-11, exits are constantly evaluated about its prevailing risk level. Two indicators are considered: average water depth and percentage of area being inundated in a specified buffer of each exit. Detailed mathematical explanation is presented in Appendix A3: **Mathematical description of dynamic exit availability**.

The dynamic selection of exits is demonstrated as in Figure 3-11.

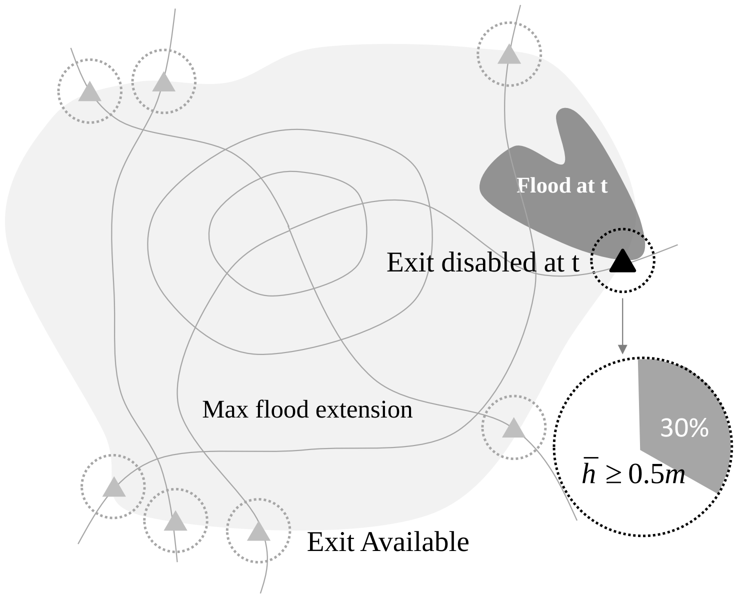

Figure 3-11 Demonstration of Dynamic Exit Selection

3.2.6. Evacuation Demand

Evacuation demand model is crucial for the whole evacuation modeling, as it provides fundamental information of people's participation in evacuation and dynamic departure-pattern. Such information is directly used by evacuation routing and exposure estimation model. As discussed in Literature review, the essential question answered by Evacuation Demand model is that how many people (or vehicles) will depart from their houses at certain time instant. Pel et al. (2012) summarize two modelling paradigms for evacuation demand modeling: sequential model in which the participation share and departure pattern are estimated sequentially, and simultaneous model that applies a utility-based logit model to get both answers at the same time. As the later approach requires more observation or survey data for model calibration, in this MSc study the first approach, sequential model is adopted as the approach for demand modeling.

By adopting the sequential modeling paradigm, the demand model could be organized by three sequentially interconnected modules:

1) Identification of Population at Risk
2) Share of Participation Estimation
3) Departure Pattern Simulation

The following sessions explicitly explain the assumptions, inputs/outputs, methods used in each of the three modules, and how they are interconnected.

3.2.6.1. Identification of Population at Risk

The first step of demand modeling is to identify the population at risk (N_{PAR}) which is considered as the maximum population possibly affected by floods. Wilmot et al. (2005) utilize GIS spatial analysis to identify evacuation zones and population needed to be evacuated, by analysing spatial relation between hazard and residential areas. This simple approach is adopted in the study.

Assumptions

- People are considered as at risk of flood once all or parts of their neighbourhoods are inundated by the maximum extent of flood (Over threshold of flooded percentage).

- For sake of simplification, it is assumed when the flood occurs; all people stay in their houses, no dynamic population distribution (at working places, schools, etc.) will be involved.

I/O Relations

Inputs (From: Representation of Flood Propagation, basic demographic data):

- Boundaries of neighbourhoods in the study area ($Neigh(P)$)
- Neighbourhood population ($Neigh.pop$)
- Maximum flood extent or maximum water depth

Outputs (To: Share of Participation Estimation)

- Population at risk for each neighbourhood $p : N_{PAR}^{p}$

Mathematical Description

Neighbourhoods at risk are simply identified by spatial intersection between neighbourhoods and flooding extend. Those neighbourhoods that certain proportion (above the threshold) would be flooded by maximum flooding extent are selected as neighbourhoods at risk.

$$\begin{aligned} & N_{PAR}^{p} = Neigh(p).pop \\ & \text{if: } \left(\text{AREA}(h>0) / \text{AREA}(Neigh(p)) \geq thresh\right) \end{aligned} \tag{3.2.8}$$

3.2.6.2. Share of Participation Estimation

The people at risk may participate in evacuation or choose to stay at homes for various reasons. So, it is necessary to estimate the share of evacuation participation among those at risk (N_{PAR}^{p}). Based on literature review about the factors taken into account for participation share estimation (Baker, 1991), a cross-classification approach (PBS&J, 2000) is applied. All neighbourhoods will be categorized into different types based on relevant factors, and then each category of neighbourhoods is assigned a uniform participation share[34].

Assumptions

- It is assumed by apply a classification method that all neighbourhoods belonging to the same category have homogeneity in participation behaviour.
- Two factors, demographic vulnerability and hazard level are assumed as relevant factors for classification[35].
- Demographic vulnerability mainly consider about the percentage of the elders who are generally considered of less mobility. So, higher percentage of the elders would lead to lower participation in evacuation.
- On the other side, obviously higher hazard level which could be indicated by flood zone types would increase the participation share, because people at higher-risk areas have stronger intention to be evacuated.

[34] Without historical evacuation participation data, the share for each category would be determined by literature review or expert knowledge.
[35] In other studies, more factors like house types have been considered, however due to limitations of research data, this study focuses on two major factors that incorporate both natural hazard and social vulnerability.

I/O Relations

Inputs (From: Identification of Population at Risk, basic demographic data, Flood Zones Classification):

- Identified neighbourhoods at risk and their population (N_{PAR}^{p})
- Percentage of age groups (65 years+)
- Flood zone types ($brcZone, rapRisZone, remZone$)

Outputs (To: Departure Pattern Simulation, Exposure Estimation):

- Share of participation for each neighbourhood $p : S_{PE}^{p}$
- Population participating in evacuation: N_{PE}^{p}
- Population not participating in evacuation: N_{NPE}^{p}

Cross-Classification Method

First, demographic vulnerability and hazard level are evaluated. For demographic vulnerability, percentage of the elders is taken as indicator. It is then categorized into two types (by distribution analysis and threshold setting): high/low vulnerability. Hazard level is directly derived from the nominal values of flood zone types, with hazard level specified as: breach zone > zones with rapid rising water > remaining zone[36].

Table 3-1 Cross-Classification Table for Participation Share Estimation

Classification Criterion		Hazard Level		
		$brcZone$ (High)	$rapRisZone$ (Mid)	$remZone$ (Low)
Demographic vulnerability	High	S1	S2	S3
	Low	S4	S5	S6

After the participation shares are specified, the other outputs are estimated as shown below.

$$N_{PE}^{p} = N_{PAR}^{p} \cdot S_{PE}^{p} \tag{3.2.9}$$

$$N_{NPE}^{p} = N_{PAR}^{p} - N_{PE}^{p} \tag{3.2.10}$$

3.2.6.3. Departure Pattern Simulation

This module estimates the fraction of evacuation participants departing their houses at each time instant. The frequently used departure curve method is applied, due to its mathematical simplicity and less intensive data requirements.

Assumptions

- Basic assumption of departure pattern is that the evacuation participants do not depart their houses at the same moment, but start evacuating following a hypothetical temporal pattern.
- The departure process could be terminated by the arrival of floods, leaving less than 100% participants successfully departed.

[36] Since flood zone types are classified on raster base, one neighbourhood may contain different zone types. Therefore, aggregation is needed (e.g. the majority of zone types are set as the flood zone type for the particular neighbourhood).

- Departure curve adopted in this study follow a logistic form.
- Departure pattern for neighbourhoods in different flood zone types may be different.
- Departure process may be stopped even before the arrival of floods. It is assumed that once people cannot find any route (due to less available roads), they are assumed to stay at home. Hence for each neighbourhood, a departure time window (ETW) is assumed.
  According to timeline model (Frieser, 2004), processes like warning, response to warning are assumed to be prior to initiation of departure. The times needed for warning, response to warning are specified by Evacuation Scenarios.
- It is assumed that people's departure rates are affected by the flood zone type where they live in. The people live in areas with higher risk (breach zones and zones with rapid rising water) could response much faster than those living in lower-risk areas.
- In smaller study area like Land van Maas en Waal, it can be assumed for all neighbourhoods a uniform warning time is set up.

I/O Relations

Inputs (From: Share of Participation Estimation, Evacuation Supply, Flood Zones Classification, Evacuation Scenarios, Representation of Flood Propagation):

- Share of participation (S_{PE}^{p}) and number of evacuation participants: N_{PE}^{p}
- Network available at time t: $availNet(t)$, for identifying time window (ETW)
- Exits available at time t: $evacExits(t)$, for identifying time window (ETW)
- Flood zone types ($brcZone, rapRisZone, remZone$)
- Time of flooding layer (ttf_q)
- Warning time needed (T_{warn}) and time of response (T_{resp}) before the actual evacuation
- Family size of neighbourhoods (FS_p)

Outputs (To: Evacuation Routing, Exposure Estimation):

- Number of vehicles departing from neighbourhood p at each time instant ($veh_p(t)$)
- Population participating in evacuation but not departing due to coming flood at each neighbourhood p (N_{ND}^{p})

Modeling the time schedule

For simulation of departure pattern, general time schedule of departing is analysed first. As shown in Figure 3-12, the total process of departing is comprised of warning, response to warning and the actual departing. As discussed, the departing process may be terminated by either decreasing network availability (people cannot find any route to the exit) or coming flood (the neighbourhood is flooded), so it is important to identify the time window for departure (ETW) which is basically defined by starting and ending time of departure.

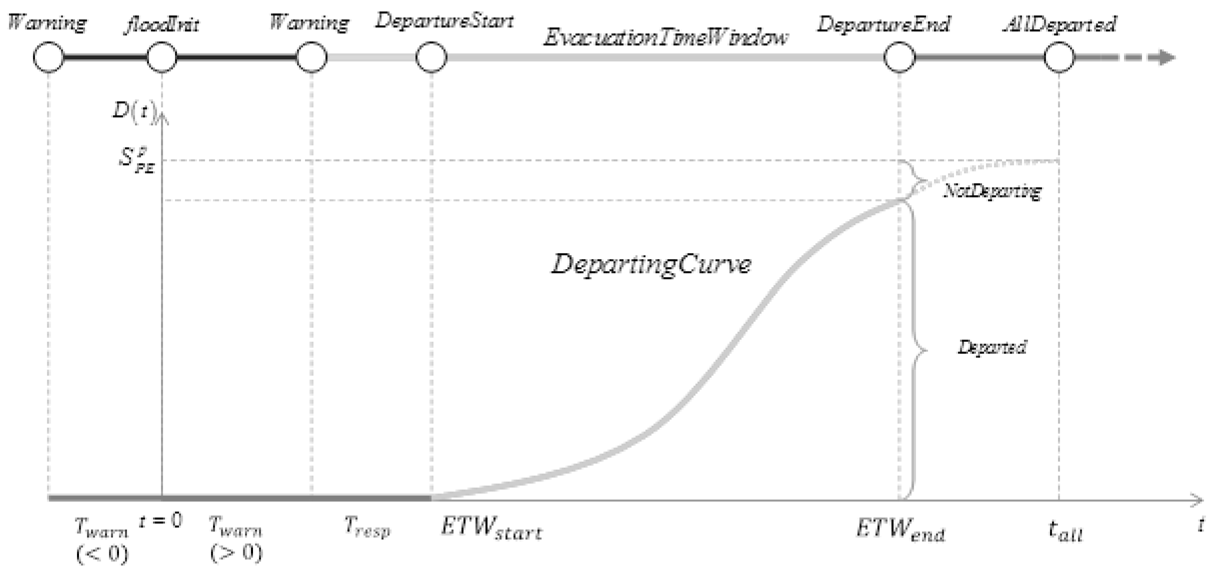

Figure 3-12 Schematic Description of General Time Schedule of Departing

Time of warning (T_{warn}): this is a parameter given by evacuation scenario. It describes how much time is needed for delivering the time. It is related to the possibility of prediction. With prediction for flood, warning may be delivered prior to the initiation of breach while time of warning is denoted as negative ($T_{warn} < 0$). Contrarily, with no prediction, message of warning is sent after the start of flood, so the time of warning is positively valued ($T_{warn} > 0$). For all neighbourhoods, time of warning is identical, which means all people receive the warning at the same moment.

Time of response to warning (T_{resp}): it is the time between the receiving of warning and the actual start of departure. Usually, it depends on people's compliance to warning and evacuation instructions (Adam J. Pel, et al., 2012; A. J. Pel, et al., 2008), household decision making process, prior knowledge of evacuation, etc. In this study, for the simplicity of modeling, time of response to warning is set as identical for all neighbourhoods.

Starting time of departure (or starting point of time window) (ETW_{start}): as illustrated in Figure 3-12 and Formula(3.2.11), start of departure depends on both time of warning and response.

$$ETW_{start} = T_{warn} + T_{resp} \tag{3.2.11}$$

Ending time of departure (or ending point of time window) (ETW_{end}): since the ending time of departure is affected by multiple factors, a comprehensive determining procedure is proposed and explained in Appendix A6: **Mathematical description of procedures determining the ending time of departure**.

Implementation of departure curve

First, the population of participants is converted to number of vehicles by estimating the number of households and assuming one car for one household.

$$veh_p = N^p_{PE} \big/ FS_p \tag{3.2.12}$$

The departure of these vehicles over time is simulated by the logistic departure curve which has been discussed in Chapter 2, with mathematical from in Formula(3.2.13) and (3.2.14)

$$E(t) = \left(1 + \exp\left[-\alpha\left(\left(t - ETW_{start}\right) - \beta\right)\right]\right)^{-1} \tag{3.2.13}$$

$E(t)$ is the share of vehicles which has departed from starting point of time window to the prevailing time instant t; α : response rate; β : half-loading time. Parameters α , β control the speed of departure. Their values are specified in Evacuation Scenarios.

So, the fraction of vehicles departing at each time instant t is estimated as below.

$$D(t) = \begin{cases} 0 & t = ETW_{start} \\ E(t) - E(t-1) & t = ETW_{start} + 1, \ldots, ETW_{end} \end{cases} \tag{3.2.14}$$

Then, based on Formula(3.2.14), the major outputs, number of vehicles departing at t and total population of participants not departing can be derived from the fraction of departure over time.

$$veh_p(t) = veh_p \cdot D_p(t) \tag{3.2.15}$$

$$N_{ND}^{p} = N_{PE}^{p}\left[1 - E\left(ETW_{end}\right)\right] \tag{3.2.16}$$

3.2.7. Evacuation Scenarios

In order to address the issue of uncertainty about human behaviour to a proposed flood, different scenarios are proposed to specify variety of behavioural characteristics. Existing studies about flood risk evaluation (S. N. Jonkman, Kok, et al., 2008; Maaskant, et al., 2009; Rijkswaterstaat, 2006) have used decision tree to build scenarios for human behaviour, particularly about evacuation process.

Evacuation scenarios are set up in a decision-tree like structure. Since similar study in Dutch context (Rijkswaterstaat, 2006) has asserted that the efficiency of human response to flood is to large extent affected by predictability of the coming flood and degree of organization of evacuation. The scenarios adapted for this case study similarly focuses on these two aspects.

The evacuation scenarios are established as Figure 3-13, each scenario is associated with hierarchical layers of conditional probability of occurrence which would be determined by expert knowledge. Issues needed to be specified for predictability of flood and organizations of evacuation are listed below.

- Predictability of flood
  - Availability of prediction and warning in advance of flood initiation
  - Time of warning for each inundation type zone (T_{warn})
- Evacuation Organization
  - Time of response for each inundation type zone (T_{resp})
  - Departing Speed: represented by parameters of departure curve(α, β)
  - Evacuation Exits Selection (static or dynamic evaluation)
  - Evacuation Routing Optimization Methods (Shortest-Path (SP) or Capacity-Aware-Shortest-Path-Evacuation-Routing ($CASPER$))

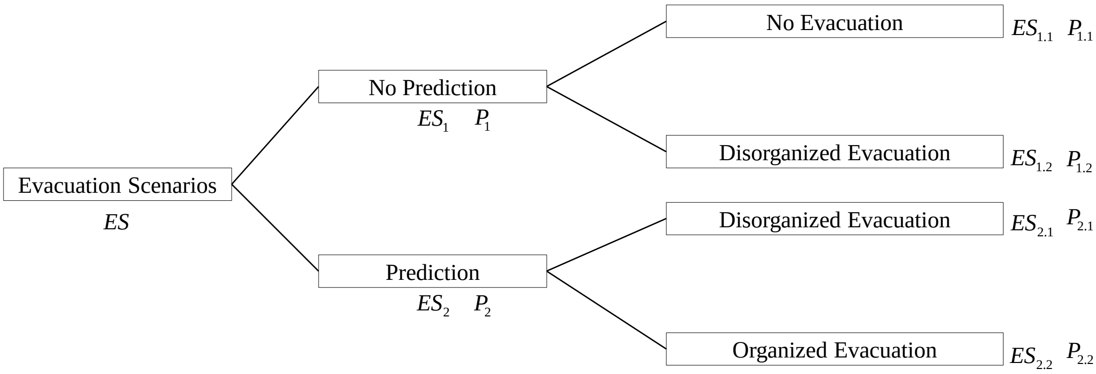

Figure 3-13 Illustration of Evacuation Scenario in a Decision-Tree Structure[37]

The specification of each evacuation scenario is illustrated in Table 3-2.

Table 3-2 Specification of Evacuation Scenarios

Evacuation Scenario	No Prediction - No Evacuation	No Prediction - Disorganized Evacuation	Prediction - Disorganized Evacuation	Prediction - Organized Evacuation
Index of scenario	S11	S12	S21	S22
Scenario Probability	P_1P_{11}	P_1P_{12}	P_2P_{21}	P_2P_{22}
Advanced Warning	Not available	Not available	Yes	Yes
Time of warning	N/A	2	-2	-2
Time of response to warning	N/A	Slow-Response (4)	Quick Response(2)	Gradual Response (phrasal by flood zone type)(0, 2, 4)
Exits Selection[38]	N/A	Static	Static	Dynamic
Routing Optimization	N/A	SP	SP	CASPER

As shown in Table 3-2, it is assumed that once prediction for the flood is available, the time to deliver the warnings of flood is 2 hours prior to the actual occurrence of the dike-break (t=0), while in scenario S12 warning is delayed by 2 hours because it is assumed that the flood happened totally unexpected. Warning information is delivered by media (TV news, broadcasting or internet). Therefore, the time when warning is delivered much be later than the actual occurrence of the flood.

Times of response to warning are specified for different evacuation scenarios. For scenario S12 (no prediction – disorganized evacuation), since only fraction of population are informed the flood warning via unofficial media, people need some time to pass on messages to family members or friends who are not informed yet. Also, additional time is spent in verifying authenticity of the warnings. Therefore, in this situation, response time is longer than that in scenarios with prediction and organizations. In scenario S21, early prediction and lack of organizations cause some degree of panic, so people start departure earlier. In scenario S22, while evacuation organization is in presence, people living in remaining zones (with lower risk of being inundated) are arranged to evacuate 2 hours later than those in high-risk areas (zones with rapid rising water). The prioritization for people in high-risk zones has at least two purposes: 1) prevent

[37] Source: Rijkswaterstaat, 2006, re-drawn by the author.
[38] See: Evacuation Exits Selector

mass exposure in high-risk areas (zones with rapid rising water) because mortality rate here is much higher than that in remaining zones; 2) hold back concentrated departure within the first several hours to avoid congestion on roads. So in S22, people's departure time windows are staggered.

As discussed above, the parameters of departure curve would be specified for both scenarios and flood zone types. Both parameters are specified based on literature review and expert knowledge. Assumptions about the departure rate include that:

1) People living in zones with higher flooding hazard (breach zone > zones with rapid rising water > remaining zones) tend to depart faster
2) Due to panic caused by early warning and lack of organization, in scenario S21 people depart faster than the other scenarios.
3) Being less informed and not organized, people in S12 depart at the lowest rate.

Table 3-3 Specification of Departure Curve Parameters

Response Rate (α)		Scenario		
		S12	S21	S22
Flood Zone Types	*brcZone*	3	5	4
	rapRisZone	1.2	2	1.5
	remZone	0.8	1.5	1.2
Half-loading Time (β)		Scenario		
		S12	S21	S22
Flood Zone Types	*brcZone*	6	1	1.5
	rapRisZone	8	4	5
	remZone	15	8	9

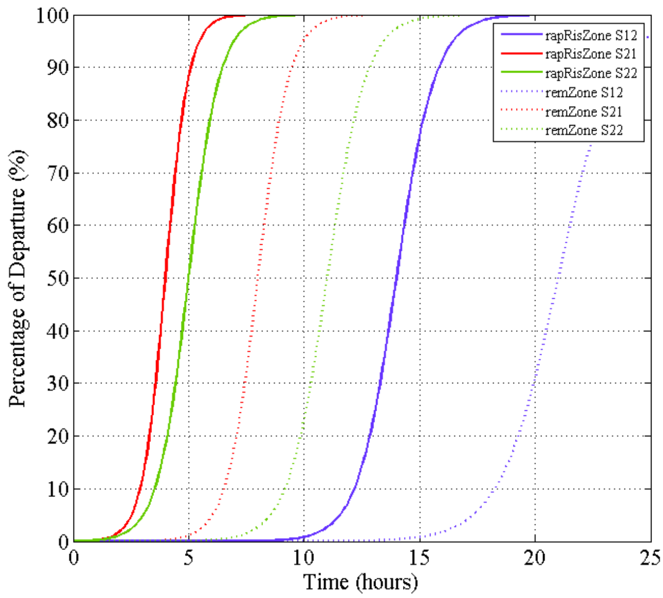

Figure 3-14 Departure Curves for all Scenarios

4. DATA COLLECTION AND PROCESSING

4.1. General Data Requirements

In order to implement the designed linked modelling procedures discussed in Chapter 3 in the case study area, different datasets within study area are needed. According to the design of model I/O relations and Table 1-1, there are three categories of datasets that are basically required in this study.

- Data of simulation about one flood scenario (flood propagation)
- Data of Transportation Infrastructure
- Demographic data based on analytical spatial unit

Data of flood simulation is basically dynamic series of flooding characteristics on raster base, e.g. water height, velocity, rising rate, time of flooding, etc. Data of transportation infrastructure describes the spatial layout and traversal properties of road network which are prevailingly affected by floods. Demographic data includes the total population, family size, age group distribution and administrative boundaries of all neighbourhoods (basic analytical unit) in the study area. Demographic data is essentially utilized for estimation of evacuation demand and exposed population.

4.2. Data of Flooding Simulation

In this study, data of flood simulation is authorized by ITC professor D. Alkema as the data and visualization materials from a research called: "Water constitutional structure of river polders: A renewed role for cultural and historical elements (Translated to English, Originally in Dutch: "Water staatkundige inrichting van rivierpolders: Een hernieuwde rol voor cultuurhistorische elementen") which was completed in April, 2003. This study carried out simulations for 28 different flooding scenarios, composed by combination of 4 future development strategies towards current water and landscape structure and 7 possible breach entries/types. This study takes one of the 28 scenarios as the input flooding scenario into modeling: "current situation – inlet location: Weurt (River Waal) - type: breach (namely: A1b)" as illustrated in Table 4-1 (Alkema & Middelkoop, 2005). Detailed description about settings of different flood scenarios can be found in Appendix C1: **Settings of Flood Scenarios**.

Table 4-1 Overview of all 28 flood scenarios[39]

			Topography			
			A[40]	B[41]	C[42]	D[43]
River	Inlet Location	Type	(Current Situation)	(Cleaned)	(Restored)	(Enhanced)

[39] Source: Alkema & Middelkoop, 2005

[40] Current situation: the reflection of current situation. Remnants of old dikes which are often not complete and contiguous in countryside are kept. Landscape is characterized by modern infrastructure such as roads, highways and railways increasingly constructed.

[41] Cleaned: All remnants of old dikes in the polder are removed and thus constitute no obstacles to flooding. Modern landscape is still present in this variant.

[42] Restored: all dike remnants dating from 1850 that are still present are "repaired" and linked with modern landscape to form a dense network of damming elements.

[43] Enhanced: selectively change upon in-polder dike elements and modern landscape to achieve optimized flood effects mitigation.

Waal	Weurt	breach	**A1b**	B1b	C1b	D1b
		spill over	A1o	B1o	C1o	D1o
	Deest	spill over	A2o	B2o	C2o	D2o
	Druten	spill over	A3o	B3o	C3o	D3o
Maas	Overasselt	breach	A4b	B4b	C4b	D4b
		spill over	A4o	B4o	C4o	D4o
	Batenburg	spill over	A5o	B5o	C5o	D5o

The flooding scenario "A1b" is modelled by the 2D flood propagation model Delft-FLS (Alkema & Middelkoop, 2005). The generic information about the flood is described as:

- Maximum flooded area: **213 km^2**
- Maximum recovered water volume: **547×10^6 m^3**

Exported modelling parameters include major water characteristics (both dynamic at hourly time instant and maximum level) listed below.

- Water depth (hourly and maximum, m)
- Velocity (hourly and maximum, m/s)
- Impulse (Product of water depth and velocity, maximum, m^2/s)
- Rising Rate of Water (maximum, m/s)
- Time to flooding (hour)

These results are generated as ASCII files, which are then imported into ArcGIS and converted to Geodatabase raster datasets with uniform projection system RD-new used in this study; all hourly maps of each flood characteristic are indexed and stored in one "Raster Catalog" appended with time fields which is more manageable for dynamic evacuation modelling. This process is replicated for all flood characteristics listed above. Snapshot illustrating temporal data about flood characteristics managed in ArcGIS is presented in Appendix C2: **Organization of flood characteristics datasets in ArcGIS**.

4.3. Transportation Data

Transportation data is obtained from the open-sourced OpenStreetMap (OSM) online dataset[44]. Because the data is downloaded as OSM format, it is converted to ESRI Shapefile format with RD-new projection which is compatible with ArcGIS via help of open-sourced PostGIS database utilities. The converted road and street data contains necessary fields with useful information like road types (hierarchical) and driving directions.

4.3.1. Data Verification and Correction

Since OSM data is open-sourced and not being strictly verified. There could be errors in geometry, topology and thematic properties. For verification about thematic information, random samples are taken by comparing road attributes (road type and driving directions) with Google Map Street View (GMSV). If any error is identified, field value of corresponding segment is corrected instantly. For possible topological mistakes, the data verification focuses on road intersections and roundabouts (both planar and non-

[44] OSM data is restricted for download by smaller spatial extent. The OSM data used in this study is retrieved from CloudMade online database which is free online OSM repository categorized by different countries and provinces. Online Link:
http://downloads.doudmade.com/europe/western_europe/netherlands/gelderland#downloads_breadcrumbs

planar). Topological errors like false intersections around roundabout shown in Figure 4-1 are corrected using ArcGIS topology tools. GMSV images are also employed for topology verification.

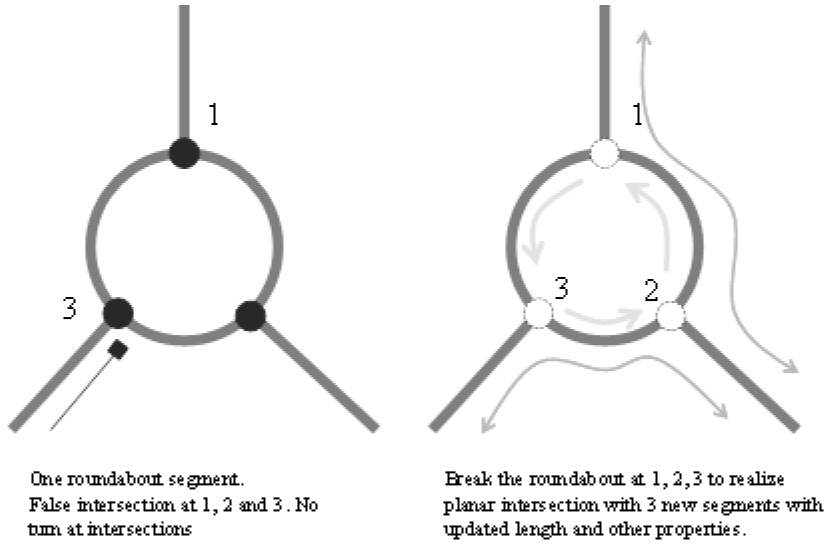

Figure 4-1 Topology Corrections at Roundabout

4.3.2. Evaluation of Road Attributes

Properties of roads including road types, <u>driving directions, number of lanes and most important travel cost</u> (by travel time) should be properly evaluated for network building. However, since OSM data has contained redundant road features (e.g. pedestrian lanes, cycling lanes, etc.) which are not necessarily needed for vehicle evacuation, thus prior to road attributes evaluation certain types of roads should be selected as automobile roads. As shown in Figure 4-2, highway, trunk roads, three major levels of automobile roads (primary, secondary and tertiary), ferries and unclassified [45] roads in the fields and residential areas are selected.

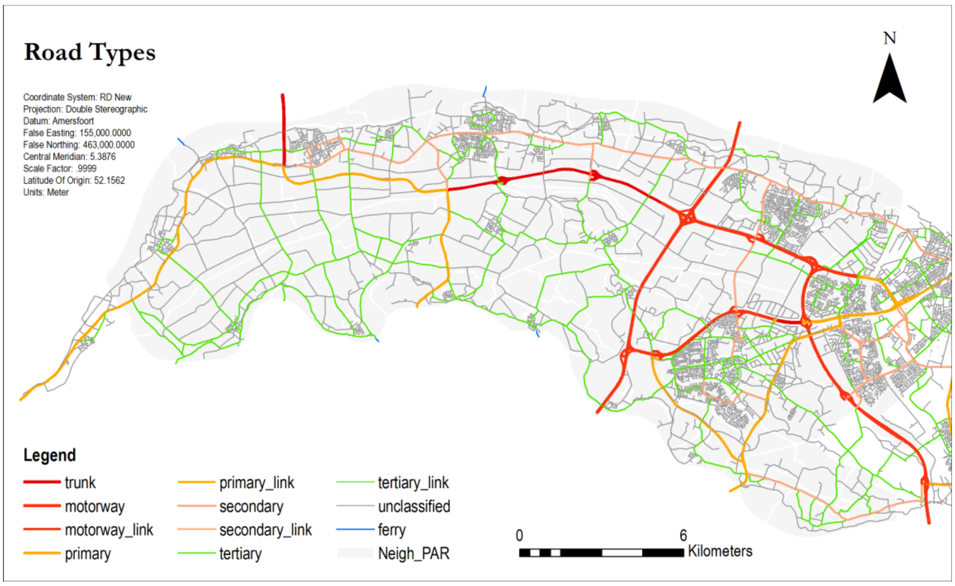

Figure 4-2 Road Types Selected in Study Area

[45] In OSM data, unclassified road type refers to minor public roads typically at the lowest level of the interconnecting grid network. Unclassified roads have lower importance in the road network than tertiary roads, and are not residential streets or agricultural tracks (Source: http://wiki.openstreetmap.org/wiki/Tag:highway%3Dunclassified).

For driving direction, as it has been evaluated in OSM data and verified, it is directly evaluated. If Boolean value of "one-way" field is true, driving is only allowed along digitization direction of the line segment, otherwise both directions are available. From Figure 4-3, it is seen that most highways, linking roads (ramp) and some roads in western Nijmegen are one-directional.

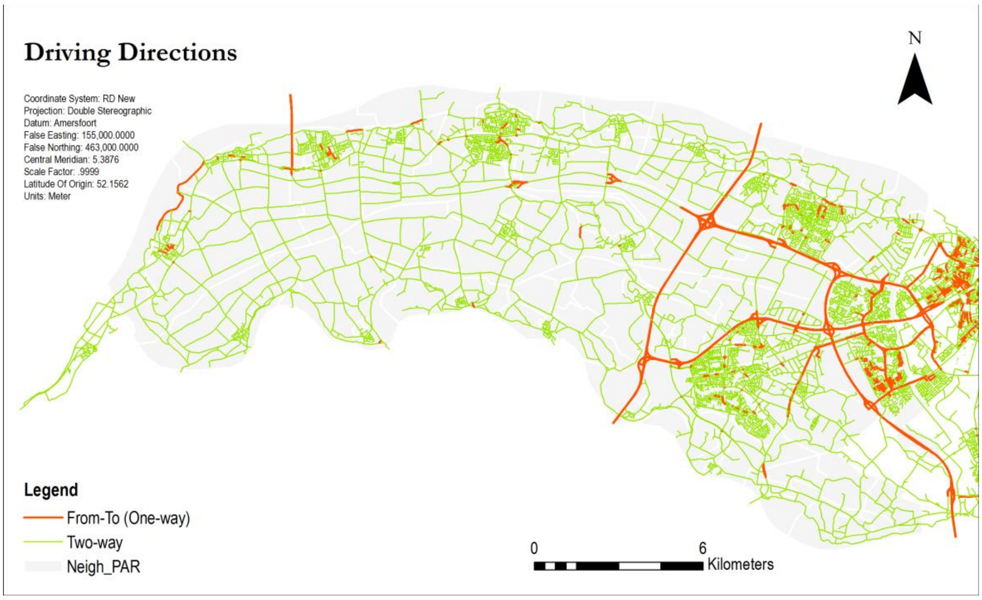

Figure 4-3 Driving Direction of Roads

For number of lanes and free-speed (highest speed), it is specified by road types via real observation via Google Street View and conventional Dutch traffic regulations. A detailed summary about road attributes specification is presented in Appendix C3: **Specification of road attributes by road types**.

After evaluation of free speed, travel cost can be estimated by dividing road length with estimated speed. Unit for travel cost is minutes.

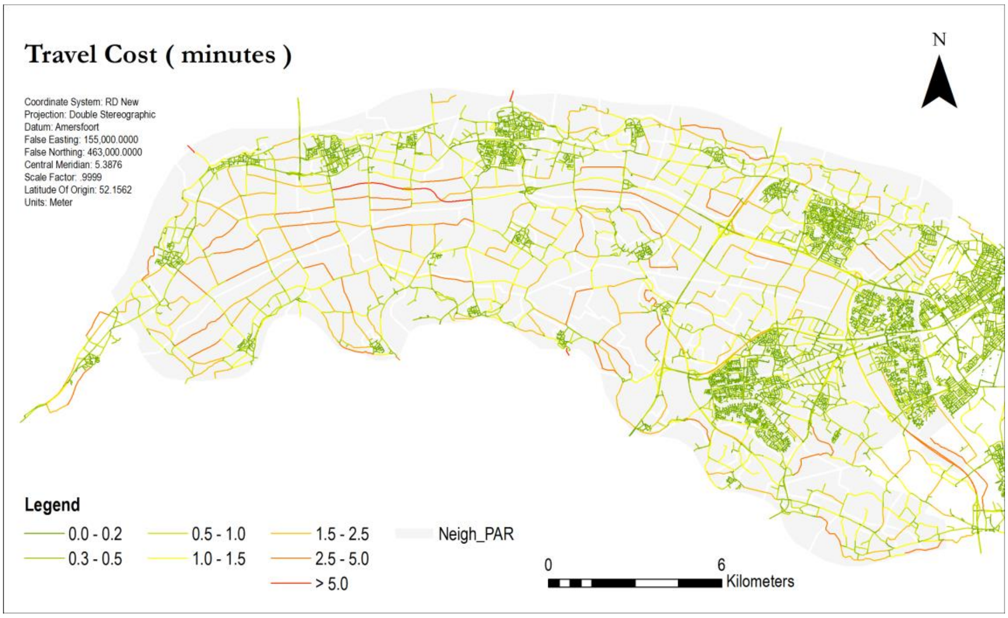

Figure 4-4 Travel Cost Estimated for Road Segments

4.4. Demographic Data

Demography statistics which are extracted from CBS Statistics Netherlands (2007) Database are organized at neighbourhood level (PC5) including population, family size and percentage of elder population (above 65 years).

As described in sub-section 1.1.2 "Case Study Area", most population in the study area concentrate in the eastern part and several scattered towns in the south bank of river Waal. As shown in Figure 4-5, unlike Zipf distribution revealed by population data, distribution of family size is close to normal, and most neighbourhoods have average family size between 2.4 and 2.8 persons/household. Concerning the aging of population, generally there are fewer neighbourhoods with higher aged population shares; still it is significant that at considerable amount of neighbourhood, there are 13%-14% of total population are elders above 65 years with less mobility who appears to be more vulnerable in flood and evacuation.

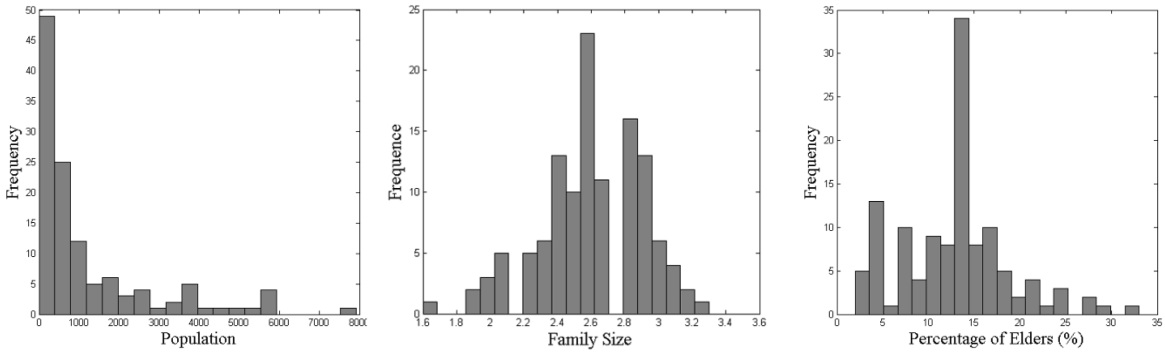

Figure 4-5 Frequency Distribution of Population, Family Size and Percentage of Aged Peoplee

Demographic data are linked with administrative boundary of neighbourhoods and stored as feature class in Geodatabase.

5. LINKED FLOODING-EVACUATION MODELLING[46]

5.1. Representing Flooding

5.1.1. Visualization of Flooding Process

As explained in Chapter 3, the linked flooding-evacuation modeling starts from a description and study about the process of flood propagation. The raster-based flood characteristics are visualized in ArcGIS to get the information about the intensity distribution and temporal progress of the flood. Static maps showing maximum intensity of the flood are created, in addition, animations depicting the flood dynamics are generated by taking advantage of temporal Raster Catalog (see in Appendix D1: **Demonstrative Animations (Hyperlinks)**). Major characteristics at their maximum levels are displayed in Figure 5-1.

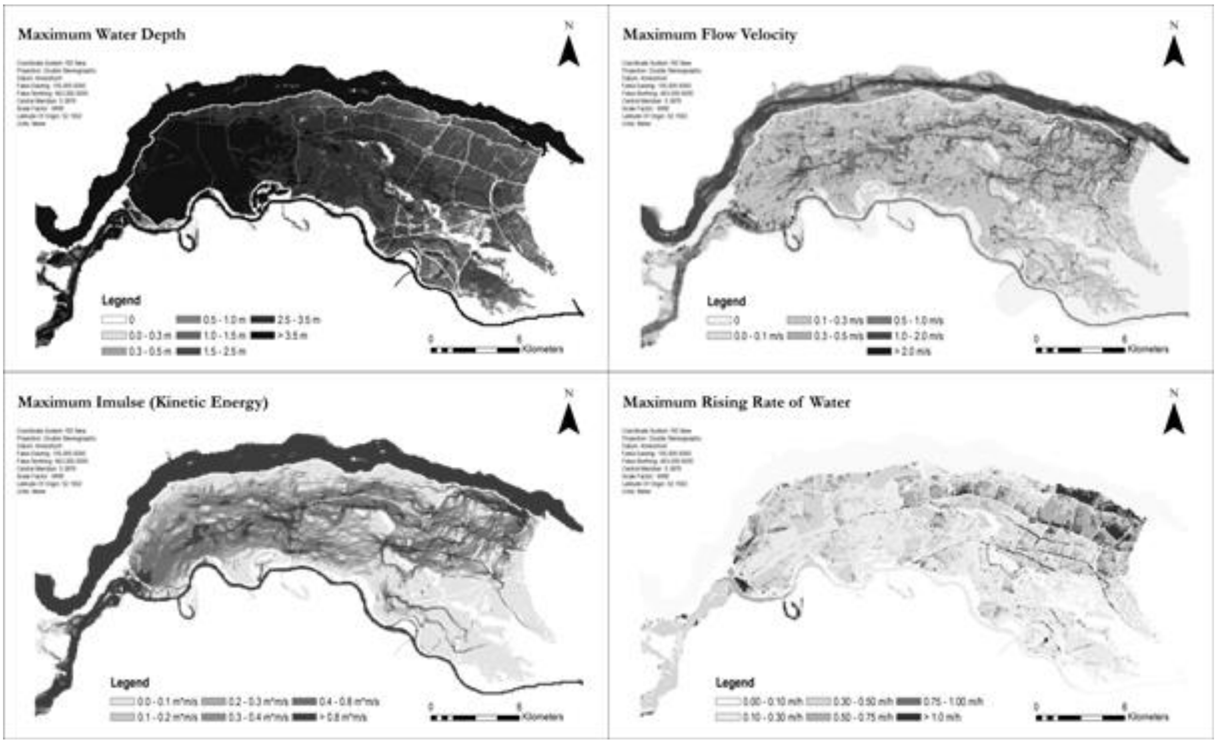

Figure 5-1 Major Flood Characteristics (Maximum Level)

Water depth, flow velocity and kinetic energy together reveal the intensity of flood over space. Because of the lower position, the western part (mainly municipality of west Maas en Waal) of the study area suffers from much higher water depth and flow impulse, while in terms of velocity, except riverbed and river plain, the north-eastern part (municipality of Beuningen) the area along existing dike remnants and other water passages are of rapid water flows (velocity) which might cause instability to human beings or vehicles exposed in flood. It is also illustrated in the map of rising rate of water that area near the breach

[46] This Chapter mainly describes how to implement the modelling procedures designed in the Chapter of Methodology with the Data prepared in the study area, by essentially linking flood simulation and evacuation modelling. It also discusses potential, pros and cons of the proposed modelling methods.

(again, mostly Beuningen) and some area in the north-western corner are most likely severely struck by rapid inundation.

Figure 5-2 shows the dynamic expansion of flood in space. First of all, in addition to the threat on vertical direction (rapid rising of water), horizontally municipality Beuningen would be the first to be flooded, due to its proximity to the breach. The general westward trend of flood expansion is quite obvious: within 12 to 24 hours, the flood expands towards the west extensively and would inundate over half of the study area, while its southward advance is deterred somehow. Even if the south-eastern part (mainly municipality of Wijchen) is closer to the breach, it is still relatively far from the actual arrival of the flood (after 2 days), which might leave more than sufficient time for residents in this area to evacuate.

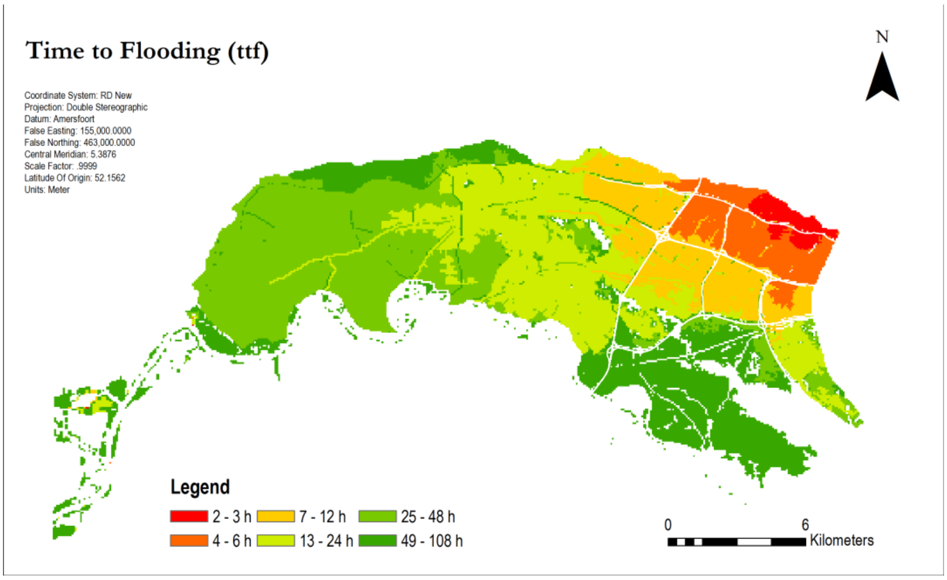

Figure 5-2 Time to Flooding in hours (ttf)

5.1.2. Classification of Flood Zones

Despite that the flood simulation model has provided fine results on a raster base (70m × 70m), the evacuation and exposure estimation modelling are yet carried out at broader neighbourhood level. In order to address the inconsistence of spatial resolution, it is necessary to aggregate flood information onto a higher neighbourhood level. The zonal classification approach (see Figure 3-4 and sub-section "Flood Zones Classification") is applied. Each 70m × 70m pixel with water characteristics is categorized by formula (3.2.1) into three types: breach zones ($brcZone$), zones with rapid rising water ($rapRisZone$) and remaining zones ($remZone$). Then each neighbourhood is assigned a sole flood zone type by majority of types of pixels contained by the neighbourhood. The pixel and neighbourhood classification results are shown in Figure 5-3. Although there are quite a few scattered lands by the north of road N322 and near western town Dreumel, much less neighbourhoods (only 4) are categorized as zones with rapid rising water.

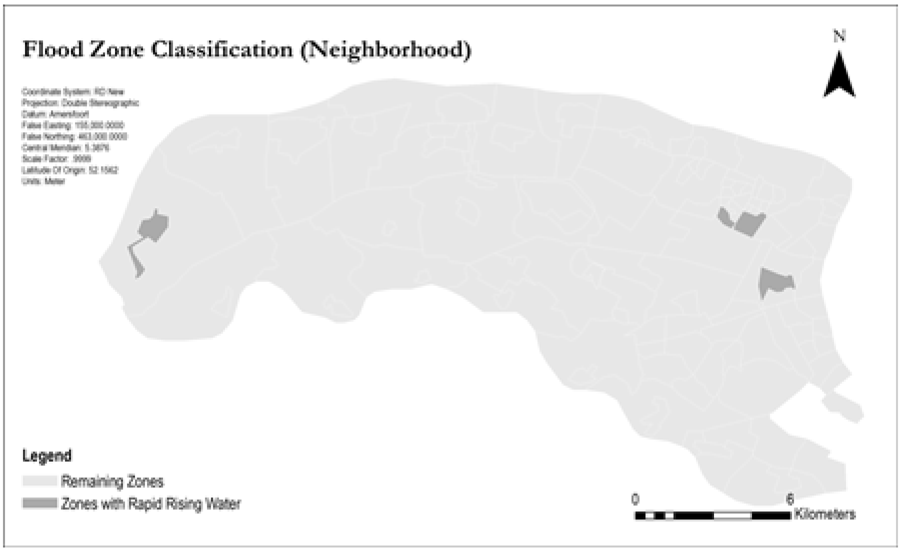

Figure 5-3 Flood Zone Classification and Aggregation on Neighbourhood

Information about flood zone types is stored in the attribute table of neighbourhood polygon feature class. It will be recalled for specification of evacuation participation and departure pattern estimation later in Modeling Evacuation Demand.

5.2. Simulation of Dynamic Network and Exits

As described in the Chapter "Methodology", in order to carry out the simulation of evacuation process in such a flash river flood scenario, prevailing availability of the major infrastructure supplied for evacuation, the road network and exits should be simulated by inspecting spatial-temporal relationship between road network and flood. Methods proposed in Section "Evacuation Supply" are implemented in the ArcGIS environment. The dynamic datasets describing availability of networks and exits over time are organized in ArcCatalog as feature datasets (see: Appendix C4: **Organization of datasets about dynamic availability of road network and exits**) which would be inputs for succeeding modules.

5.2.1. Network Availability

As illustrated in Fig. 7, generation of dynamic network availability is divided into two steps. First, a Geoprocessing model is constructed in ArcGIS model builder (see Appendix B1: **Implementation of Evacuation Supply Module**) to calculate the available road feature class for each time instant (from t = 0 to 48), by iterating through the water depth raster catalogue. For each time instant, as the geometry of road segments may be changed by intersection with flood (previous road segments are split up to smaller segments by flood), related road attributes should be updated (e.g. travel cost). Second, after all roads feature classes have been executed and generated by the model, road network for each time instant is constructed in ArcCatalog. Some snapshots of the dynamic road availability over time are display in Figure 5-4.

From Figure 5-4 it can be seen that as the expansion of flood over time, more and more roads are inundated and no longer available for evacuation. However, due to elevated road bases, some major highways survive in floods, which might provide possibilities for people who are threatened by approaching flood to evacuate.

Finer temporal pattern could be observed from Figure 5-5. First, generally the road network is being affected by the flood in a rather steady manner, with stable decreasing rate of total length. Second, the time period during which road system is most affected with a fast inundation rate could be identified.

Some 5 hours after the occurrence of breach, road length sharply declines possibly because at that moment most roads in the town of Beuningen which is quite close to the breach are flooded.

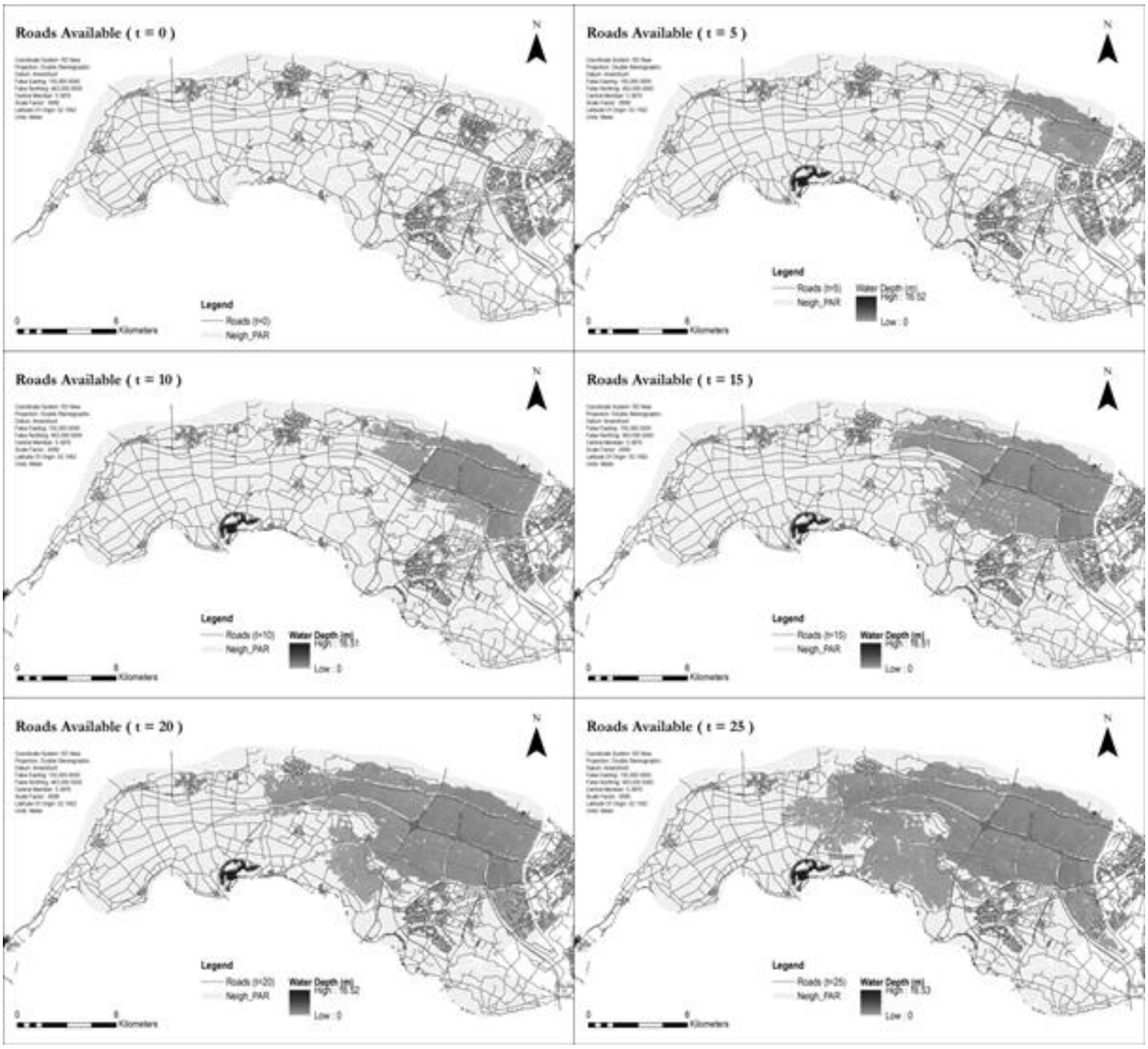

Figure 5-4 Flood Expansion and Roads Available Over Time

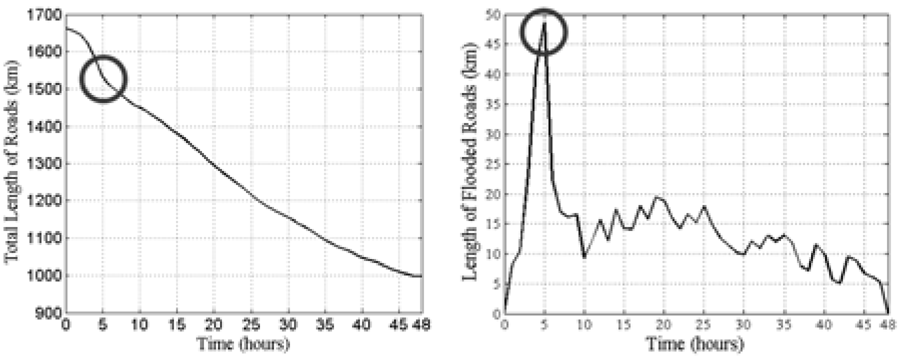

Figure 5-5 Change of Road Lengths over Time

(Left: Length of left roads; Right: Length of flooded roads)

5.2.2. Exits Availability

As explained in sub-section "Evacuation Exits Selector", for evacuation scenario "S22: Prediction – Organized Evacuation", exits are dynamically selected and informed to the evacuees based on instant evaluation of risk level at each exits. Models designed are implemented in ArcGIS via Geoprocessing models (see: Appendix B1: **Implementation of Evacuation Supply Module**).

The process is divided into two steps. First, select locations of exits at the beginning of flood (evacExits(0)) by intersecting major roads with maximum flood extent. Second, by iterating all water depth maps over time, prevailingly evaluate the risk that is faced by each exits and select relatively "safe" exits over time. Exits too close to flood or most of area (1.0 km buffer zone) around has been inundated would be deactivated forever for later evacuation.

Figure 5-6 and Figure 5-7 reveal the relationship between expansion of flood and deactivation of exits in space. Many exits in the eastern edge leading to western Nijmegen have to be shut down because of advancing floods, while other exits in the south and west that are basically solid bridges over river Waal and Maas stand over the time.

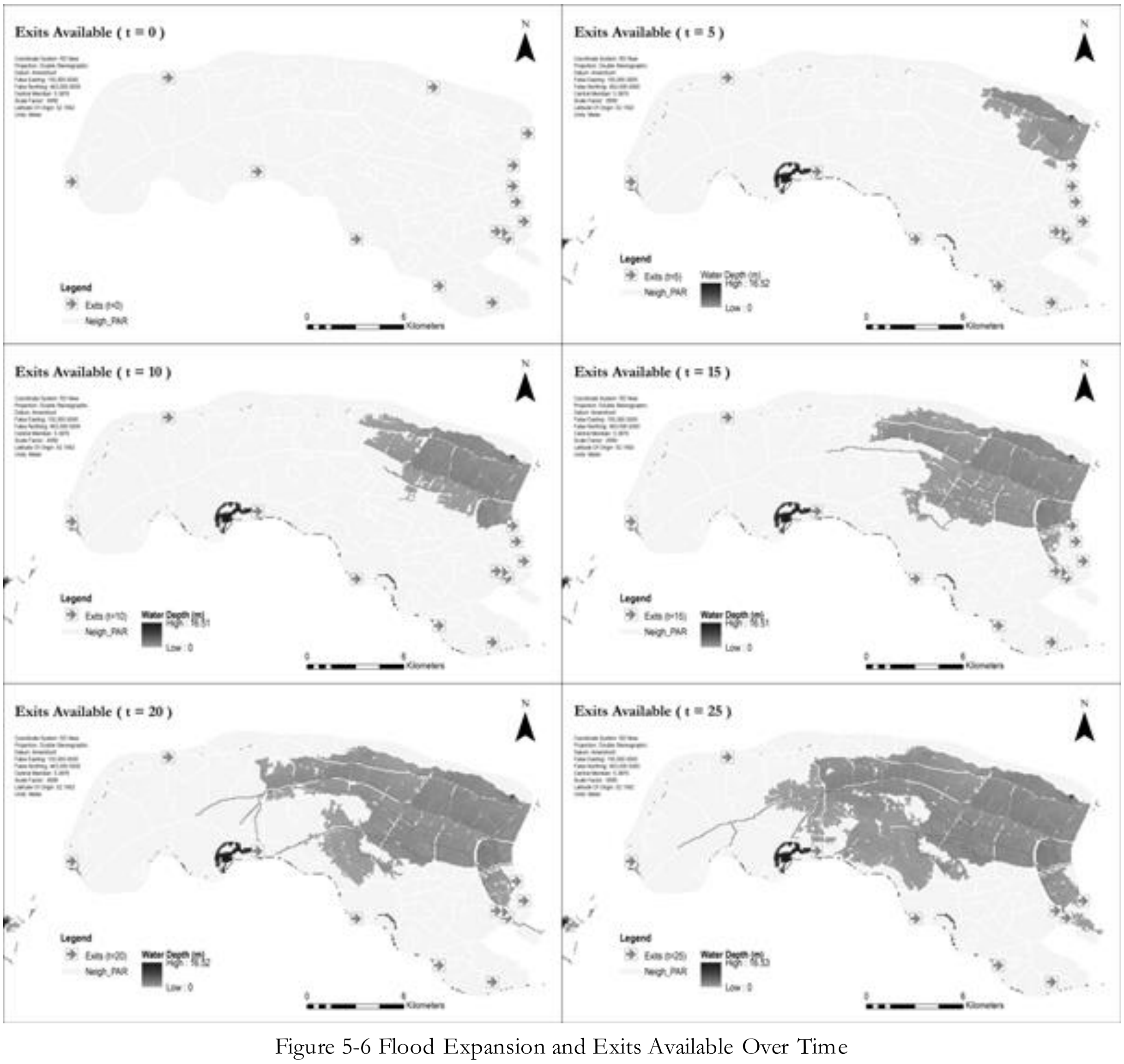

Figure 5-6 Flood Expansion and Exits Available Over Time

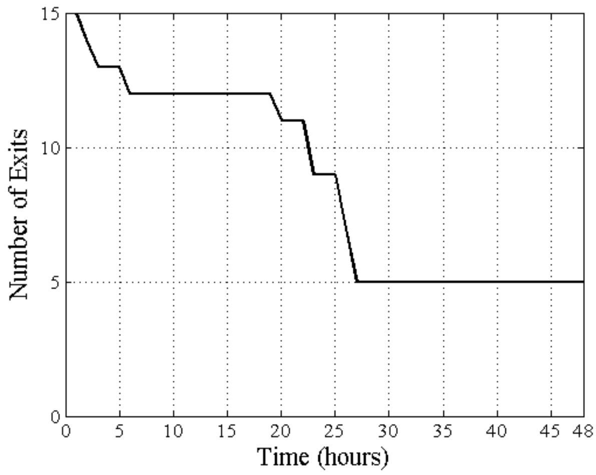

Figure 5-7 Number of Exits Available Over Time

5.3. Modeling Evacuation Demand

Another crucial side of evacuation modelling is to estimate dynamic departing population or amount of vehicles that are entering the transport network over time. As discussed in section "Evacuation Demand", estimation of evacuation demand is accomplished by 3 interconnected steps: **1) Identification of population at risk; 2) estimation of participation share and 3) simulation of departure pattern**. With data prepared, models designed in the previous chapter are implemented with specifications of different evacuation scenario profiles. Both ArcGIS Geoprocessing models and MatLab scripting programmes are developed and linked to carry out the modelling objectives.

5.3.1. Who are at risk? Identification of PAR

The identification of population at flood risk, as discussed in sub-section "Identification of Population at Risk (PAR)", is rather straight forward. Neighbourhoods with more than 20% area being flooded[47] are considered at risk[48]. The implementation logic in ArcGIS Geoprocessing environment is illustrated by the flowchart Fig. 11 in Appendix B2: **Implementation of Evacuation Demand Module**.

The process of identification of PAR is demonstrated by Figure 5-8 and Figure 5-9. First, percentage of area being flooded throughout the event are calculated, shown in Figure 5-8. Second, neighbourhoods with percentage of flooded area above the threshold are selected. Total population at risk of the flood is **143,060**. The distribution of PAR is apparently concentrated in several densely resided medium-small sized districts and towns, including: Lindenholt and Dukenburg (two west Nijmegen districts), Druten and Wijchen (two municipalities). Also, there are some larger villages with more than 1500 residents in this area, including: Deest, Dreumel, Beneden-Leeuwen and Overasselt.

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[47] Here only area being flooded is taken into consideration as criterion.

[48] The threshold 20% is determined by speculation from data distribution. There is a distinctive frequency "gap" at the level of 20% (percentage of flooded area) and those neighbourhoods below this level in practice are either too far away from the breach (with very late time to flooding) or well-protected by interior dikes (e.g. eastern neighbourhoods in Western Nijmegen).

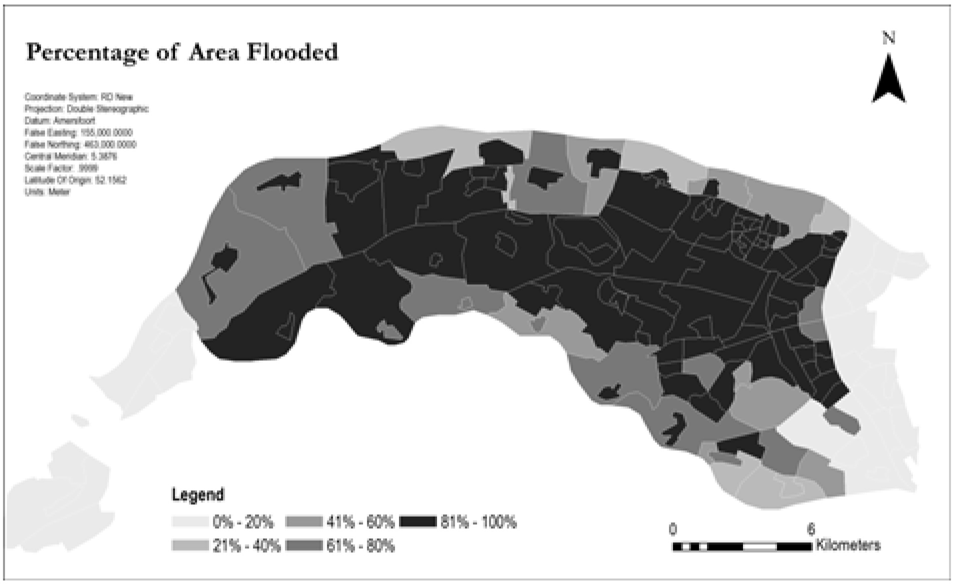

Figure 5-8 Percentage of Area being Flooded at Neighbourhood Level

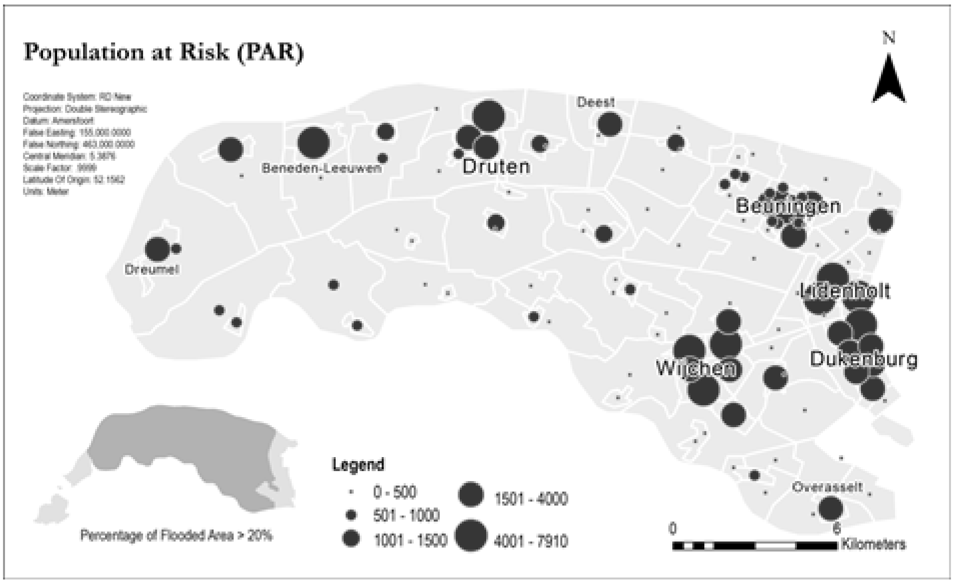

Figure 5-9 Distribution Population at Risk (by neighbourhood)

5.3.2. How many join evacuation? Estimation Participation Share

As discussed in the sub-section: "Share of Participation Estimation", cross-classification method is applied to specify different participation share. Two indicators, the percentage of elder population[49] and flood zone types are selected to represent demographic vulnerability and hazard risk level.

For demographic vulnerability, a neighbourhood with more than 12.6%[50] elder percentage are considered being highly vulnerable. Further, it is also assumed that neighbourhood with high vulnerability tend to be less active to participate in evacuation, since elders (65 years +) are generally considered with less mobility, which makes it objectively harder for them to take departure decision.

[49] Number of people aged above 65 years.
[50] 12.6% is the average level of elder population for all neighbourhoods at risk.

For hazard risk, it is obvious that people in zones with rapid rising water have stronger intention of participation than those in remaining zones.

Since no calibration data for evacuation participation is available in the Netherlands, other evacuation studies (South Florida Regional Planning Council, 2009) with similar context are referred to estimate the particular value of participation share for each category.

Table 5-1 Specification of Participation Share

Participation Share		Hazard Level	
		remZone (1)	rapRisZone (2)
Demographic Vulnerability (Threshold=12.6%)	High	**70%**	**85%**
	Low	**80%**	**95%**

The workflows in ArcGIS are described as in Appendix B2: **Implementation of Evacuation Demand Module**.

5.3.3. When to leave? Departure Pattern Simulation

Simulation of departure pattern is the most important step in evacuation demand module. On one hand, it generates directly the dynamic departure (number of vehicles) which is the major output of evacuation demand module and the direct input for evacuation routing. On another hand, it takes diversion of evacuation scenarios (assuming different human behaviours in emergencies) into account.

Departure curve approach is adopted in this study for estimation (see: the sub-section “Departure Pattern Simulation”). Departure curves are specified by different scenarios and flood zone types, which is demonstrated in section “Evacuation Scenarios”.

Since the starting and ending time points varied at different neighbourhoods, another important task is to estimate the time span of ETW (departure time window) for each neighbourhood. First, starting time is derived from evacuation scenario profiles, which is specified for different evacuation scenario and flood zone types (refer to Fig. 13 in Appendix B2: **Implementation of Evacuation Demand Module**). Second, it is more complicated to determine the ending time for departure since as explained (see: sub-section “Departure Pattern Simulation” and Appendix A6: **Mathematical description of procedures determining the ending time of departure**) several temporal issues like the full-departure time, time failing to find any evacuation route, time to flooding and of course, the starting time of departure. The implementation of finding out the ending time of departure using linked Geoprocessing – MatLab scripting method is explained below.

First of all, the full-departure time is identified by inspecting the departure curve of each scenario and participation types in Table 5-1. The time at which the participation share is reached along the departure curve is identified as the full-departure time, as shown in Fig. 14. A MatLab scripting programme (see in Appendix B: **Implementation of Evacuation Demand Module**) is developed for carrying out this task. The full-departure time identified for all evacuation scenarios are listed in Table 5-2.

Table 5-2 Full-Departure Time

Scenario: Prediction - Organized Evacuation (S22)			
Full-Departure Time (h)		Hazard Level	
		remZone (1)	rapRisZone (2)
Demographic Vulnerability (Threshold=12.6%)	High	12	7
	Low	13	7
Scenario: Prediction - Disorganized Evacuation (S21)			
Full-Departure Time (h)		Hazard Level	
		remZone (1)	rapRisZone (2)
Demographic Vulnerability (Threshold=12.6%)	High	11	7
	Low	11	8
Scenario: No Prediction - Disorganized Evacuation (S12)			
Full-Departure Time (h)		Hazard Level	
		remZone (1)	rapRisZone (2)
Demographic Vulnerability (Threshold=12.6%)	High	23	16
	Low	23	17

Second, the time failing to find any route is estimated by iteratively performing a dummy shortest path routing for all neighbourhoods at risk. Those neighbourhoods that are not able to search any route at certain time instant are marked as "failure", and then this instant is linked to all neighbourhoods marked as their "time failing to route". This analysis is performed in ArcGIS, by linking iterative network analysis with Geoprocessing model (refer to Fig. 15 in Appendix B2: **Implementation of Evacuation Demand Module**).

Finally, according to the algorithm explained by formula(A.25), (A.26) and (A.27), the ending time of departure time window (ETW_end) is estimated by comparing starting time of departure, full-departure time, time failing to route and time to flooding.

The overall modelling procedures for identification of ending time of departure in ArcGIS are explained in Fig. 16. Then the departure time window (ETW) for each neighbourhood can be visualized in ArcGIS, as shown in Figure 5-10, Figure 5-11 and Figure 5-12.

For scenario S12 (No Prediction – Disorganized Evacuation), since there is no prediction available, and the response time are also longer, the starting time of departure for all neighbourhoods are quite late, which makes the residents close to the breach (almost all neighbourhoods in Beuningen, Lindenholt, villages like Eijk and Winssen, and some districts near North-western Nijmegen) have almost no time for departure. The neighbourhoods in the south and west still have sufficient time for departure.

In the scenario S21 (Prediction – Disorganized Evacuation) and S22 (Prediction – Organized Evacuation), due to available prediction (even only 2 hours), the time spans of departure window for all neighbourhoods increase significantly, as shown in Figure 5-11 and Figure 5-12. However, in disorganized evacuation, because people are assumed to response and depart faster than in organized evacuation (the effect of panic and chaos), duration of departure window in little longer in organized evacuation scenario (S22).

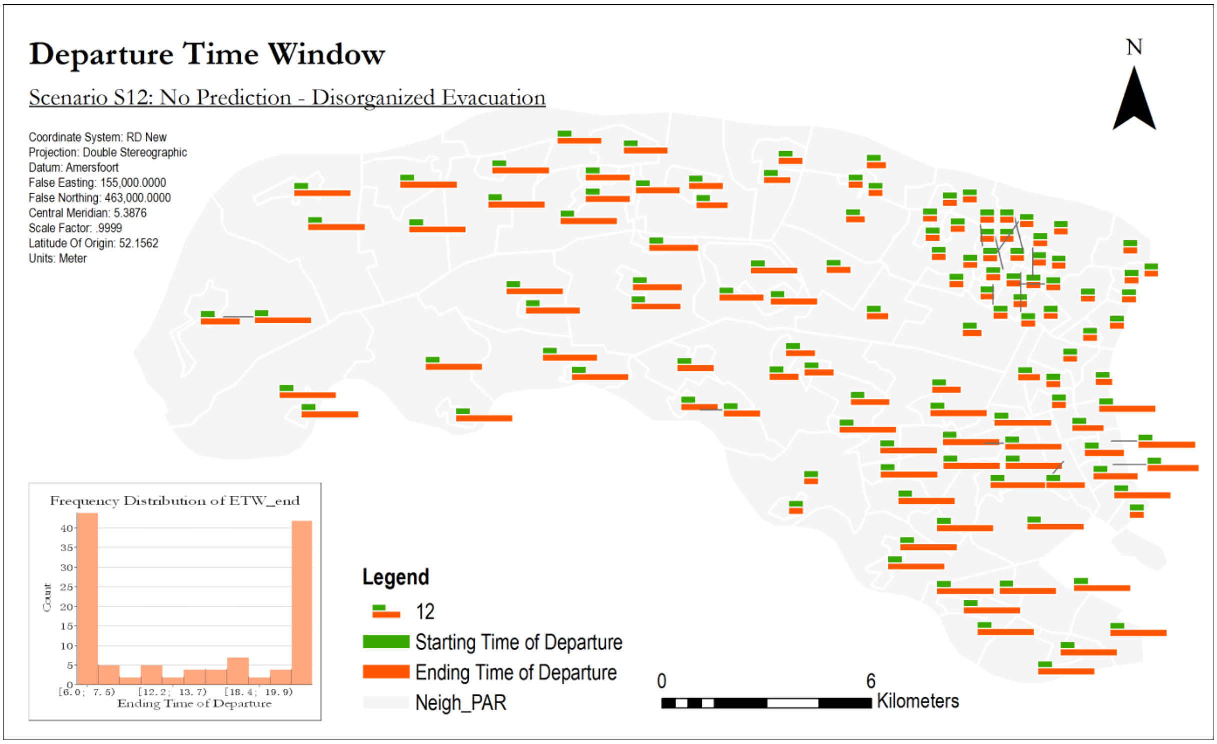

Figure 5-10 Departure Time Window of Scenario S12

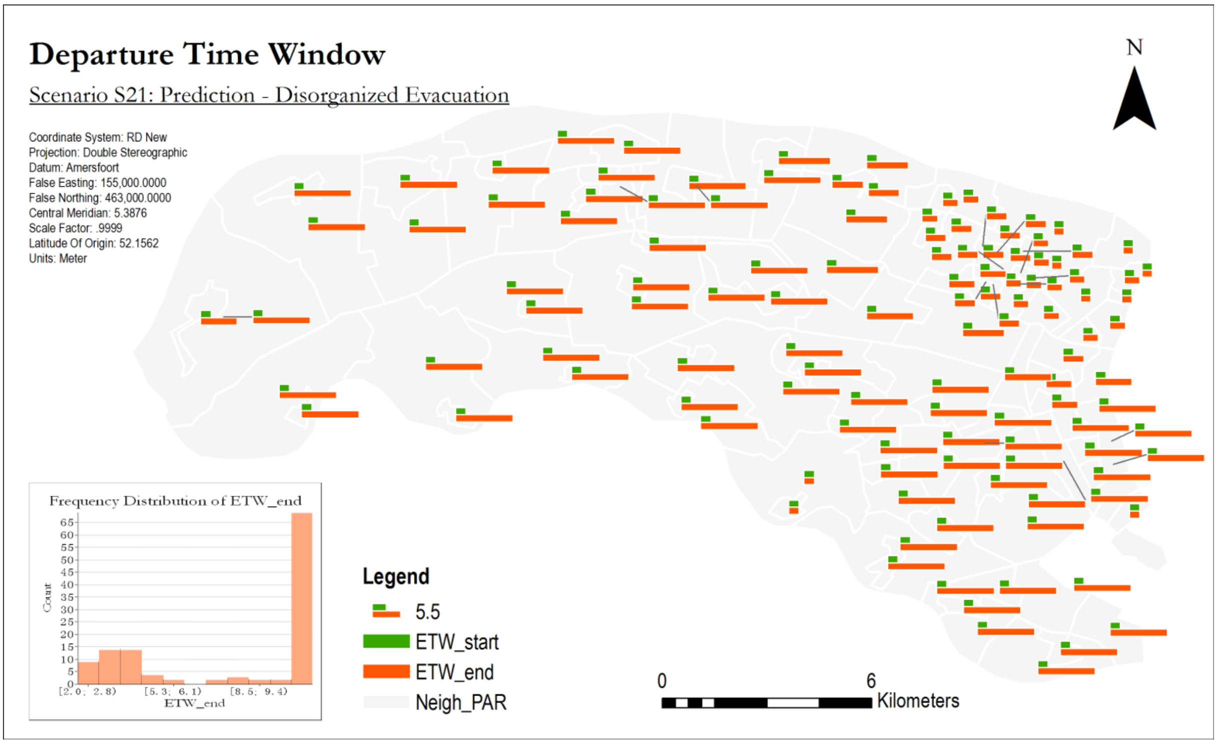

Figure 5-11 Departure Time Window of Scenario S21

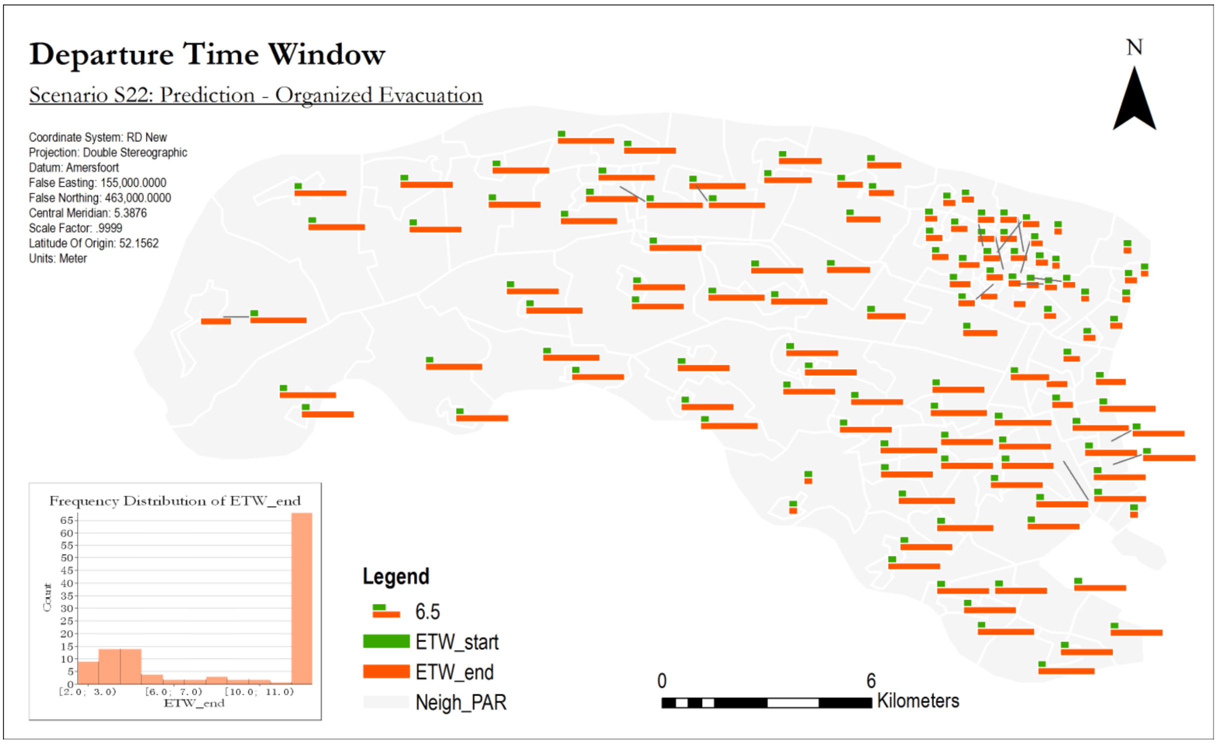

Figure 5-12 Departure Time Window of Scenario S22

After the departure time window has been estimated, the number of vehicles departing in each time instant within the time window can be estimated using departure curve, as described in formula(3.2.13), (3.2.14) and (3.2.15). The estimation is performed in an iterative manner over all 3 scenarios. A Matlab scripting programme (see in Appendix B2: **Implementation of Evacuation Demand Module**) is developed according to the logic in Fig. 17. The estimation results are exported from MatLab as tabular data and linked with ArcGIS feature classes. Figure 5-13, Figure 5-14 and Figure 5-15 shows the spatial distribution of departure dynamics for all scenarios.

Figure 5-16 shows the dynamics of total departing vehicles for all scenarios. Among three scenarios, scenario S12 (No prediction - disorganized evacuation) has lagged, rather mild increase of departing volume over time, which is attribute to its longer response time and slower departure rate. In contrast, in scenarios with prediction available, people tend to depart much earlier and more rapidly. In addition to that, interestingly there is a small peak 5 hours after the occurrence of flood in scenario S22 (Prediction – Organized Evacuation), which could be explained by the early departure of the neighbourhoods in zones with rapid rising water.

In addition, out of this module temporal data about departure patterns are generated and visualized dynamically in animation (see in Appendix D1: **Demonstrative Animations (Hyperlinks)**).

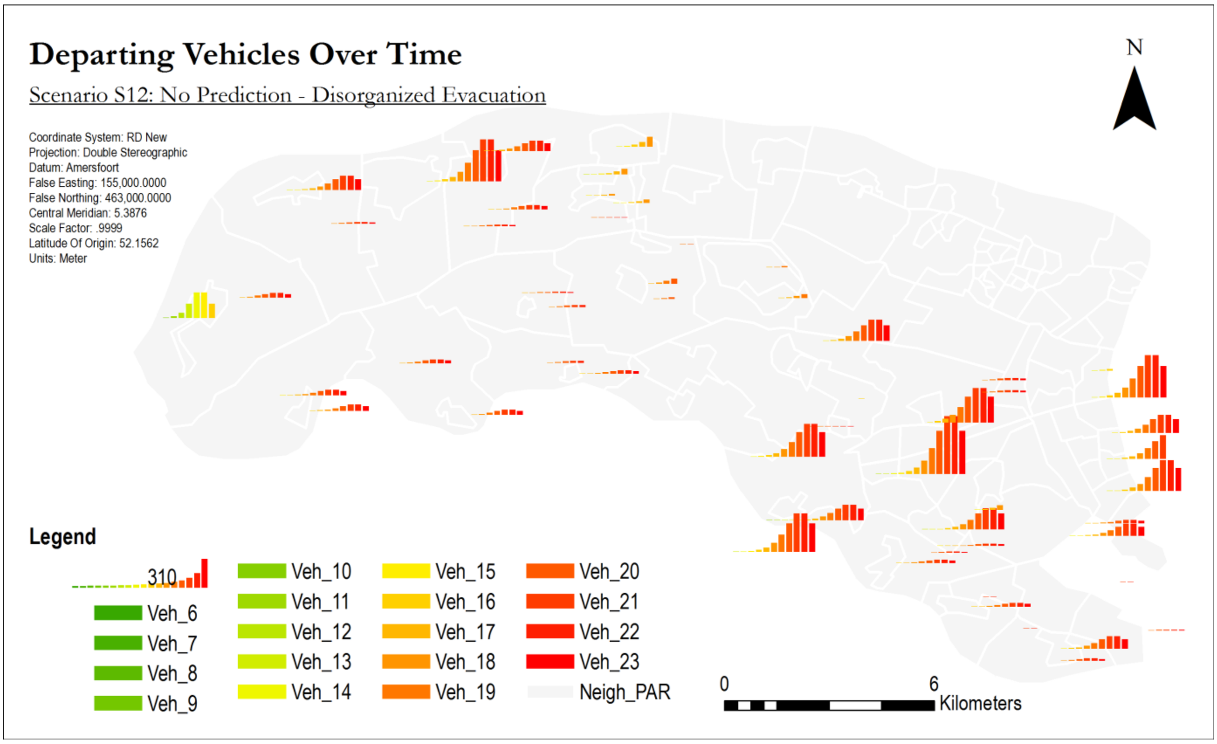

Figure 5-13 Departing Vehides Over Time in Scenario S12

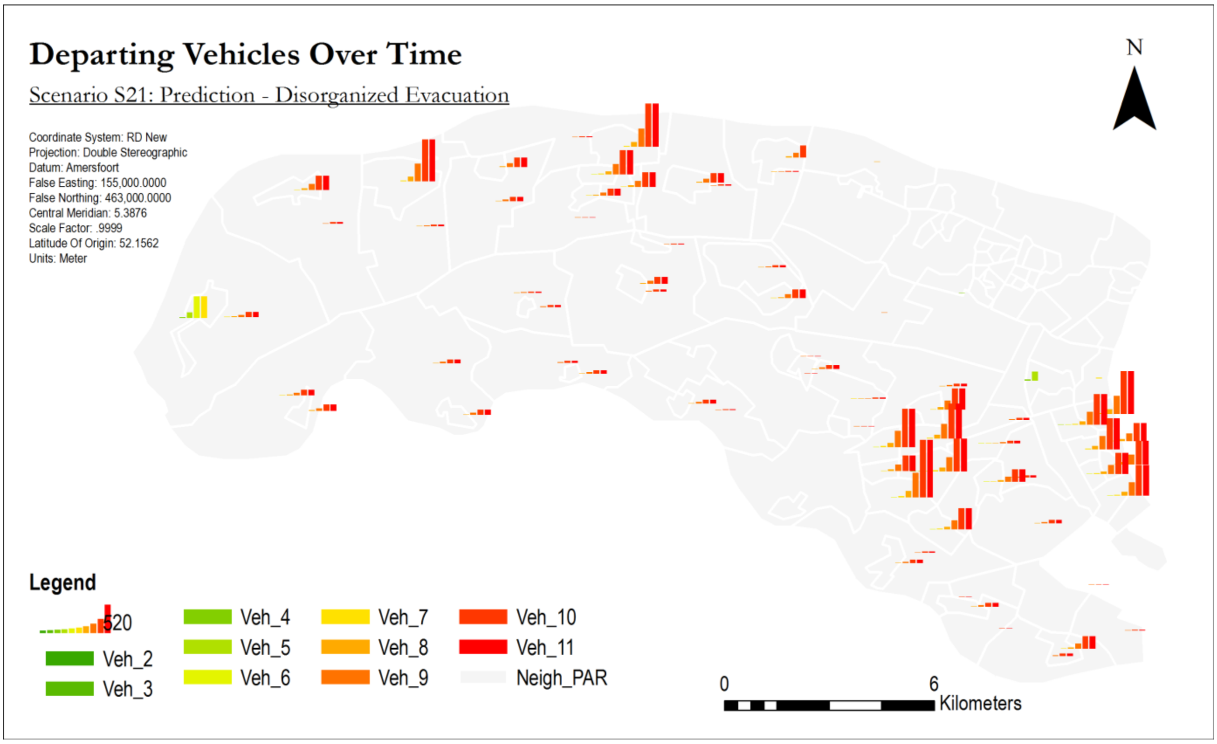

Figure 5-14 Departing Vehides Over Time in Scenario S21

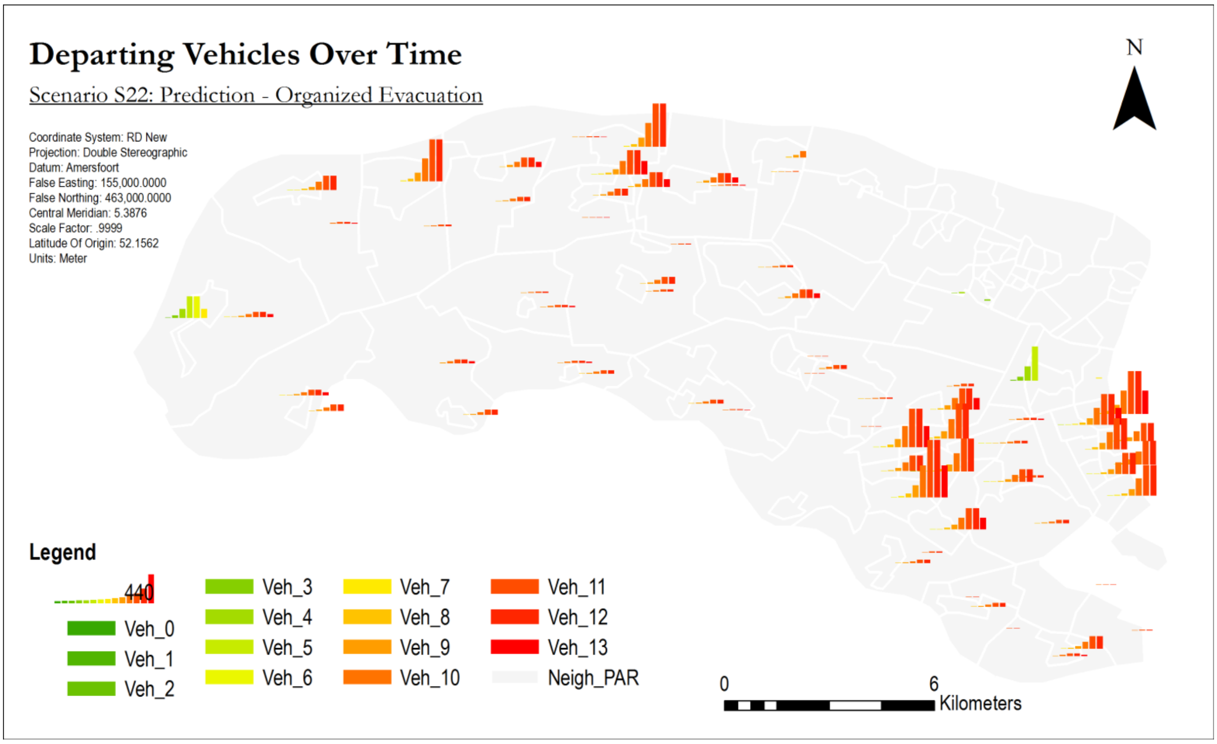

Figure 5-15 Departing Vehides Over Time in Scenario S22

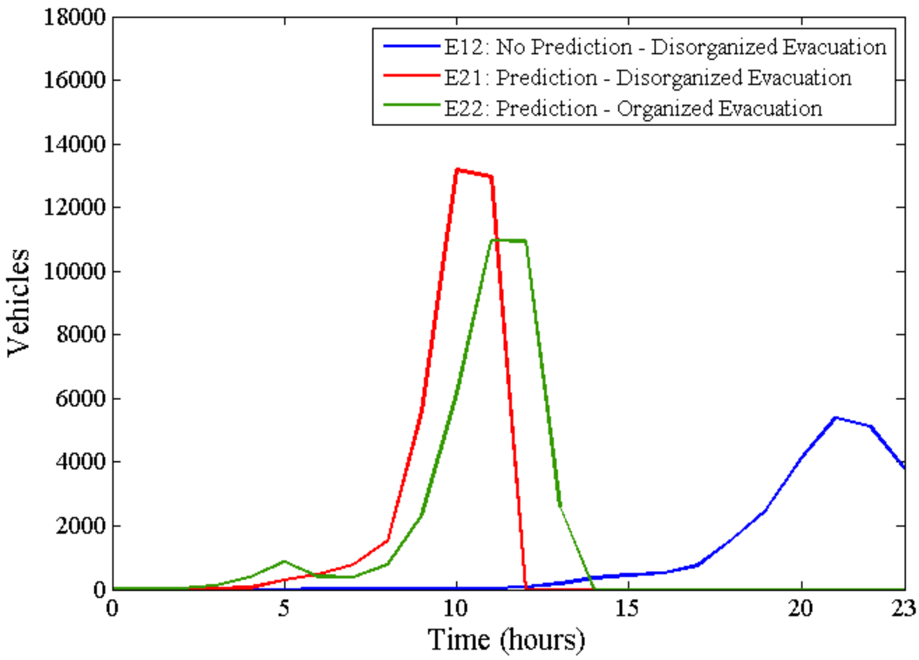

Figure 5-16 Departing Vehides over Time for all Scenarios

After the departing vehicles have been estimated, the last step of demand module is to calculate the population participating in evacuation but not successfully departing due to decreasing network availability. The workflow in ArcGIS is based on formula(3.2.16) and represented in Fig. 18. The estimated fraction of population is taken as inputs for exposed population estimation (see section "Exposure Estimation").

Three fractions of the total population: the population successfully departing, the population participating but not departing (due to decreasing network availability or fast coming flood) and the population not participating in evacuation, together can reveal the overall pattern of departure. The spatial patterns of these three fractions of population in each scenario are visualized as below in Figure 5-17, Figure 5-18 and Figure 5-19. By comparing these 3 maps, it can be concluded that:

1) Early prediction does improve the condition of departure. By starting departing earlier, the people living in area which is hit by flood earlier (district of Lindenholt, municipality of Druten and some villages in the middle) can get better chances to depart their houses.
2) There is clear distinction between the area of Beuningen and other places, in all scenarios. Due to the rapidly coming flood which simply cut off the major road links between communities and evacuation passages, the residents living in the area seem to have almost zero chances to depart.
3) There is no big difference between S21 and S22, except for a few neighbourhoods located in rapid rising water zones. Since people in this flood zones would be arranged or organized to depart earlier (around 2 hours earlier than situation of no organization) by urging evacuation orders, the fraction of successful departure are higher in these regions.

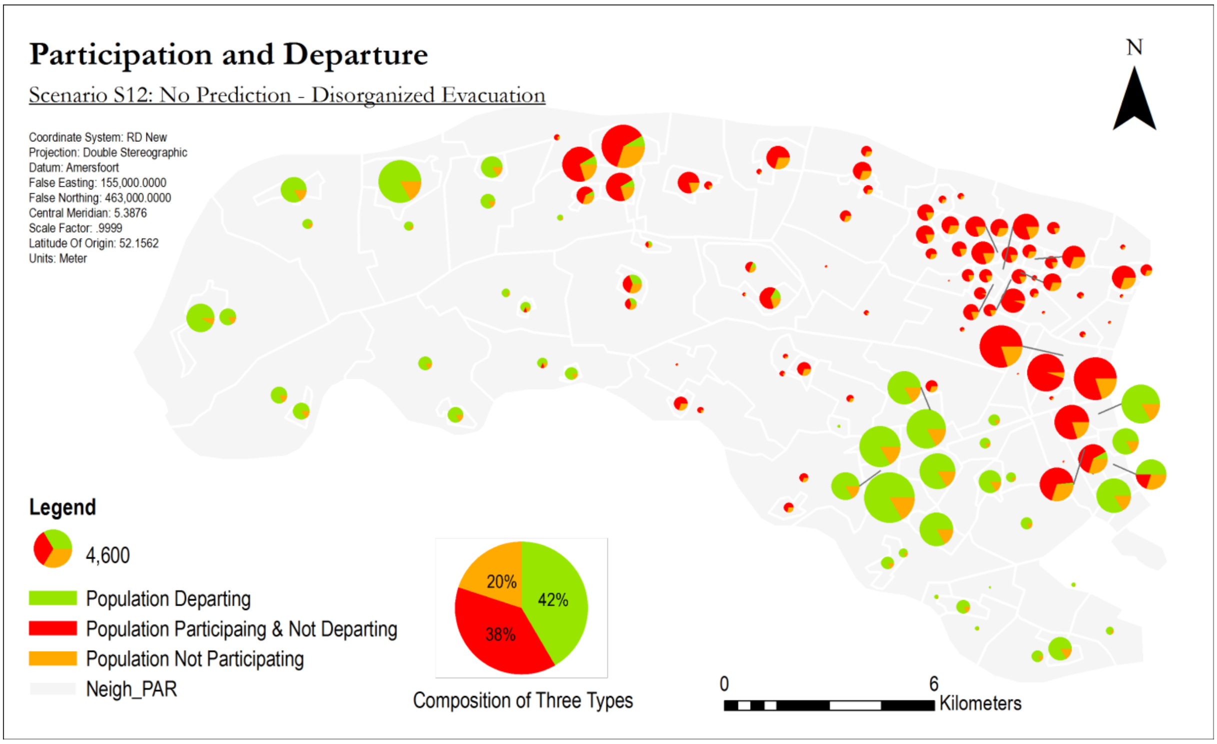

Figure 5-17 Fractions of Total Population in Scenario S12

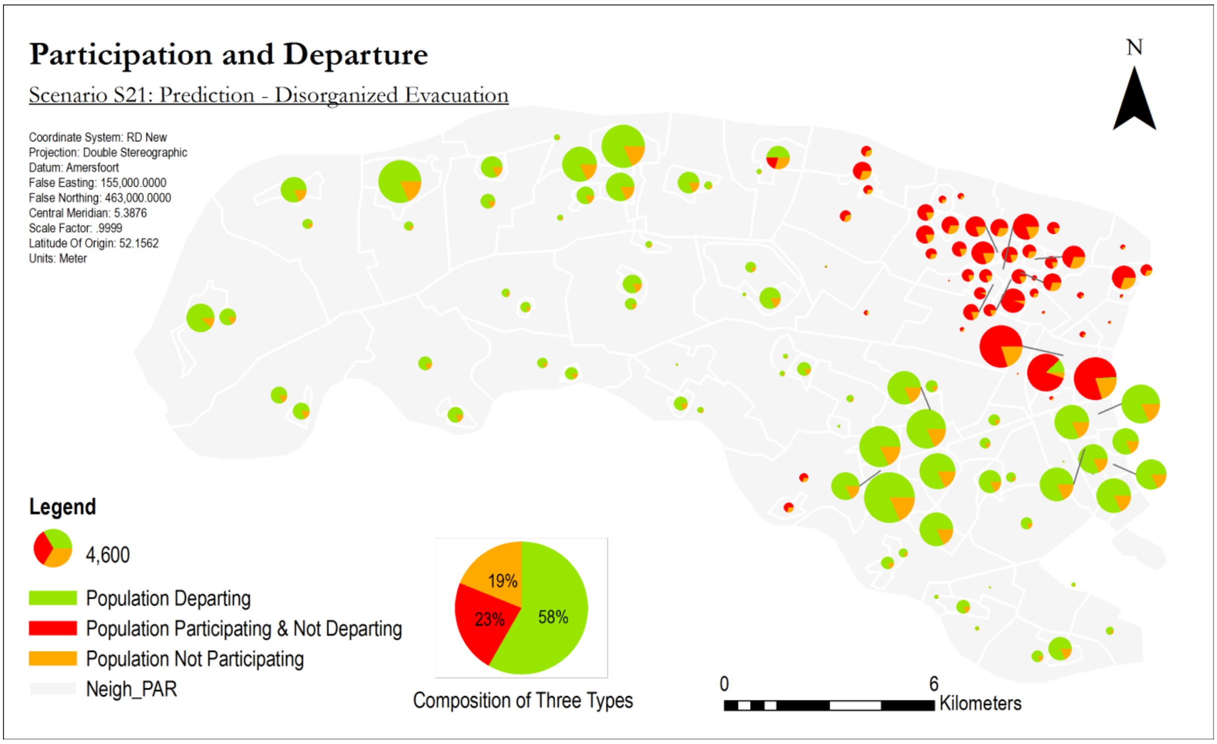

Figure 5-18 Fractions of Total Population in Scenario S21

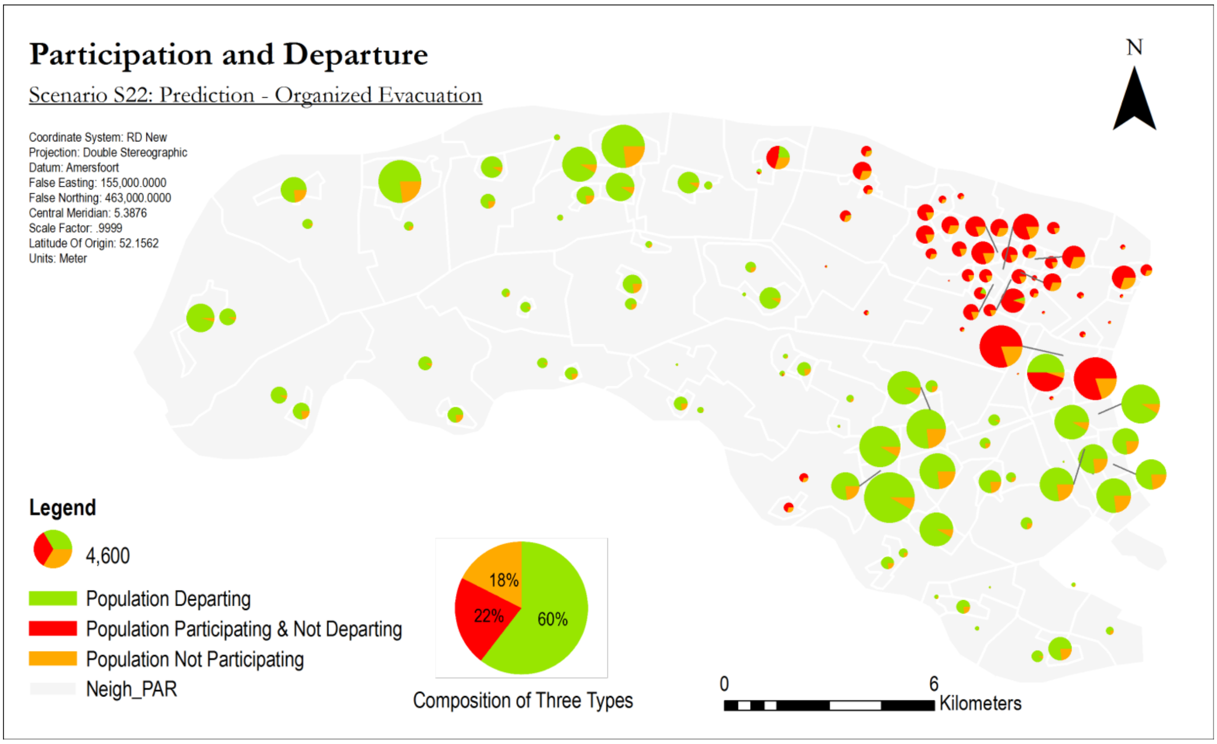

Figure 5-19 Fractions of Total Population in Scenario S22

5.4. Finding the Way Out: Evacuation Routing

5.4.1. Performing Evacuation Routing

Once both sides of evacuation demand (amount of vehicles departing over time) and supply (road and exits available) are determined, evacuation routing algorithm is performed as described in section

"Evacuation Routing". As shown in workflow presented by Fig. 19, the dynamic network and exits are specified as evacuation supply data (see in Appendix C4: **Organization of datasets about dynamic availability of road network and exits**), and number of vehicles departing from every neighbourhood centres (as origins) demonstrated in Figure 5-13, Figure 5-14 and Figure 5-15 are taken as demand of evacuation. As assumed in scenario settings, different routing method (shortest path or CASPER) is performed for disorganized or organized evacuation. This is alternated by different options in ArcCASPER tool's GUI (Graphic User Interface) (see in Appendix B3: **Implementation of Evacuation Routing Module**). For each evacuation scenario, the routing is performed iteratively for each time instant, which in result generates evacuation routes and engaged road segments with route travel time, congestion level information. These results (organized as feature dataset in Geodatabase) are not only crucial for evacuation performance evaluation, but also taken as inputs for exposure estimation module to be discussed in the next chapter.

5.4.2. Performance of Evacuation

The general performance of evacuation is evaluated by average traveling cost of evacuation routes which is shown in Figure 5-20 for all scenarios. The general trend is that as performance of evacuation declined as the later in the course of evacuation the traffic increases. In Scenario S12 (No prediction – disorganized evacuation), the increase of evacuation traffic is rather mild, which in comparison makes performance declining less than the other two scenarios that are characterized by earlier and faster departure.

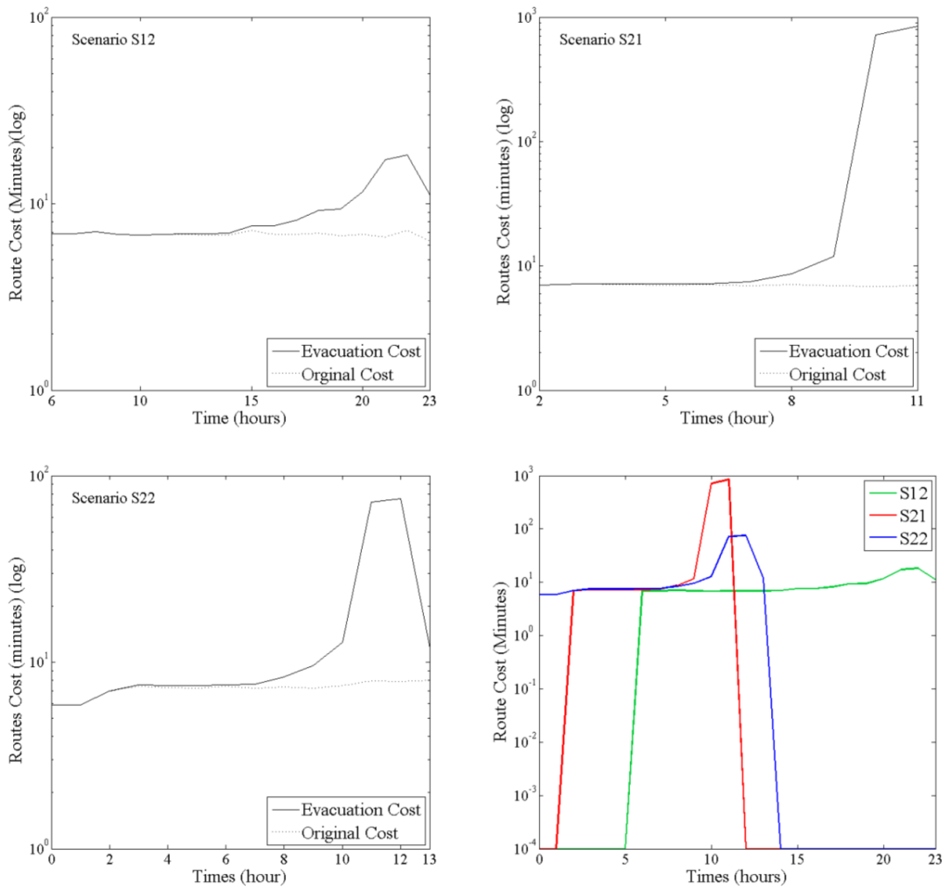

Figure 5-20 Evacuation Cost Curves for all Scenarios

From Figure 5-20 the peak hour in each evacuation scenario is identified. Evacuation route costs and congestion levels at the peak hour are visualized in ArcGIS and compared as shown in Figure 5-21. In scenario S12 (no prediction – disorganized evacuation), at the peak hour (t = 22), despite of the vast inundation of road network, vehicles departing still can find a route to the closest exits with travel cost less than one hour. Due to moderate departure amount, there is basically no severe congestion level on the roads engaged in routing. In scenario S21 (prediction – disorganized evacuation) in which people depart more rapidly and take the shortest route to exit regardless of others' routing choices, the peak is reached at the 11th hour. While most evacuees head for the three major exits in the south along river Maas, the artery roads **<u>"Noord Zuid (N329)"</u>** and **<u>"Graafseweg (N32)"</u>** are mostly likely highly congested, which makes vehicles evacuating through these channels suffer a much higher travel costs than normal level. In scenario S22 (prediction – organized evacuation) while routing is optimized by CASPER algorithm, congestion level is significantly lower comparing to scenario S21 while global congestion is avoided by more dispersed routing arrangement. Only a few congested road segments could be identified near the exits.

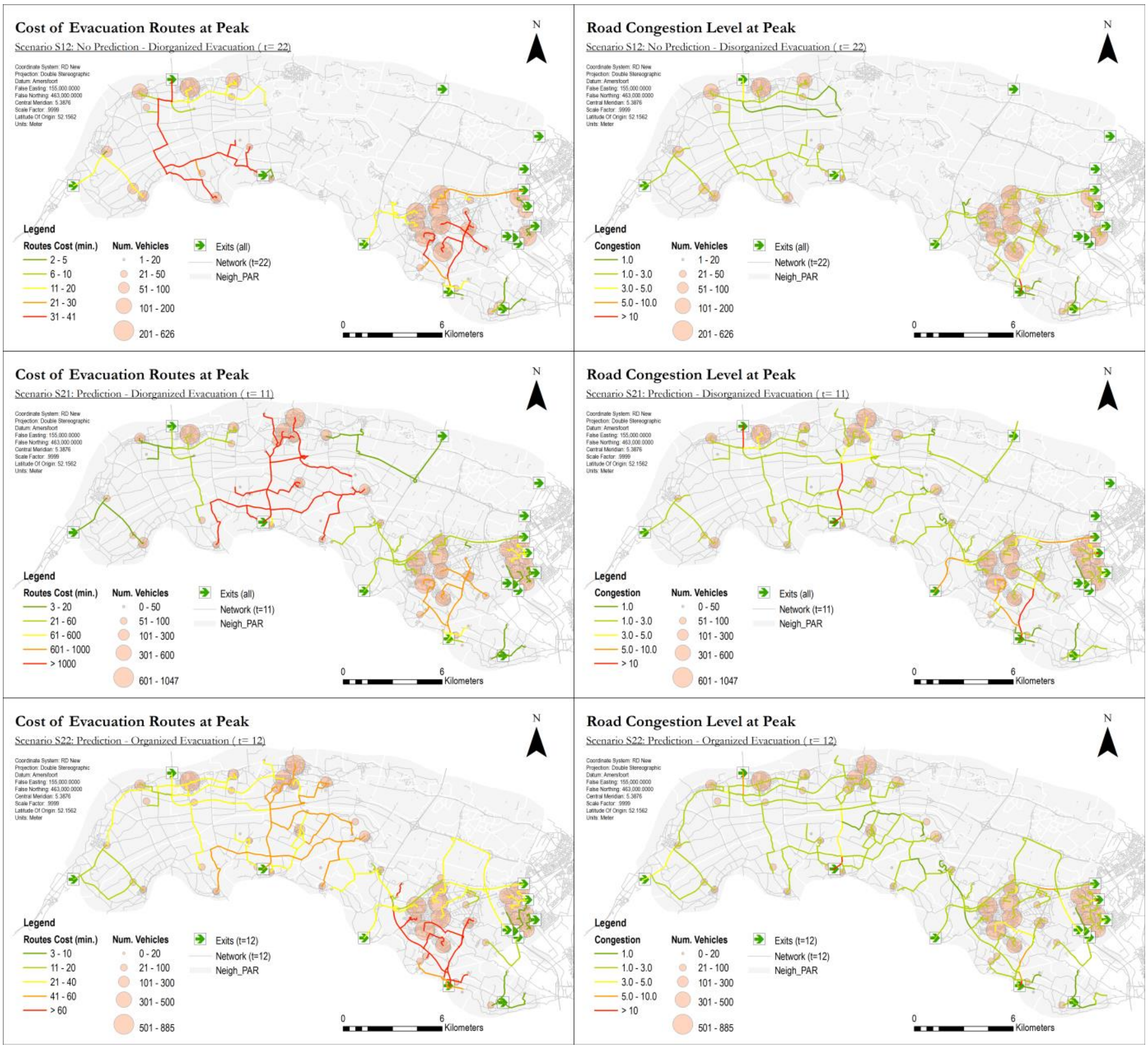

Figure 5-21 Evacuation Route Cost and Congestion

5.5. Conclusion and Discussion

Some conclusions can be derived from linked flooding – evacuation modelling and analyses. First, the fast spreading of flood over the dike-ring area, and the spatially uneven distribution of population at risk together lead to a distinctive difference of departure pattern between the municipality of Beuningen and other areas. There is hardly sufficient time for people in Beuningen to response, depart and evacuation. However, it seems that early prediction can to some degree potentially improve this situation. Second, there is significant difference of departure pattern among different evacuation scenarios. While early prediction and evacuation organization are available, evacuation participants can seize the best time and depart early and rapidly, though benefits of early departure may be offset by congestion on common routes and degradation of evacuation network performance. Third, it is proved that comparing to egoism-based shortest-path routing, organized routing (utilized by CASPER approach) in favour of remotest evacuees is capable of improving overall evacuation performance. This point also gives insights into the following identification of en-route exposure.

While the model designed in the chapter "Methodology" is applied in the study and proved capable in dealing with the complex relations between flooding and evacuation processes. However, some limitations and drawbacks of the method proposed are recognized in its application. First, the evacuation demand model is based upon rather coarse and deterministic assumptions about human behaviour which might deviate from the complex reality in emergencies. Particularly the uniform starting time of departure assumption may be too simplistic to deal with people's real-time departure decision-making which takes area-based hazard risk into account.[51] Second, though the specification of departure curves has considered hazard risk level (flood zone types) and level of organization, it is still incapable of dealing with day-night differences, particularly in terms of origins of evacuations and departure pattern. Third, the routing algorithms, both SP and CASPER are still fundamentally static traffic assignment approach. Even they are performed in a semi-dynamic, time-sliced manner; due to the static simulation nature it is still difficult to handle the inter-time-instant traffic interactions to achieve real dynamic routing and traffic assignment. Finally, the inconsistency of time resolution between flooding simulation and evacuation modelling is another major concern. The flood is simulated by hours, which may be too rough for minute-level evacuation routing simulation.

[51] This problem may be addressed in future development by a departure time function engaging prevailing flood hazard evaluation over time, or in general, by a utility-based departure decision model.

6. EXPOSURE AND VICTIM ESTIMATION

6.1. Estimating Exposed Population

According to model design in section “Exposure Estimation” in Chapter “Methodology”, the estimation for exposed population in flood is specified into two parts: “exposed population at home” and “exposed population on evacuation routes (en-route exposure)”. Each type is estimated separately.

6.1.1. Exposed Population at Home

As explained by formula(3.2.7), the estimation for exposed population at home is rather straight-forward. It takes population not participating in evacuation (N^p_{NPE}), population participating but not departing (N^p_{ND}), and the effects of sheltering into account. Since both N^p_{NPE} and N^p_{ND} have been estimated by evacuation demand model (shown in Figure 5-17, Figure 5-18 and Figure 5-19). They can be directly summed up in exposure estimation module.

Then, the effect of sheltering is considered by multiplying the ratio of population being sheltered (R_s), which is specified for either rural ($R_s = 0.1$) and urban area ($R_s = 0.2$)(S. N. Jonkman, Vrijling, et al., 2008). Rural and urban areas are distinguished by population density[52], shown as in Figure 6-1.

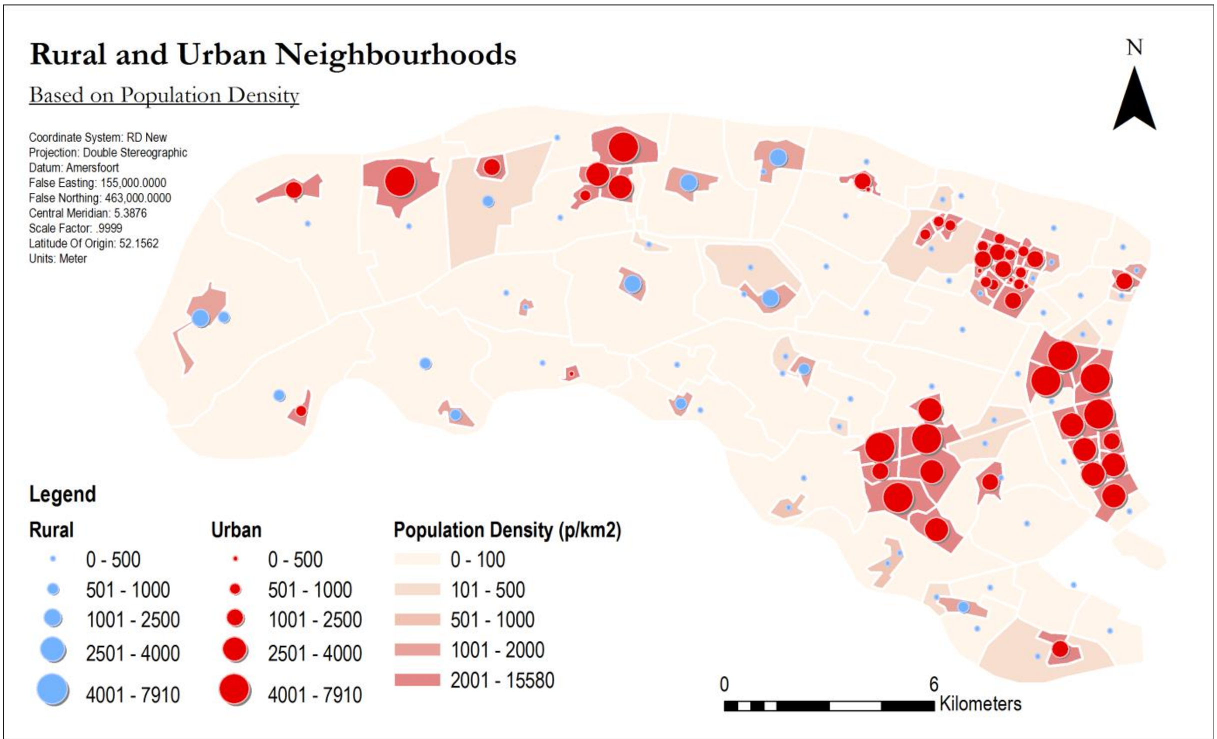

Figure 6-1 Rural and Urban Neighbourhoods

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52 Threshold of population density for distinguishing rural and urban neighbourhoods is 2000p/km², according to judgement on both data distribution and satellite image interpretation.

The workflow for estimation in ArcGIS in demonstrated in Appendix B4. The distribution of exposed population at home for all scenarios are displayed as blow in Figure 6-2.

Figure 6-2 Exposed Population at Home (all scenarios)

It is obvious in Figure 6-2 that generally evacuation can significantly reduce the population exposed by comparing S11 with other 3 evacuation-available scenarios. In addition, it is revealed that early prediction can cut off exposed population to some extent. However, whether organization of evacuation (arranged departure starting time, reduced panic and less rapid departure rate) exists seems to make no big difference while S21 and S22 are compared. This trend is also observed in Figure 6-3. From the worst-off scenario to the best-off one exposed population declines by more than 50%.

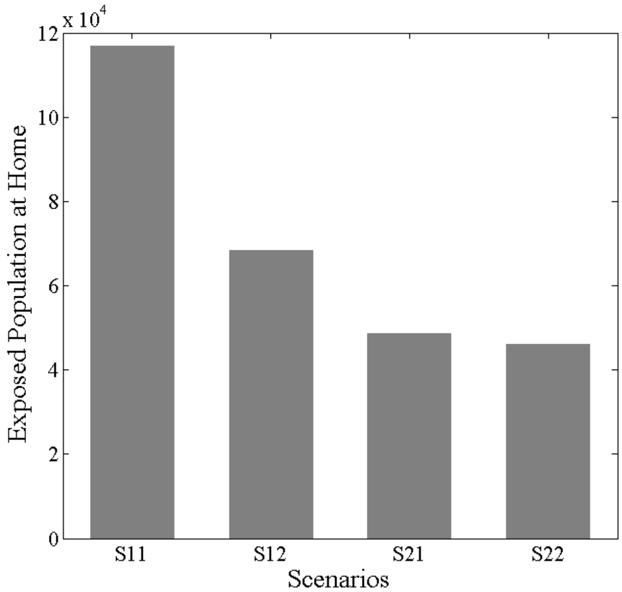

Figure 6-3 Total Exposed Population at Home

6.1.2. En-route Exposed Population

The population exposed to flood on their evacuation routes are estimated using the method explained in the subsection "Exposure Estimation - Mathematical Description" and data structure proposed in this study: Evacuation Milepost Series (EMS), a linear spatial-temporal description of evacuation routes of each neighbourhood departing over time. A Geoprocessing model (see Appendix B4) was established to construct data structure of EMS in ArcGIS, by taking the evacuation routes and engaged road segments datasets exported by evacuation routing module as shown in Fig. 19. The implementation workflow of building EMS data is demonstrated as in Fig. 22 and Fig. 23.

Once EMS datasets are constructed as Shapefiles, they are imported into a MatLab scripting programme (see the Fig. 24 in Appendix B4: **Implementation of Exposure Estimation Module**). In this programme, passing time at each "milepost" is compared against arrival time of flood in an iterative way, which looks into the spatial and temporal interaction between human evacuation routes and flooding dynamics. Once any exposure incident is discovered, it is exported and stored in table structure in MatLab with XY coordinates, exposure time and all other necessary information. Finally, all incidents identified are exported as Shapefiles which can be taken back to ArcGIS for further analysis and visualization. The manipulation of EMS data and identification of exposure incidents in Matlab are explained by Fig. 25.

In ArcGIS, identified hotspots of en-route exposure incidents are visualized, companied by detailed story-telling maps showing the interaction between evacuations and flooding processes, as shown in Figure 6-4, Figure 6-5 and Figure 6-6. These hotspots may need specific caution and risk-mitigation measures.

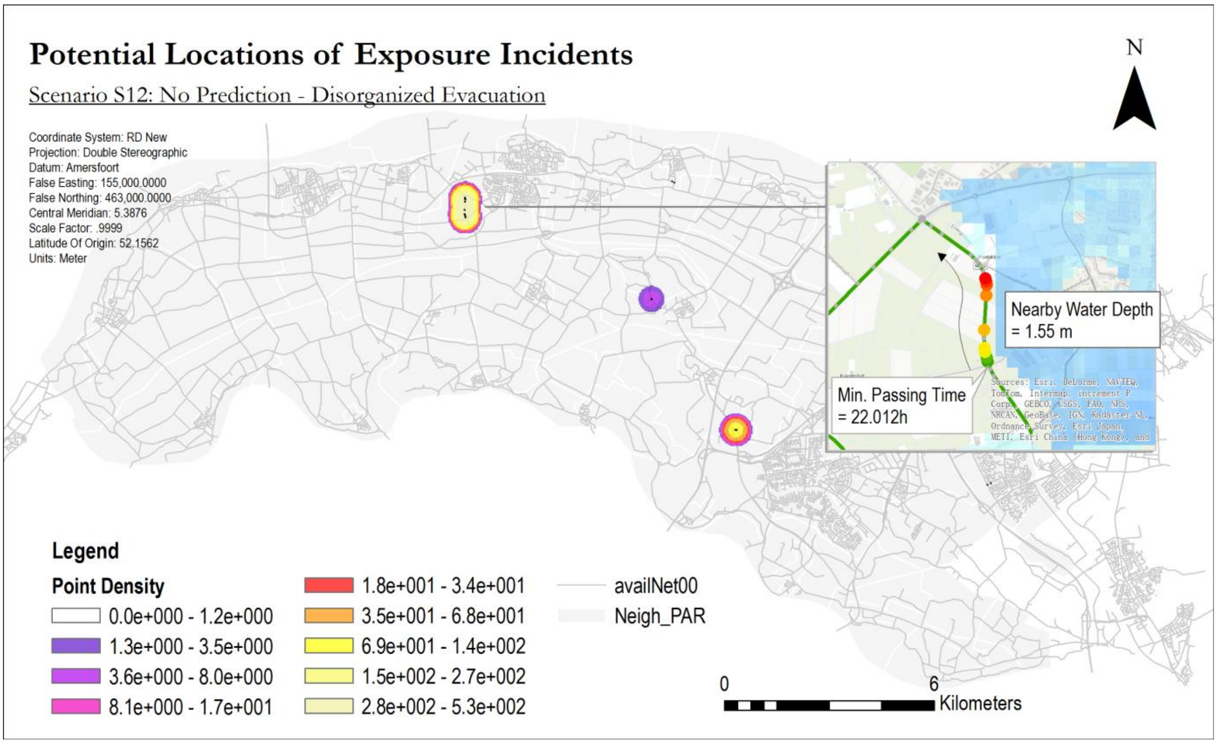

Figure 6-4 Hotspots of En-Route Exposure Incidents (Scenario S12)

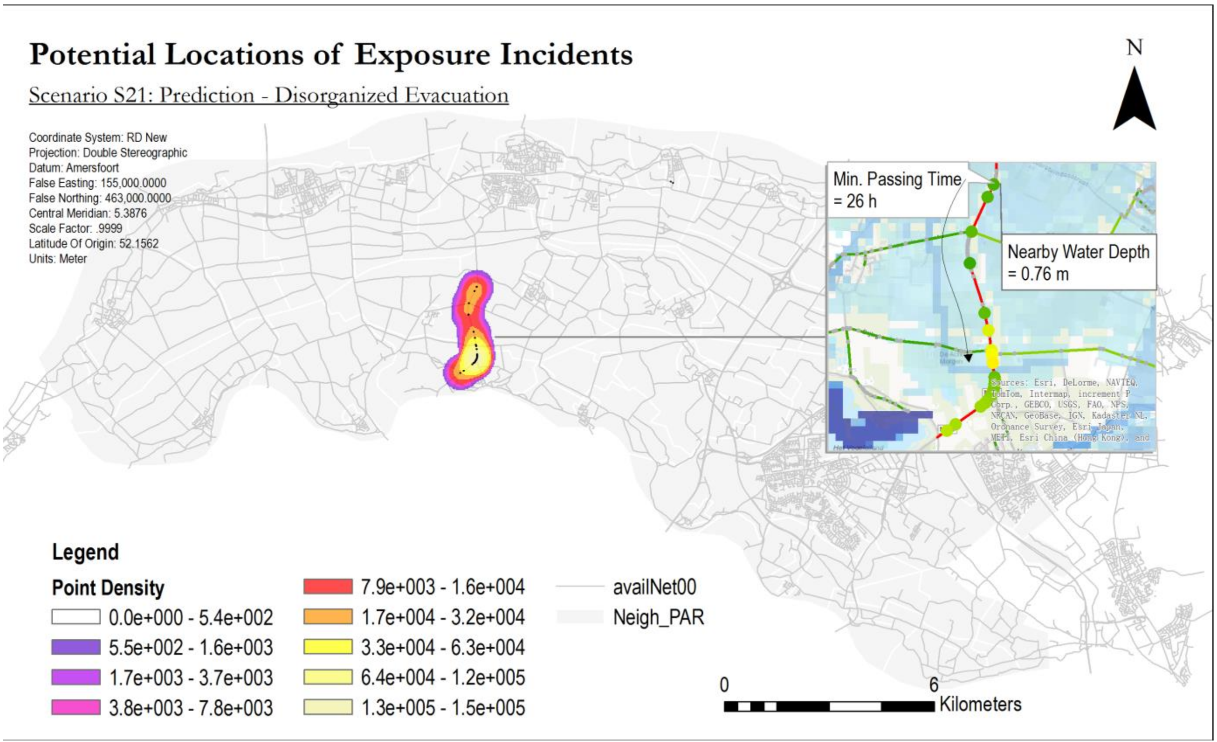

Figure 6-5 Hotspots of En-Route Exposure Incidents (Scenario S21)

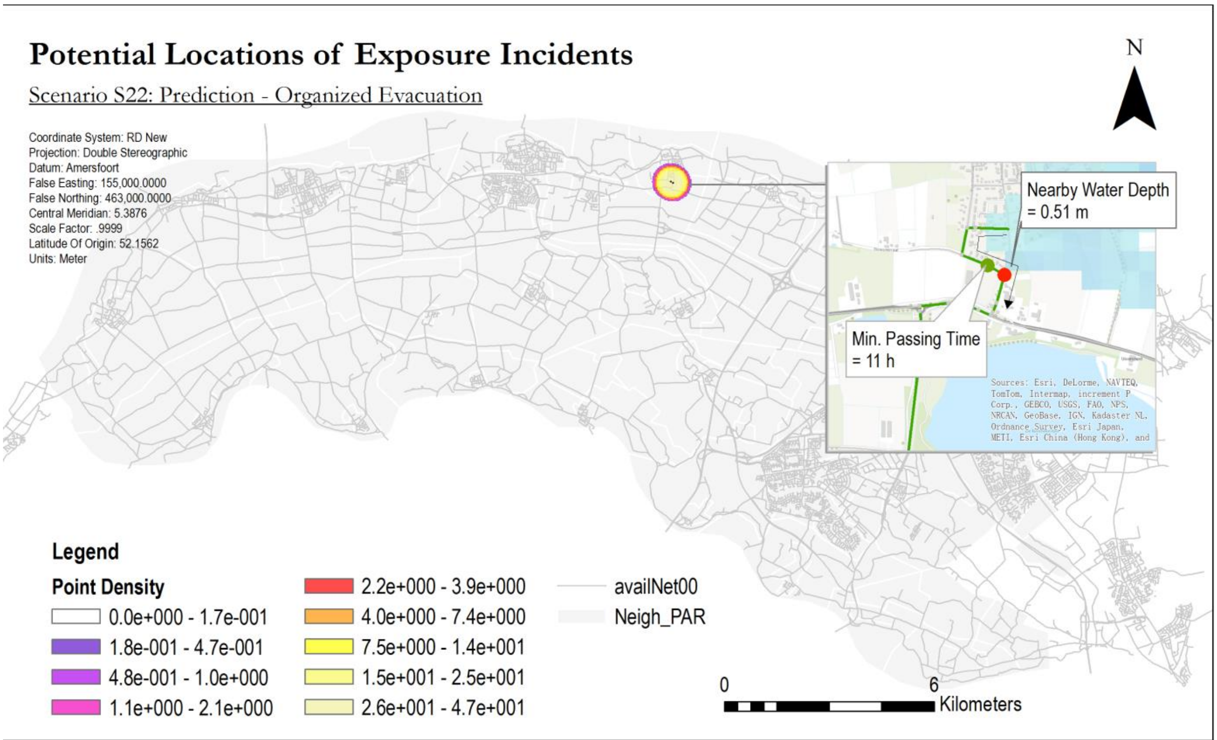

Figure 6-6 Hotspots of En-Route Exposure Incidents (Scenario S22)

In different evacuation scenarios, occurrences of exposure incidents concentrate at different time period which is associated with the departure pattern. Numbers of exposure incidents over time of different scenarios are compared in Figure 6-7. It can be seen that among three scenarios, because of the congestion led by high evacuating traffic volume, in scenario S21 there are the most number of incidents while if evacuation organization is available (scenario S22), en-route exposure may be significantly reduced.

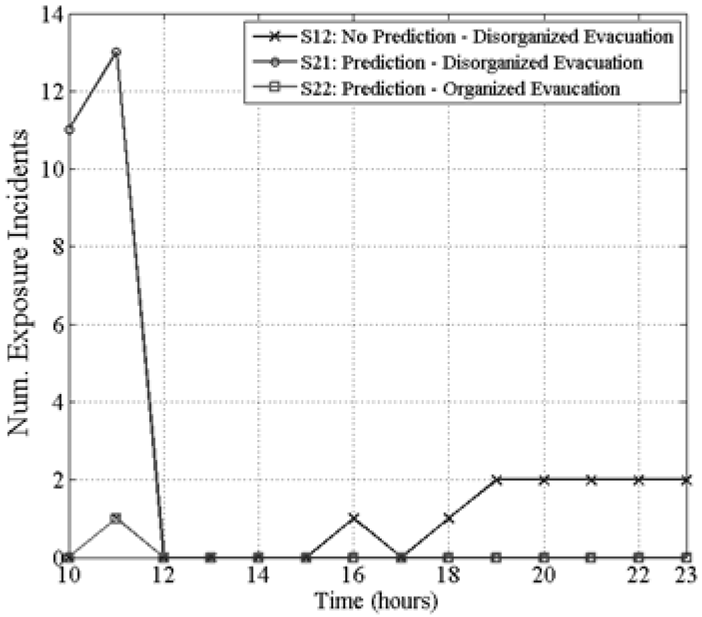

Figure 6-7 Number of Exposure Incidents over Time

The total population exposed on evacuation routes are summarized by multiplying the number of vehicles exposed with the corresponding neighbourhood's family size (persons per vehicle). Exposed population for all scenarios are compared in Figure 6-8. In Figure 6-8, exposed population in scenario S21 are much higher than in the others (more than 2 orders of magnitude). It is obvious that due to the serious congestion and degradation of network performance, it is most likely in scenario S21 to have large scale en-route exposure.

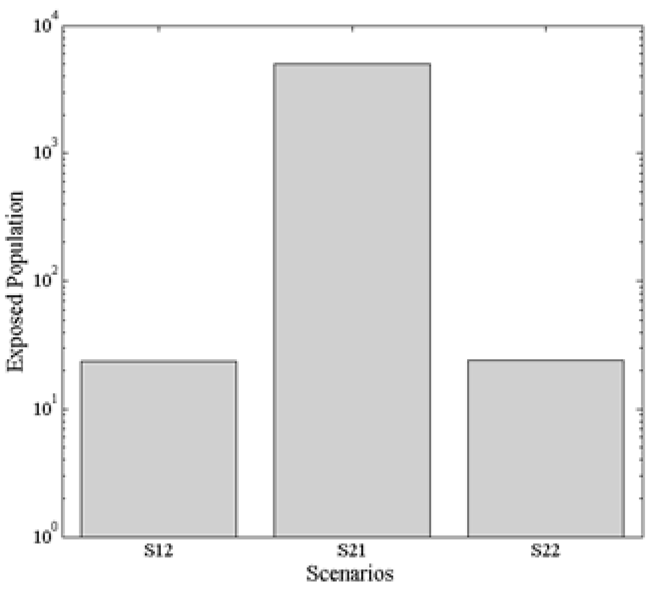

Figure 6-8 Exposed Population on Evacuation Routes

6.2. Victim Estimation and Analysis

6.2.1. Victim Estimation

Estimation for total number victims in this flood incident follows the approach proposed in sub-section "Victim Estimation" of chapter "Methodology" and formula(3.2.4). So home-based victims and en-route victims are estimated separately, which is based on the exposed population which is already calculated.

For home-based victims, it is estimated by multiplying exposed population with mortality rate which basically relies on maximum water depth. The function of mortality, as explained in formula(3.2.6), is specified for each flood zone type (see Appendix B5). As shown in Figure 6-9, mortality rate in the western part is higher than the eastern and southern areas, similar with pattern of water depth.

The spatial distributions of estimated victims at home for all scenarios are displayed below. Several spatial patterns of victim distribution can be observed. First, in each scenario, the populous neighbourhoods close to the breach, or neighbourhoods far from the breach but located in low areas with high level inundation (e.g. the town Kern Dreumel, centre of the municipality West Maas en Waal) suffer the most loss of human life. Second, by comparing different scenarios, it is obvious that early prediction and organized evacuation can significant reduce loss of human life, particularly in the area of Dukenburg, Wijchen and Druten).

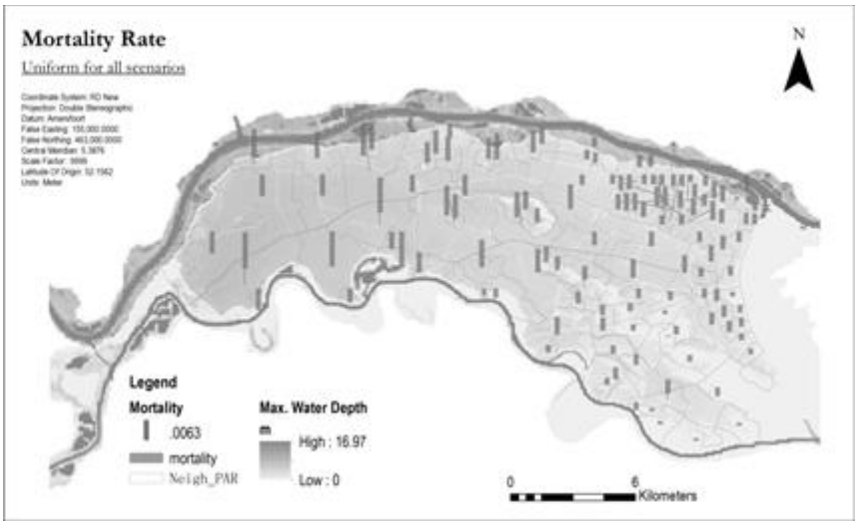

Figure 6-9 Estimated Mortality Rate

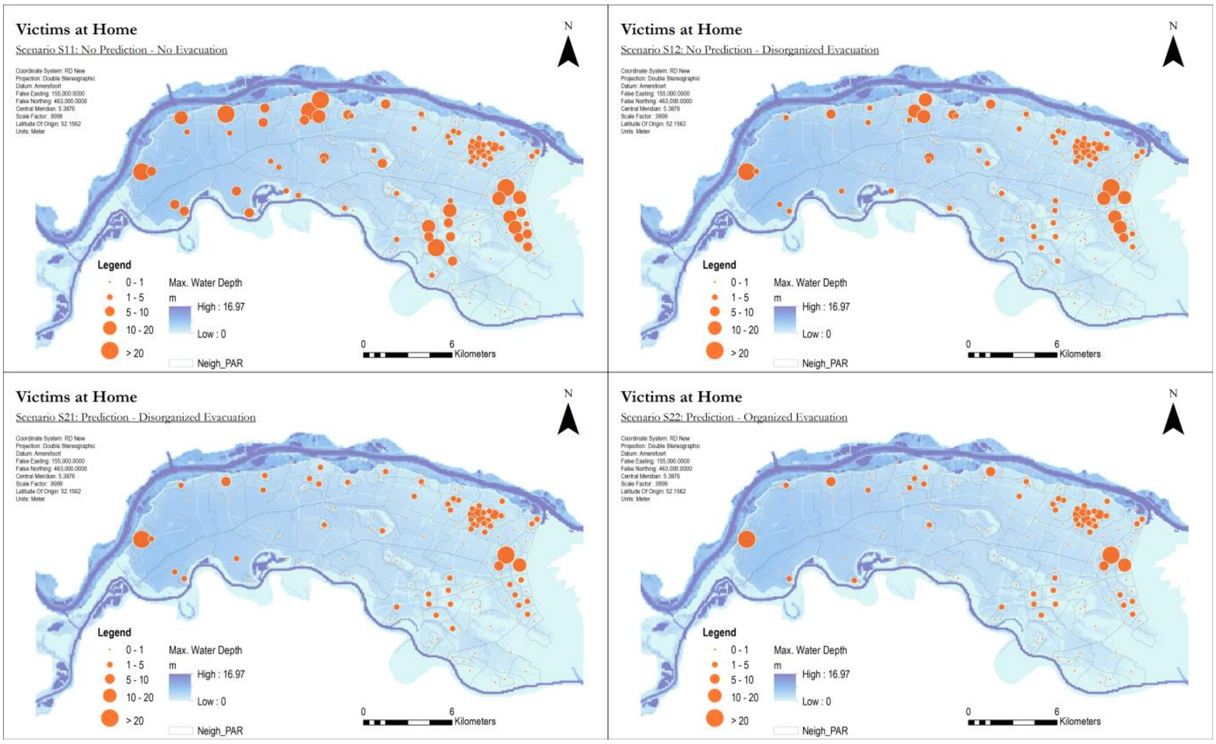

Figure 6-10 Distribution of Victims at Home

For en-route victim, it is calculated by multiplying the en-route exposed population with the mortality rates specified at the exact location of exposure incidents. The estimation results for en-route victims are shown in Figure 6-11.

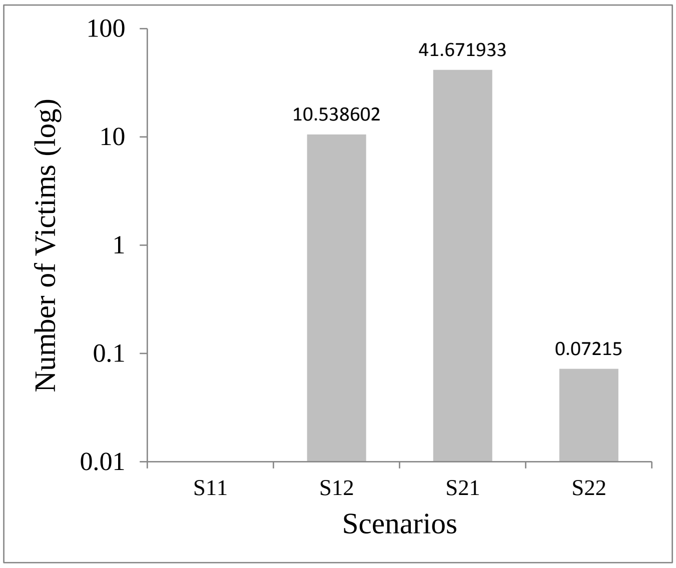

Figure 6-11 Numbers of En-route Victims

Both victims at home and on the routes are summarized to get the total number of victims for each evacuation scenario, as shown in Table 6-1.

Table 6-1 Number of Victims of Different Scenarios

Scenario	Home-based Victims	En-Route Victims	Total Victims
S11	1188	0	1188
S12	370	10.538602	381
S21	291	41.671933	333
S22	234	0.07215	234

As described in section "Evacuation Scenarios", scenarios are proposed to address the problem of complexity and uncertainty of behaviour and interactions in human society. In this study, the scenarios as explained are designed by a form of decision tree with two dimensions of branches: availability of early prediction for flood and level of organization for evacuation.

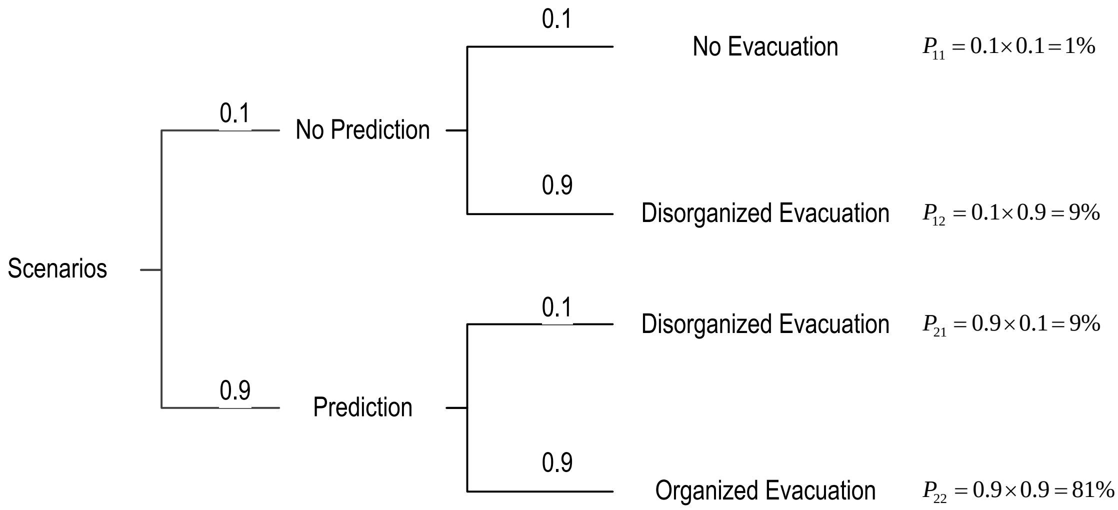

Figure 6-12 Conditional Probabilities for Scenarios

In order to quantify the definite number of victims in one flood, probabilities for different evacuation scenarios need to be known. This study refers to existing study with comparable context of Dutch flood risk assessment (S. N. Jonkman, Kok, et al., 2008) to specify conditional probabilities for each scenario. Jonkman (2008) estimated probabilities for scenarios by means of group discussion with experts. The probabilities assigned for scenarios are specified in Figure 6-12.

The total number of victims is estimated by combining estimations of all scenarios with conditional probabilities in Figure 6-12. **There would be 266 victims in total estimated if such a flood occurred in Land van Maas en Waal**. The spatial distribution of total victims is demonstrated in Figure 6-13. As the significance of home-based victims and scenario S22, the final estimation results follow a similar general pattern with that of home-based victims in S22. However, some less populous neighbourhood in the south are of relatively high risk of human life loss (e.g. village Verspreide huizen Horssen, Buitengebied Appeltern and Buitengebied Altforst, etc.) possibly because of the highly congested evacuation routes in these neighbourhoods that lead to en-route victims.

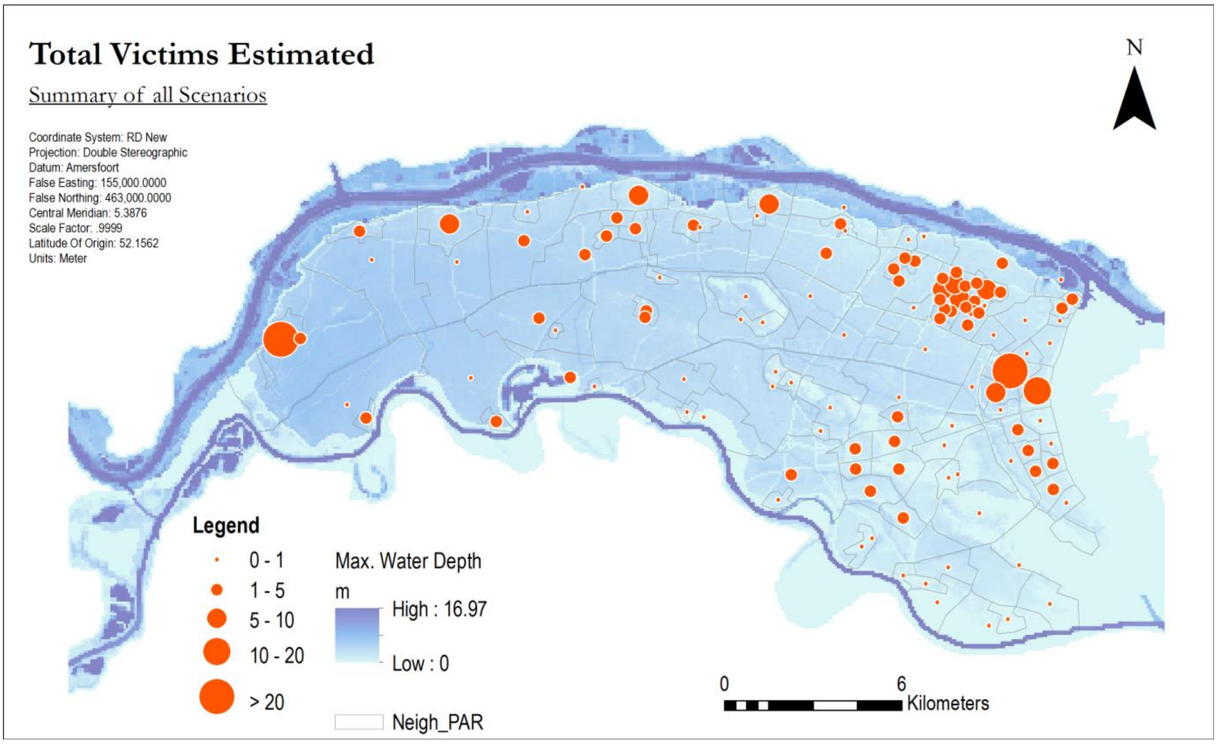

Figure 6-13 Total Victims Estimated for Land van Maas en Waal

Since real hazard incident observation data is basically not available for this area, it is not possible to calibrate the model with realistic data. Hence, the result of estimation of total victims is compared with estimation results from similar study which has also been carried out under the same flooding scenario. Alkema (Alkema & Middelkoop, 2005) used victim estimation module of the Dutch Flood Information System (In Dutch: Hoogwater Informatie Systeem, HIS) from Rijkswaterstaat, which is based on a different mortality function (Kok, Huizinga, Meijerink, Vrouwenvelder, & Vrisou van Eck, 2002) which takes both water depth and rising rate of water into account. It is estimated by Alkema using HIS model that under such a flood scenario (A1b), there would be 151 victims due to flood. The estimation result of this study (266 victims) is to some extend higher than Alkema's forecast, which may be caused by different mortality function and exposure estimation approaches. However, considering the fact that the application of the new proposed model in the study area is at its very prototype stage and many model calibrations are needed, the similarity of estimation results between the model proposed and a well-developed model (the same order of magnitude) suggests that the general design of the modelling framework is appropriate and it has potential to generate credible forecast for flood risk assessment.

6.2.2. Spatial Pattern of Victim Distribution

Spatial pattern of the overall victims in the study area can be explored by spatial statistics tools in ArcGIS. First, the global pattern of the whole study area like whether the distribution of victims is spatially clustered is analysed. Different from the pattern identified by visual interpretation, statistical methods are often applied in academic researches to detect the pattern or "hot zones" that is statistically significant in space. Frequently used spatial statistics include Moran I index and Getis-Ord Gi index, both of that provide standardized Z-Score and p-value for clustering or dispersion pattern identification, via setting null hypothesis that the distribution of observations is out of random process. The result of global clustering analysis is displayed in Figure 6-14. Moran I, index of spatial autocorrelation denies the existence of global clustering pattern, while a positive significant Z-Score of General Getis-Ord suggests that at significance level of 0.1, there is a pattern of clustering (similar values are close to each other than different values), which might have suggested some local clusters of high risk of human life loss.

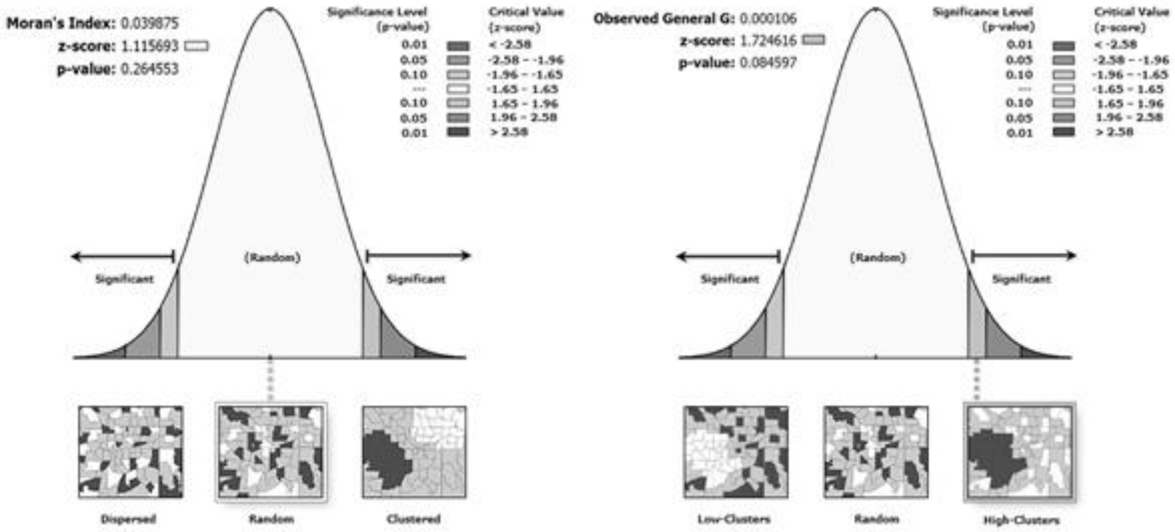

Figure 6-14 Spatial Statistics of Global Pattern

(Left: Moran I; Right: General Getis-Ord Gi*)

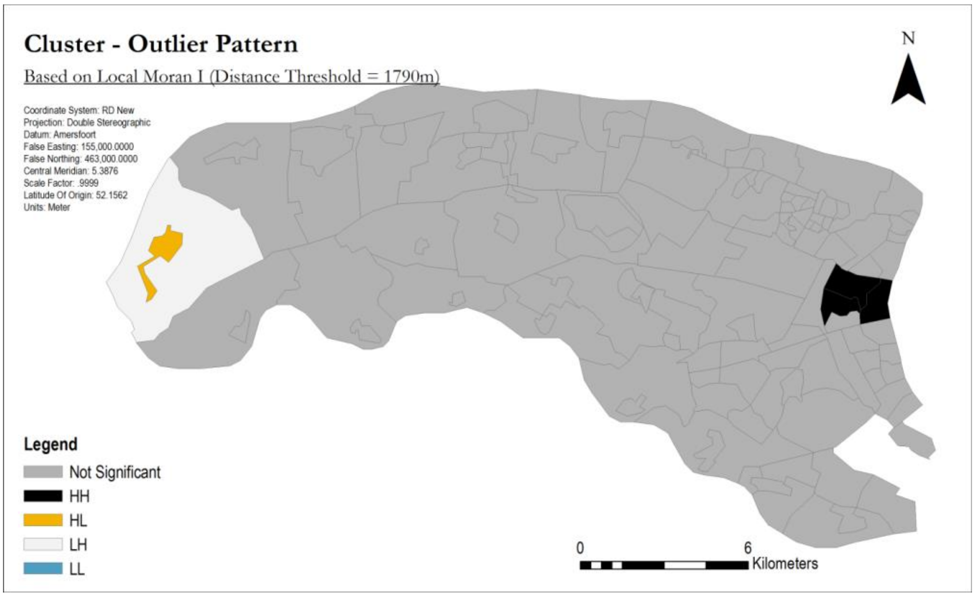

Figure 6-15 Cluster-Outlier Pattern based on Local Moran I

Since some degree of global pattern of clustering is identified, the next step is to find out locally where these clusters of similar victims are. The local indices of Moran I and Getis-Ord are performed in ArcGIS. Local Moran I is used to identify spatially significant clusters of High/Low victims combinations, while Local Getis-Ord index is performed to highlight significant hotspots of geographic phenomenon (e.g. loss of human life due to flood). The results are shown in Figure 6-15 and Figure 6-16.

In Figure 6-14, it is identified that neighbourhoods in the district Lindenholt near west Nijmegen all suffer serious loss of human life, presenting a High-High cluster, while in the west, neighbourhoods Kern Dreumel and Buitengebied Dreumel form a High-Low cluster.

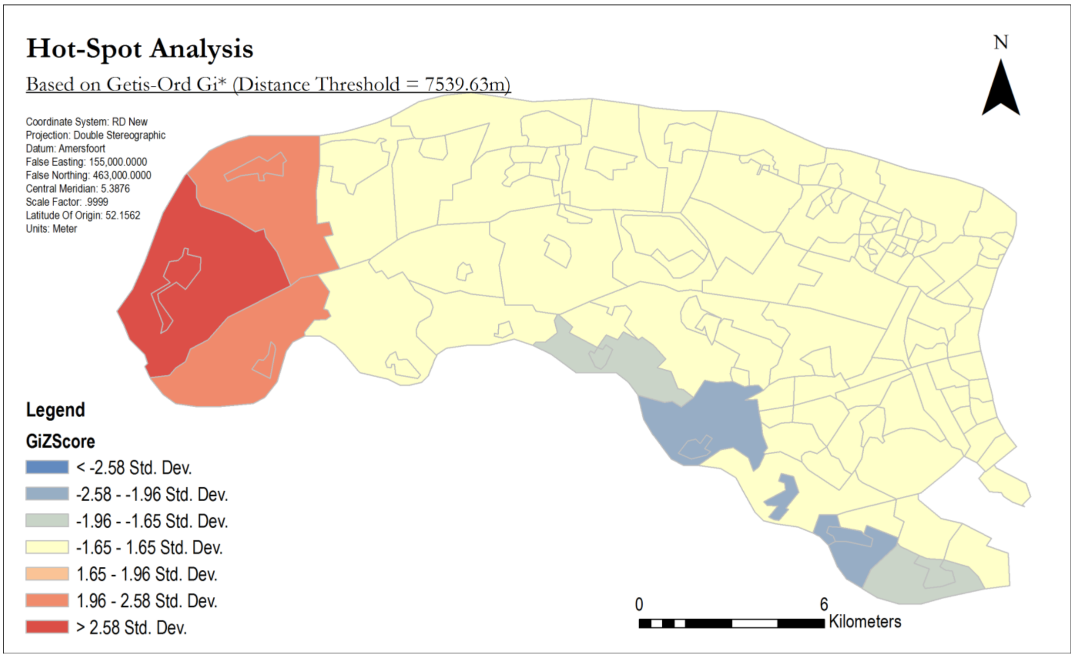

Figure 6-16 Hot-Spot Analysis based on Local Getis-Ord

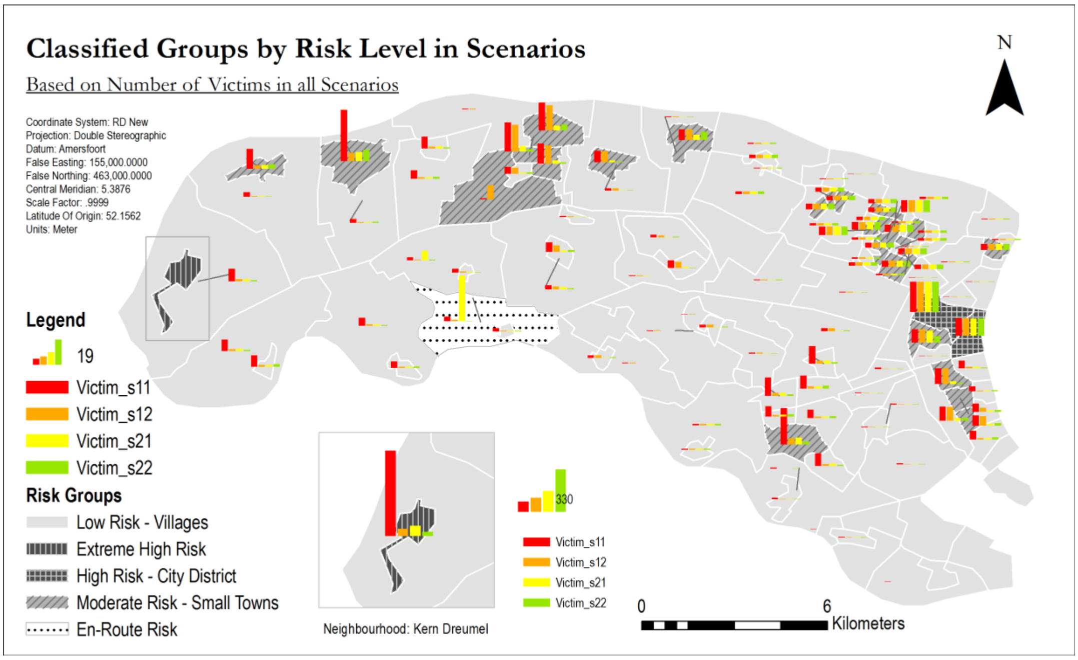

Figure 6-17 Classified Groups by Number of Victims in Scenarios

From local Getis-Ord index, the pattern of local "Hot/Cold Spots" is visualized as in Figure 6-16. "Hotspots" of victims are identified in the municipality of West Maas en Waal, while in the south along river low risk of human life loss can be identified, in municipalities like Wijchen and Heumen.

Beyond the simple clustering pattern revealed by spatial statistics, deeper insights about spatial pattern can be obtained via looking into the complexity of human behaviour and social organization which in this model is characterized by four distinguished scenarios. From the analysis of total victims among different scenarios, it is known that globally risks of human life loss are quite different in different situations. Then by further analysing spatial pattern over scenarios, it is possible to identify different types of neighbourhoods of varied risk level in different situations (scenarios). In ArcGIS, numbers of victims in different scenarios are taken into a multi-variable classification and 5 groups of neighbourhoods are classified.

As shown in Figure 6-17, five groups of neighbourhoods with different risk nature are classified. First, most villages are of low risk of human life loss. Second, because of being located in a high-water depth and rapid-rising water zone, the neighbourhood Kern Dreumel are facing with extreme high risk, which means in all possible situations, this small town will have high victim numbers except it successfully evacuates most of its residents. Third, the "high-high clustered" neighbourhoods in District Lindenholt near West Nijmegen are always facing with relatively high risks caused by their large populations and proximity to the breach, even though flood water doesn't rise rapidly in this area. Forth, another group, medium-sized towns with moderate level of victim risk, are identified. Neighbourhoods in Beuningen, Druten, Beneden-Leeuwen and Wijchen belong to this group. Among them, neighbourhoods in Beuningen are less populated, but quite close to the breach thus have little or no time for departure and evacuation. Others suffer from mixed effect of high population and decreased network availability during flood. Finally, the only one neighbourhood for the fifth group is distinguished because most of losses of human life in it occur on the highly congested routes once panic departure and disorganized evacuation routing happened.

This detailed analysis of victim distribution pattern can provide useful insights into different mechanisms of victim occurrence in different regions. As a result, it is capable to provide recommendations for area-specific risk mitigation measures.

6.3. Conclusion and Discussion

In this chapter, results generated by linked flooding-evacuation modelling are used to reach the main objectives of this study: estimations of exposed population and number of victims due to proposed flood. The estimation process is carried out by linked ArcGIS-MatLab modelling and analyses. From the results of exposed population and victim estimation, some important conclusions are summarized.

1) It is proved that early prediction of flood (even only two hours prior to actual occurrence of flood) can significantly reduce number of people exposed and died of flood. This fact suggests the model seems to be quite sensitive to the estimation results. In future improvement of modelling, the robustness of the model should be tested with sensitivity analysis, in order to figure out the impacts of variations in variables and parameters settings in actual prediction. From this study, <u>departure timing schedule</u> (departure time window span) and <u>departure response curve</u> have been recognized as quite influential for the final estimations. Therefore, in such deterministic approaches these modelling specifications are strongly recommended to be carefully studied and calibrated by survey, field study or exquisite psychological and social studies.
2) The organized evacuation (optimized evacuation routing, hazard-level specific departure schemes, prevailing evaluation of risk level of exits) to some degree reduce the population exposed in flood and home-based victims, but extent of improvement is not as significant and inspiring as expected. However, through dynamic en-route exposure simulation, it is discovered that organization of evacuation, particularly optimized routing approach, can bring benefits for maintaining performance of evacuation network and preventing serious congestion, thus saving lives on evacuation routes by preventing evacuating vehicles being stuck in advancing flood.
3) It is confirmed that if there is only prediction but no proper organization of evacuation, the panic people may depart within a short period of time and choose routes considering nothing of others. This would probably lead to serious congestion on the roads (particularly on artery roads for

major exits) and declined performance of the whole network, which gives rise to considerable en-route exposure and casualties.

4) By combining victims in all scenarios, the total number of victims in this flood event is estimated as 266, which is comparable to the estimation result of similar research under identical flood simulation. The difference of estimation results may come from different mortality function used. Comparing to home-based evacuation, in Land van Maas en Waal, en-route victims are not significant, which may be attributed to the relatively small population and well-developed transport network in this area.
5) Spatial pattern of victim distribution are inspected by spatial statistics. Globally, the distribution of victims in the study area is insignificantly clustered. Locally, different high-high or high-low clusters are identified[53]. Via spatial classification by risk levels across all scenarios, different groups of neighbourhoods with varied risk characteristics are specified, which may provide insights for area-specific risk mitigation.

In terms of application of the proposed new methods, especially the dynamic en-route exposure simulation backed by new data structure EMS, the newly designed exposure and victim estimation modules has exhibited potential in dynamic en-route analysis, visualization of temporal-spatial exposure and victims and story-telling. The model proposed by this study supports automated workflows for evacuation-flooding interactive process analysis, automated mortality rate estimation and scenario-based victim estimation. The application of spatial statistics for victim distribution pattern analysis may provide useful insights for risk mitigation measures. However, limitations in the methods applied are also recognized, as listed below.

1) Though effect of sheltering has been modelled, it is merely specified between urban and rural areas. Realistic sheltering capacity based on field survey (e.g. building types and floors) is not yet considered. In addition, no effects of rescuing have ever been taken into account.
2) The simulation of en-route exposure is based on deterministic assumption that people would fully comply with prescribed routes, which deviate from reality since people can flexibly dodge around the water if it is already within evacuees' sight. Simply speaking, the assumptions about evacuees' behaviour in such emergent situations are still too simplistic. In future integration with Agent-Based Model may address this problem to some extent.
3) Limited by research time and resources, this study has referred to conditional probabilities for scenarios from other studies with similar context. This may cause problems of generalization. As completed in other studies, the probabilities of scenarios which are crucial for final victim estimation should depend upon more comprehensive understandings of the study area, the flood simulation and social organizations of local communities.

[53] The credibility of local clustered pattern revealed by spatial statistics may be limited by insufficient observations, as this study is carried out at neighbourhood level.

7. CONCLUSION AND DISCUSSION

7.1. Conclusions from the Case Study

Besides some specific conclusions drawn in Chapter 5 and 6, several generic conclusions are reached by viewing the entire case study.

First, under a flood event simulated and adopted in this study, there would be significant loss of human life in Land van Maas en Waal. The total number of victims estimated is 266, which is relatively higher but still at the same order of magnitude comparing to estimates from Dutch HIS model by Rijkswaterstaat. The distribution of victims in the study area is insignificantly clustered globally. Locally, several hotspots, spatially auto-correlated clusters are identified. Casualties occur in five categories of regions which are characterized by different relative risk in different situations (presented by scenarios).

Second, in Land van Maas en Waal the home-based casualties (victims due to flood at home) are more significant in both spatial occurrence and absolute scale. The amount of home-based victims is to large extent affected by population of community, the proximity to dike breach, availability of early prediction for flood, response and departure rate, etc. The identification of impact factors for home-based victims can provides insights for area-based mitigation measure. For example, for populous towns or city districts (e.g. Beuningen, Lindenholt, etc.) which is close to the breach, the focus of mitigation measures should be provision of local sheltering facilities or rescuing actions so as to decrease population exposed in water. For towns farther from the initiative location of flood, early prediction delivery, strong order of departure and proper departure arrangement over time may be crucial.

Third, the en-route casualties are much less significant in comparison with home-based victims, because of the small population and completed transport network in Land van Maas en Waal. Most evacuees departing from houses only spend less than 30 minutes getting out of the area at risk. It is identified that the major impact factors of en-route victims include departure concentration in time, routing optimization and exogenous issue of flood expansion speed. At least, two lessons can be learned for reducing en-route exposure and casualties. 1) The delivery of prediction and warning of flood must be followed by proper arrangement of departure and evacuation routing. Otherwise, in such emergency, once organization of evacuation were absent, the panic caused by warning can lead to rapid departure and concentrated route choices both of which may cause serious congestion and declined network performance, and finally mass en-route exposure and casualties. 2) Some roads may be available at the time of departure, but in the cause of the whole flood event, they may be seriously inundated by later coming flood. If this kind of roads is attractive for evacuation routing, they should be highlighted, warned or even disabled during the whole evacuation to prevent en-route dangers.

Fourth, from the large variation of estimates between different scenarios, it should be noted that uncertainty or complexity (represented by scenarios) of human behaviour and social organizations can have significant impacts on loss of human life. In modelling, even by roughly differentiating human behaviour and organization assumptions, the estimation results can be quite different. Therefore, it is recommended that any emergency actions or policy measures are established on solid study of human behaviour and response to top-down organizations in emergencies.

7.2. Discussions of Methodology Development

7.2.1. Comprehensibility of Modeling

Being the major objective of this study focusing on methodology development, whether the criteria of "strategic modelling" have been satisfied is examined by the end of the study.

It can be concluded that in terms of the following aspects, the modelling framework and procedures proposed by this study has reached the target of "comprehensibility" for a strategic model.

1) The conceptual model set up for describing the logic of victim estimation is easy to understand, because it streamlines the major processes of flooding occurrence, evacuation, sheltering, exposure and casualty generation in a story-like sequence. The crucial linkages between flooding and evacuation process are clearly described in the conceptual model (see Chapter 3: "General Approaches and Methods".
2) The operational model which evolves from conceptual model, has explicitly defined important modeling issues, variables, parameters, relations using both unambiguous schematic and mathematic languages (see Chapter 3: "Design of Modeling Framework").
3) The workflows in both ArcGIS and MatLab are clarified and well documented, via flowcharts and open-sourced scripting codes for each module of the model (see Chapter 5 and 6).
4) Comparing to other sophisticated evacuation demand model (see Chapter 2: "Travel Demand Modelling"), this study adopts a simplified version (simple cross-classification and departure curve) to achieve a balance between comprehensibility and capability in describing sufficient complexity of human behaviour.
5) The evacuation routing algorithm is explained (see Chapter 3: "Route Optimization") by demonstration of a dummy model. It is also easily understood since its foundation is the well-known and often used Shortest-Path (SP) algorithm.
6) The spatial-temporal relation between flooding and transport infrastructure is clarified (see Chapter 3: "Evacuation Supply").
7) The approach applied for exploring interaction between evacuation process and flooding expansion is clarified. This highly dynamic, non-linear problem is solved by an iterative scanning algorithm backed by EMS, an innovated data structure that is compatible with both ArcGIS Geoprocessing and MatLab scripting workflow (see Chapter 3: "Exposure Estimation" and Chapter 6: "En-route Exposed Population").
8) A comprehensive evaluation of flood hazard is performed by an explicit method (flood zonal classification, see Chapter 3: "Flood Zones Classification") which is based on concrete literature basis. The three types of flood zones classified by this method are served throughout this study as the foundation for all flood-related analysis.

7.2.2. Model Validity, Practicability and Adaptability

The quality of modelling is not evaluated only by "comprehensibility", but also in aspects of validity, practicability and adaptability. These aspects are discussed by looking at the design and application of the modelling framework and procedures proposed in the study.

<u>In terms of validity</u>, most methods and approaches (e.g. flood zonal classifications, participation share estimation, departure curve, scenario settings, mortality functions, etc.) adopted are well grounded in sufficient literature studies that are of similar context or research objectives. However, since there is basically no data for model calibration (except for flood zonal classification and mortality rate function, these two models are verified and calibrated by Jonkman (2008)), the validity of the model is reduced.

In terms of practicability, the model proposed is argued as practical with regard to the following 4 aspects. First, data requirement is not demanding. Dataset like basic demographic statistics at neighbourhood level is generally accessible via publications and other sources, while there are usually even multiple sources for network data, including open-sourced, constantly updated OSM data. Second, models and methods in this study are tangible. No difficult mathematics is ever included. In addition, modelling procedures in this study are readable with help of visualized flowcharts and documentations. If needed, algorithm and workflow can also be customized by modifying Geoprocessing models or MatLab scripts. Third, this model is implemented on the widely accepted, friendly user-interfaced platforms (ArcGIS and MatLab) in both academic and government circles. For data management, this study employs Geodatabase which is gradually becoming standard for many geo-spatial modelling studies. Finally, as probably the most issue of practicability, this model doesn't merely generate the final one-figure victim estimates but also provide meaningful, inspiring results for the whole process (e.g. transport infrastructure being dynamically affected by flood, departure pattern in time and space, monitoring of evacuation performance over time and its interaction with flooding, spatial pattern of victim distribution, etc.).

In terms of adaptability, this model is not only dedicated for Land van Maas en Waal, but also for studies in other areas with comparable context. The model has put forward a uniform data scheme which can be adapted to datasets of different areas. Also, by calibration and fine tuning, some modules in this model (e.g. flood zone classification, demand module, supply module, mortality functions) may be applied in other areas. However, it should be noted that this model is built in context of low-lying dike-ring area and river-induced floods. Thus, it should be very cautious for application of this model in other cases.

7.2.3. Rethinking about Functions of Modelling

In scientific modelling paradigm, one important function of models is for accurate prediction and approximation to reality (reductionism philosophy). But for a highly dynamic and complex phenomenon like casualties in a flood, the modelling work is always challenged by uncertainties, complexity and unpredictability of personal and societal behaviours.

Also, because of its close relation with public policy, community knowledge and awareness and social interactions, it should be realized risk assessment and victim estimation is neither a mathematical problem, nor an engineering program. Since in many areas, the validation data is simply not in presence, risk assessment and victim estimation would be undoubtedly an open question engaging more social, political and psychological concerns.

Through the application of the designed modelling procedures in the study area, it is strongly recognized that much more inspiring lessons are learned during the whole process rather than at the end when only one figure (266 victims) is generated. For instance, estimates of victims for all scenarios are aggregated to get the final result, but the classification of neighbourhood with varied risk characteristics by detailed analysis over each scenario could bring insights into public discussions on regional planning and mitigation policies.

Therefore, by the end of this MSc study it is learned that the primary function of modelling in this field is to provide clarified clues for story-telling and a platform for discussion about our common future. Web applications and websites are established and published to explore the potential of platform.

7.2.4. Limitations and Future Improvements

Due to time and resource limits of MSc study, the model proposed by this study is still an early prototype which inevitably has lots of limitations and drawbacks. Limitations of this study and some suggestion on future improvements are discussed below.

First, in order to avoid being overcomplicated, some oversimplified assumption about human behaviour are made, which might to certain extent deviate from the complex reality. Examples of simplified behavioural assumptions are uniform departure origins at home locations rather than time-of-day specified locations (homes, working place, schools, etc.), "one family – one vehicle" assumption, uniform response and depart pattern, solo evacuation destination choice (no multi-destination choices), full compliance with prescribed routes rather than en-route routing, etc. In future model development, this problem may be addressed by survey based approaches, corporative planning processes, and even Agent Based modelling based upon detailed behavioural and social network studies. However, it is always important to maintain a balance between simplicity and approximation to reality. Otherwise, it would be difficult to understand and interpret over complicated models. Possible compromise in methodology may be mixed deterministic (top-down) and agent based (bottom-up) modelling. For example, people still follow predefined rules to choose evacuating routes. However, on the routes evacuees behave as agents that may circumvent route parts threatened by flood instantly.

Second, in transport modelling (evacuation routing), being unfortunately constrained in technical support, instead of fully dynamic traffic assignment, a semi-dynamic or time-sliced routing algorithm (CASPER) is applied. The biggest drawback of it is no consideration of traffic between time instants. Also, there is no delay at the road intersections and traffic lights being modelled. In the future, CASPER routing may be replaced by dynamic traffic assignment and en-route routing algorithm (see Chapter 2: "En-route routing model"). But the preconditions for adoption of advanced dynamic transport model are: 1) it is explicitly explained; 2) it can generate dynamic routes and engaging road segments datasets that are required for en-route exposure simulation.

Third, inconsistency of spatial/temporal resolution can cause inaccuracy problems. In this study, the flood simulation is performed on raster data and monitored by each hour; while the vector-based evacuation modelling has much finer resolution of minutes. In en-route exposure simulation, inconsistency in resolution may cause inaccuracy and uncertainty problems. It would be nice if flood simulation is performed at finer resolution. However, benefits of improving resolution might be offset by more demanding data storage and computation capacity.

Fourth, instead of collecting demographic data at neighbourhood level as in this study, future development may be more detailed modelling at household level. In fact, many studies in the US about hurricane evacuation have utilized household data massively in demand estimation and destination choice models.

Finally, concerned about the model development, the model of this study is realized by loosely-coupled modelling between ArcGIS and MatLab. Advantage of linking these two platforms is that either software's strength can be fully utilized (ArcGIS in geoprocessing, MatLab in matrix manipulation and iterative programming). However, many limitations remain. For example:

1) Datasets have to be tediously exchanged between ArcGIS and MatLab with format conversions.
2) The workflow of the whole model is fragmented so that errors or operation mistakes are easily generated between model pieces.
3) Lack of unified workflow management, modeling platform and user-customizable interface result in less feasibility of the model.

Possible solution to this is to develop a unified model based on ArcGIS using Python scripting. Powered by variety of open-sourced libraries (even including library retrieving MatLab functions back into Python), Python may act as "glue" and link user customization, geoprocessing procedures, model calibration and even automated visualization of results into one package.

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APPENDIX A: EXPLANATION OF MODELLING THEORIES

A1. Description of Simultaneous Evacuation Demand Model

The main objective of simultaneous model is to estimate the probability (share) of each household (Fu, 2004; Fu & Wilmot, 2004) or population class (A. J. Pel, et al., 2008) to take an evacuation decision at each time instant. In order to estimate the decision probability, it is assumed that, by adopting a random utility theory, the decision probability is primarily determined by relative utility of evacuation against continuous stay at each time stake. Further, because the relative utility, generally denoted by $V_t^s - V_t^e$ (V_t^s: the utility of stay at instant t, V_t^e: the utility to evacuate at instant t) could be proved logistic distributed (Fu & Wilmot, 2004). Therefore, the relation between decision probability for evacuation over stay and the relative utility could be characterized by a binary logit model, denoted as below:

$$P_t^{e/s} = \frac{e^{V_t^e}}{e^{V_t^e} + e^{V_t^s}} \tag{A.1}$$

In Formula(A.1), $P_t^{e/s}$ is the conditional probability of evacuation over stay at time *t*. It could be easily transformed to:

$$P_t^{e/s} = \frac{1}{1+\exp\left(V_t^s - V_t^e\right)} \tag{A.2}$$

In Formula(A.2), to estimate conditional probability, dynamic utility in prior should be simulated. Construction of utility model has been argued as the central part of simultaneous model (Adam J. Pel, et al., 2012) as it has revealed how the behaviour and decision-making processes are simulated. The utility model contains a series of variables which would be specified first. The early studies in this field was initiated by Fu and Wilmot (2004), who in their case study of south-eastern Louisiana proposed factors being taken into account for utility modeling in Hurricane evacuations:

- distance to storm
- forward speed of hurricane
- time-of-day (morning, afternoon and night)
- presence of evacuation order

Besides regularly used hazard attributes, two remarks about Fu and Wilmot's factors could be noted. First, the inclusion of dummy variables for time-of-day overcomes the limits of response curve. Second, the engagement of evacuation order was a remarkable advance because of the well-discussed effects of order on evacuation demand. Unluckily, due to data limits, order variable in Fu and Wilmot's model was quite limited as its static binary nature. However, this bottleneck was later quite relaxed by Pel et al. (2008). Based on Fu and Wilmot's model, dynamic evacuation order component was installed onto a new utility model, while people's dynamic response and compliance were even equipped and seamlessly integrated with order variable.

Utility model could be formulated in various ways, but usually simple multi-linear model has been adopted by existing studies (Fu & Wilmot, 2004; A. J. Pel, et al., 2008).

$$V_t^e - V_t^s = \beta + \alpha_t^i X_t^i + e_t \tag{A.3}$$

In Formula(A.3), arrays of independent variables X_t^i could be verified by significance test. The error e_t, needs to be independent and Gumbel distributed, to avoid sequence autocorrelation. Parameter vectors β

α_t^i need to be estimated and calibrated. In order to estimate parameters of formula 1.4, 1.4 should be put into 1.3, and the dependent variable, the binary conditional probability (0/1) could be obtained either from stated preference survey (Alsnih, Rose, & Stopher, 2005) and real observation data collected during hurricanes, usually by local government (Fu & Wilmot, 2004).

After the estimation for conditional probabilities, the unconditional probability for evacuation at interval t is calculated by formula(A.4).

$$P_t = P_1^{s/e} \cdot P_2^{s/e} \cdot \ldots \cdot P_{t-1}^{s/e} \cdot P_t^{e/s} = P_t^{e/s} \prod_{i=1}^{t-1} \left(1 - P_i^{e/s}\right) \tag{A.4}$$

Seen from Formula(A.4), not only the conditional probability at instant t, but also all previous ones need to be estimated. This approach (Fu & Wilmot, 2004) was quite complicated to perform as it is a household-based iterative estimation process[54].Later Fu, et al. (2004) developed an alternative approach to pool data into a panel data set so that related problems could be addressed.

The repeated binary logit model is a utility-based model at micro level with usually analytical unit of household. The estimated household depart probability needs to be aggregated for the whole population to generate the travel demand. The share of total N households departing at t is

$$\chi_t = \prod_{n=1}^{N} \overset{n}{P}_t = \prod_{n=1}^{N} \left(\overset{n}{P}{}_t^{e/s} \prod_{i=1}^{t-1} \left(1 - \overset{n}{P}{}_i^{e/s} \right) \right) \tag{A.5}$$

Where χ_t is the share of evacuees aggregated, $\overset{n}{P}_t$ is the unconditional probability of evacuation at t. After reviewing each step of simultaneous model, the computational modeling framework could be figured out.

A2. Mathematical description of dynamic network availability

First, inundated part of the network is generated by simple spatial intersection.

$$inundNet(t) = originNet \cap \left(waterDepth(t) > 0.3\right) \tag{A.6}$$

Then, the network remained as available is generated.

$$availNet(t) = Cs\left(inundNet(t)\right) = originNet - inundNet(t) \tag{A.7}$$

For static exit selection under disorganized evacuation scenario:

$$evacExits(t) = originNet \cap h_{\max} \tag{A.8}$$

A3. Mathematical description of dynamic exit availability

For dynamic availability of exits in organized evacuation:

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[54] If cross-section data is given, within each time interval, model parameters are estimated by normal fitting models, using independent variables and decision status (binary, 1=evacuation, 0=go on staying) as dependent variable. However, the household with status 1 at interval t need to be excluded from the sample as they have departed. Thus, after each round, data needs to be refreshed and new models with changed parameters are repeatedly estimated. In additional to that, problems like less observations at later intervals after continuously excluding departed households will make the estimation less reliable.

First, all exits are engaged at time zero. Exits are selected as intersection of primary roads with maximum flood extent.

$$evacExits(0) = originNet \cap h_{max} \tag{A.9}$$

Then, for each time instant, a buffer of each exit (the radius of buffer may be specified by emergency planners or evacuation organizers) is generated.

$$buffer(t) = \mathrm{BUFFER}(evacExits(t), r) \tag{A.10}$$

The risk of exits being threatened by advancing flood is evaluated by calculating average water depth and area being flooded in these buffers.

$$avgWatDepthExits(t) = \mathrm{MEAN}(h(t) \mid h(t) \in buffer(t)) \tag{A.11}$$

$$percAreaFlooded(t) = \mathrm{AREA}(h(t) > 0) / \mathrm{AREA}(buffer(t)) \tag{A.12}$$

Exits are selected depending on the risk evaluated by both indicators calculated by formula(A.11) and (A.12), as shown in formula(A.13).

$$\begin{aligned} &evacExits(t) = \mathrm{SELECT}(evacExits(t-1)) \\ &if: avgWatDepth(t) \geq 0.5 \ \& \ percAreaFlooded(t) \geq 30\% \end{aligned} \tag{A.13}$$

A4. Mathematical description of EMS data structure and en-route exposure identification

First, as shown in Figure 3-8, The "Evacuation Milepost Series" (EMS) is constructed based on evacuation routes $RT_p(t)$.

Set: at time instant t, for the evacuation route $RT_p(t)$, k number of vertexes (mileposts) are contained.

$$V_p = (v_1, v_2, \ldots, v_k), V_p \in RT_p \tag{A.14}$$

The route is composed by j number of road segments (edges):

$$Eg_p = (e_1, e_2, \ldots, e_j)\text{[55]} \tag{A.15}$$

As the output of evacuation routing, each road segment is attached to attribute of real traversal cost:

$$Eg_p.\ cost \tag{A.16}$$

By spatial join (j to k), traversal time statistics as the outputs of Evacuation Routing are assigned to each milepost V :

$$V.c = Eg_p.\ cost \tag{A.17}$$

The traversal time between every two neighbouring mileposts are derived from disaggregating the total route travel time weighted by traversal cost estimated in Formula(A.17). Then the cumulative travel time at each milepost is calculated as the sum from the first milepost.

Set: the total travel time of the route is:

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[55] Usually, there are fewer road segments than vertexes in one route ($j \leq k$).

$$T_{evac}^{p} \tag{A.18}$$

Then, the incremental travel time from the nth milepost to the (n+1)th is derived from disaggregating the total route travel time weighted by traversal cost estimated in Formula(A.17)

$$v_n.\,dt = T_{evac}^{p}\frac{v_n.c}{\sum_{i=1}^{k} v_i.c} \tag{A.19}$$

Then the cumulative travel time at the nth milepost is calculated as the sum of incremental travel time from the first milepost.

$$v_n.\,T = \sum_{i=1}^{n} v_i.dt \tag{A.20}$$

The "passing time" is the sum of departing time t and the cumulative travel time from post 1 for each milepost.

$$V.\,passTime = \{v_n.\,passTime\} = \{t + v_n.\,T\} \tag{A.21}$$

The "time to flooding" and water depth at each milepost is assigned by spatial join with the flood characteristic layer (ttf).

$$V.\,ttf = ttf\left(x,y\right),\ \text{if}\left(x = V.x \text{ and } y = V.y\right) \tag{A.22}$$

$$V.h = waterDepth\left(t\right).\left(x,y\right),\ if\left(x = V.x \text{ and } y = V.y\right) \tag{A.23}$$

So far, the data structure of EMS has been constructed, as described below:

$$EMS : V = V\left\{p, N_p, t, T, passTime, ttf\right\} \tag{A.24}$$

p : the ID of the neighbourhood; N_p : the number of evacuees; t :the departing time ; T : the cumulative travel time from departure; $passTime$: the "passing time" at each milepost; ttf : the "time to flooding" at each milepost.

To identify the location and time of exposure, it is necessary to perform an ordinary scan following the sequence of EMS. Its procedure is described below:

For $i = 1 : k$

if $v_i.passTime \geq v_i.ttf$ and $v_i.waterDepth > 0.3$

export v_i as "Exposure of neighbourhood p "

end if

end

This procedure is repeated for all neighbourhoods departing at t , then for all time instants.

A5. Mathematical description of CASPER algorithm and a demo model

Set up the OD and network:

The origins of evacuees: $O\left(M\right)$

$O.population = P_j$

The destinations: $D\left(N\right)$

$Net = E(e_1, \dots e_n)$, // E :the set of edges of network

$e_k = e_k\{fl, C, t_0, t\}$, // attributes of network edges. fl :flow on edges, C :capacity of edge, t_0 :free-speed traversal time; t :estimated traversal time considering congestion.

Routing Initialization:

$R^0(M) = ShortestPathRouting(O, D, Net)$ //Perform SP with initialized origin, destination and network settings, retrieve the SP routes for M origins.

$R^0(M) = R^0\{T\}$ //Get travel times for all routes

$O^s(M) = DescendSort(O(M), R^0(M).T)$ //Sort the origins by travel time from highest to lowest

Incremental Assignment:

For: $i = 1 : M$

$R(O^s(i)) = ShortestPathRouting(O^s(i), D, Net)$ //Assign the most attractive route from farthest origin

$R(O^s(i)) = E_i(e_{k_1}, \dots, e_{k_i})$ //Route for the ith origin in $O^s(M)$ consists of ordered edges.

$Net = Update(Net, R(O^s(1)), \dots, R(O^s(i)))$ //Update the network attributes (flow on edges, estimated traversal time of edges, with assigned routes information

End.

Updating the network for each iteration:

Function $Update(Net, R(1), \dots, R(J))$

$\forall j,\ j = 1, \dots, J$ //for route of any origin j, which has been imported as variable of the function

$R(j) = E_j(e_{k_1}, \dots, e_{k_n}),\ E_j \in E$ //the route for any origin consists of edges of the network

if: $e_i \in R(j)$ //for those edges contained by the imported routes

$e_i.fl = \sum_j^J R(j).population$ //calculate flow on the edges by summing up all evacuees using it

$e_i.t = e_i.t_0 * f(e_i.fl, e_i.C)$ //increased traversal time is multiplied by congestion function

$$f = \begin{cases} 1 & e_i.fl/e_i.C \in (0, \gamma_{\min}) \\ f & e_i.fl/e_i.C \in (\gamma_{\min}, \delta\gamma_{\max}) \\ 1000 & e_i.fl/e_i.C \in (\gamma_{\max}, +\infty) \end{cases}$$ //specification of the congestion function by settings

critical values of traffic flow per capita[56].

For better illustration of the modeling procedures of CASPER, and to compare the differences of system performance between SP and CASPER, a simplified dummy network model is developed and demonstrated below.

As shown in Fig. 1, a simple network is composed by edges with different free-speed travel time. 3 origins: A, B and C are with identical population of 100, the yellow triangle is the destination.

[56] In ArcCASPER, the form of congestion function is not completely known yet. However, it is for sure that the function is non-linearly positive to increasing flow per capacity unit. Capacity unit in real road network is represented by number of lanes.

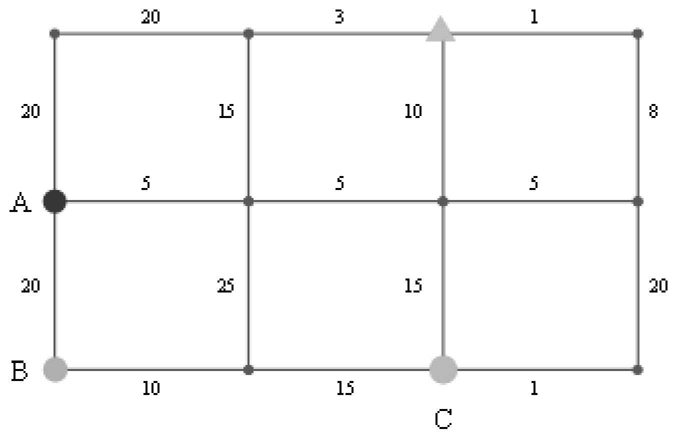


Fig. 1 Setting of a simple routing problem: network, origins and destination

Congestion functions are specified: $f(100,1)=1.84$, $f(200,1)=2.82$, $f(300,1)=4.77$

First, Shortest Path Routing is performed for A, B and C simultaneously, shown in Fig. 2.

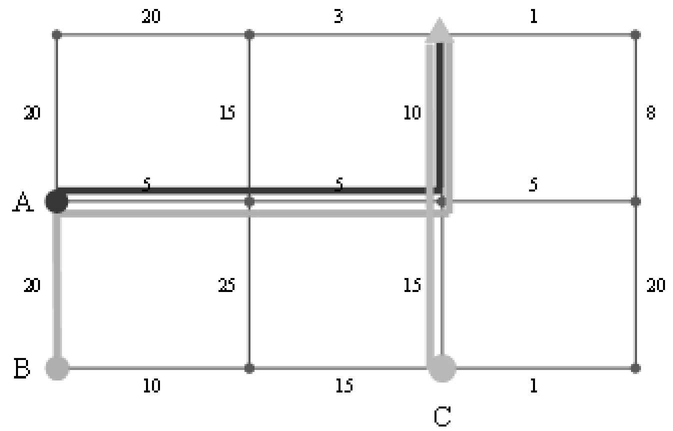


Fig. 2 Shortest Path Routing for A, B and C

After SP routing, the time distance of 3 origins are sorted from highest to lowest, shown in Tab. 1.

Tab. 1 Sorted list of origins by travel cost

Origins	Dist.
B	40
C	25
A	20

In the list, the worst-off origin, B gets the priority to route first. An SP routing is performed for B and the route is generated, as shown in Fig. 3.

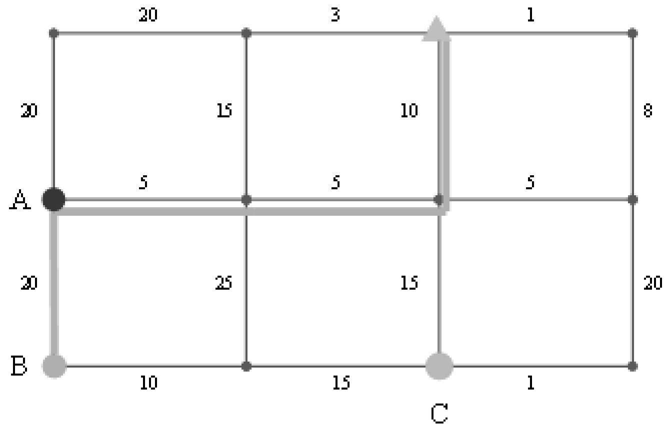


Fig. 3 SP routing for the prioritized origin B

After routing for B, traversal times on edges are updated with the traffic flow assigned. Then, the second place on in Tab. 1 Sorted list of origins by travel cost, origin C is assigned route, shown in Fig. 4.

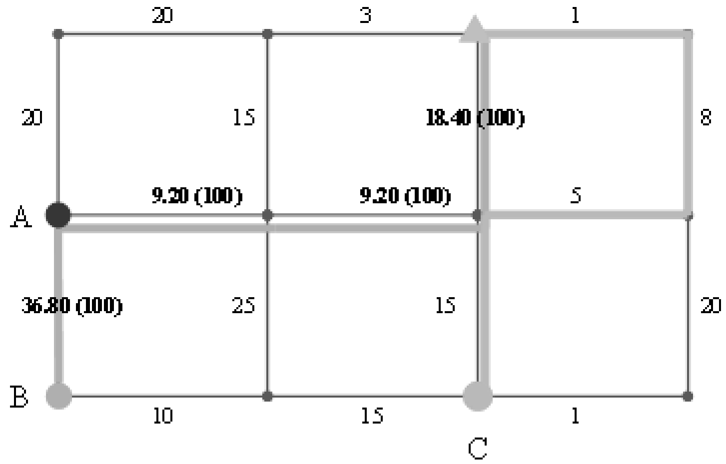


Fig. 4 Update the network and routing for C

Similarly, network gets updates after C's routing, and then the last one in Tab. 1, origin A gets routed based upon the updated network.

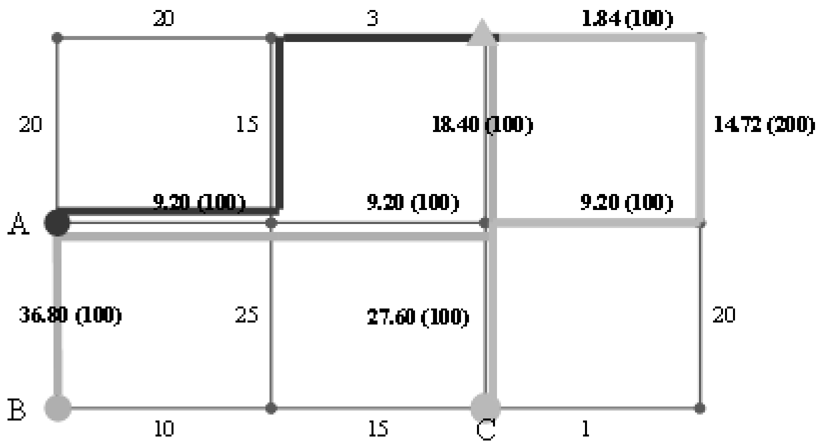


Fig. 5 Update the network and routing for A

Finally, all traffics have been assigned with the final updates of network, as shown in Fig. 6. Then the estimated travel times based on the corrected traversal time on edges are aggregated for each route. The performances of SP against CASPER are compared in Tab. 1. It is obvious that either at individual level or system level, CASPER has optimized the network performance by avoiding those highly congested segments.

Tab. 2 Comparison of System Performance between SP and CASPER

Route	free.Time (SP)	est.Time (SP)	free.Time (CASPER)	est.Time (CASPER)
Ra	20	75.957	23	47.219
Rb	40	112.75	40	78.494
Rc	25	75.34	29	53.352

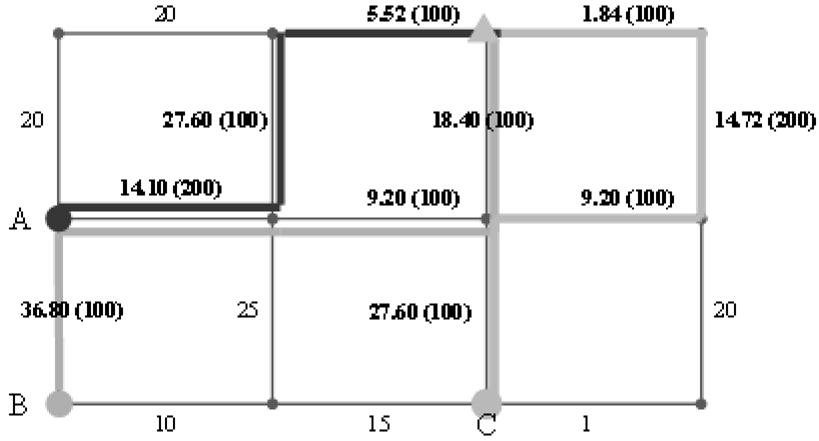


Fig. 6 All origins are routed and the network is updated

A6. Mathematical description of procedures determining the ending time of departure

According to conceptual analysis the specification of ending point of time window depends on relation of the following factors:

- Staring point of time window (ETW_{start})
- The time point when participants can no longer find any route to any exits because of inundation of road network ($t_{failRoute}$). It is determined by repeatedly performing a simple routing search using dynamic network and exit availability information ($availNet(t)$ and $evacExits(t)$)
- The time to flooding (ttf) which is one of the flooding characteristics indicates the time of arrival of the flood at each neighbourhood. There would be no chance at all for anybody to depart and evacuate once their houses have been flooded. It can be inferred that the time of failing to depart $t_{failDep}$ would be determined by the minimum of time failing to route and time to flooding.
- The time when all participants have departed (t_{all}). It is determined by the share of participants (S_{PE}^{p}) which is estimated in the previous module, and the departure curve proposed for the neighbourhood in this module.

Then, several situations are analysed to determine ending time of departure.

1) Determining the time failing to depart ($t_{failDep} = \min(t_{failRoute}, ttf)$) out of a comparison between time failing to route and time to flooding.

2) If the time failing to depart is prior to the starting point of time window, it may suggest that the neighbourhood may be too close to the breach that the flood comes at very early stage, or there is a substantial delay in response so when participants decide to start departing the water has come. Under this situation, the ending time of departure coincides with the starting time, which means there is no time at all for departure.

$$if: t_{failDep} \leq ETW_{start}$$

$$ETW_{end} = ETW_{start} \tag{A.25}$$

3) If the time of failing to depart is later than the starting point, but prior to t_{all} , it means that there are some time for available for departure but due to different reasons (decreased network availability over time or coming floods) not all participants can manage to depart their homes. There is a fraction of the total participants who have decided to join evacuation whereas eventually failed to depart.

$$if: t_{failDep} > ETW_{start} \text{ and } t_{failDep} \leq t_{all}$$

$$ETW_{end} = t_{failRoute} - 1 \tag{A.26}$$

4) The time of failing to depart is later than t_{all}, which suggest under this situation there is sufficient time for departure and all participants can depart.

$$if: t_{failDep} > t_{all}$$

$$ETW_{end} = t_{all} \tag{A.27}$$

APPENDIX B: MODEL IMPLEMENTATION

B1. Implementation of Evacuation Supply Module

Network Availability

First, a flowchart showing the workflow in ArcGIS to build up dynamic network dataset is illustrated

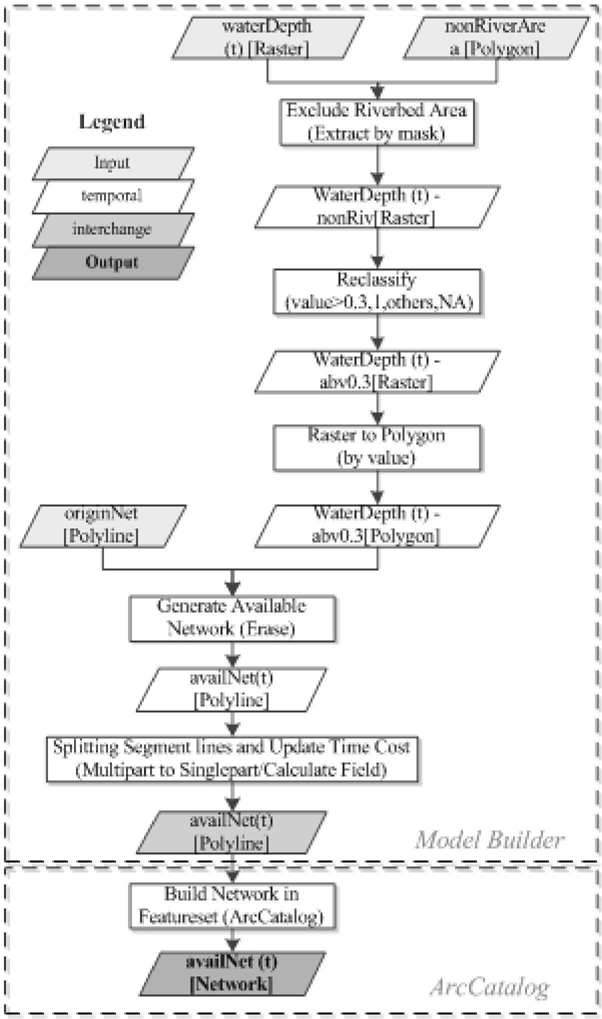


Fig. 7 Flowchart of Dynamic Network Generation

Second, a geoprocessing model for network availability simulation is constructed in ArcGIS to facilitate the workflow design in Fig. 7, as shown in Fig. 8.

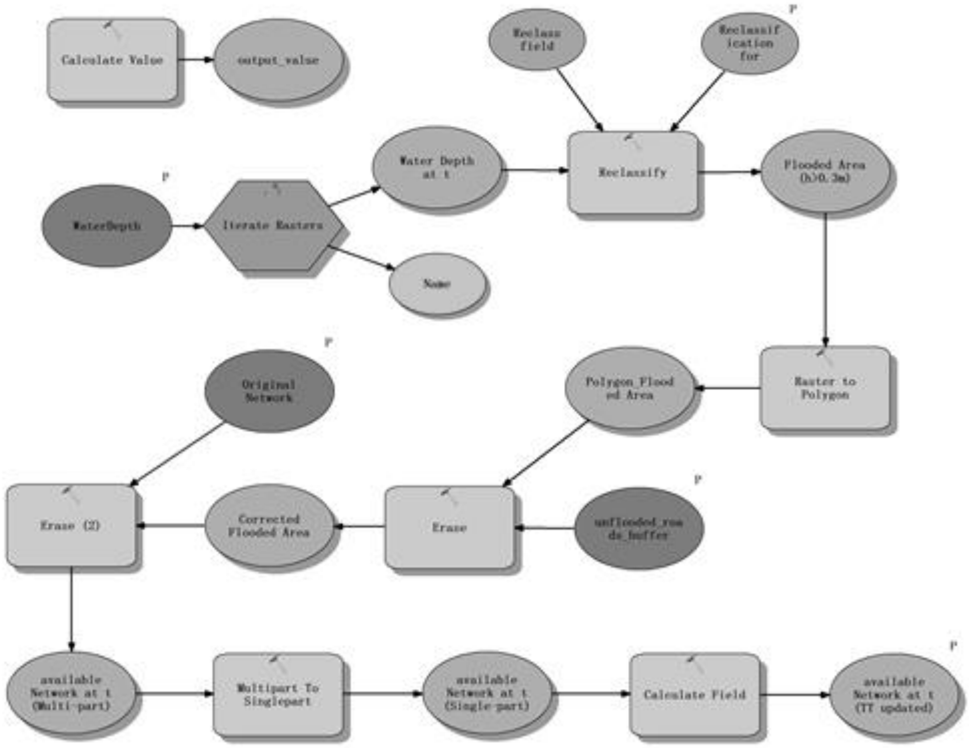


Fig. 8 Geoprocessing model of Network Availability

Exit evaluation and selection

For evacuation exits availability, the method proposed in **Mathematical description of dynamic exit availability** is applied. Below the flowchart showing the workflow in GIS and the demo of geoprocessing model are presented.

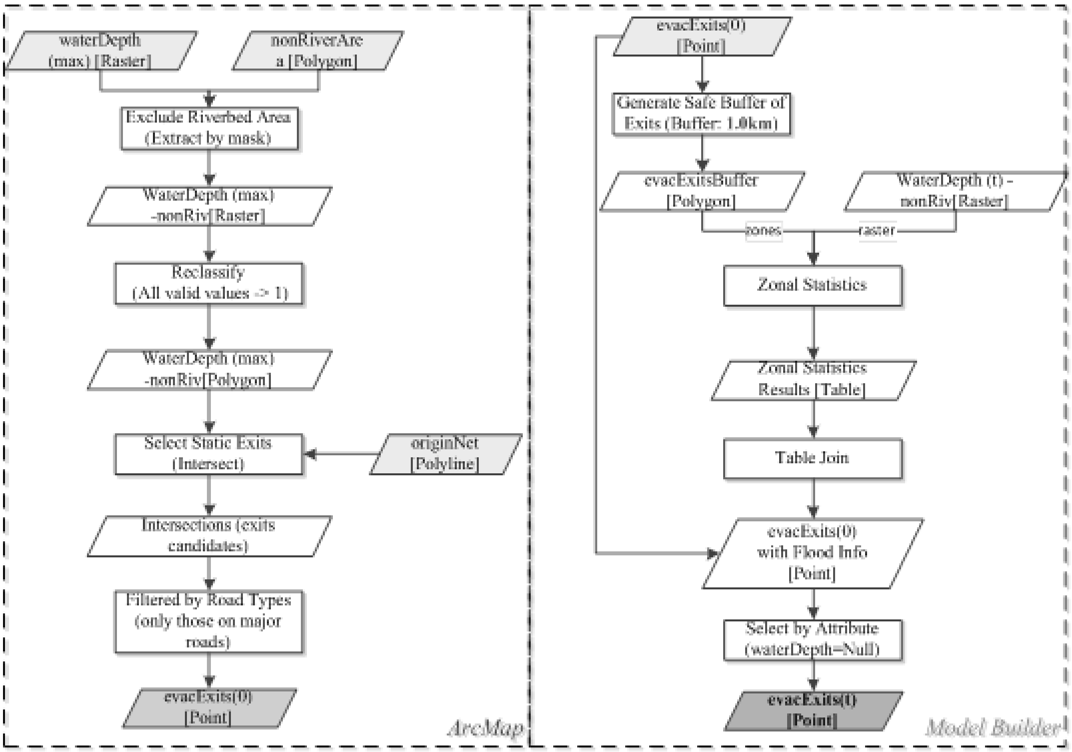


Fig. 9 Flowchart of Dynamic Exits Generation (Left: generation of all potential exits; Right: dynamic evaluation of exits' risk and selection of available exits over time)

Fig. 10 Geoprocessing model of Exits Availability

B2. Implementation of Evacuation Demand Module

Identification of PAR

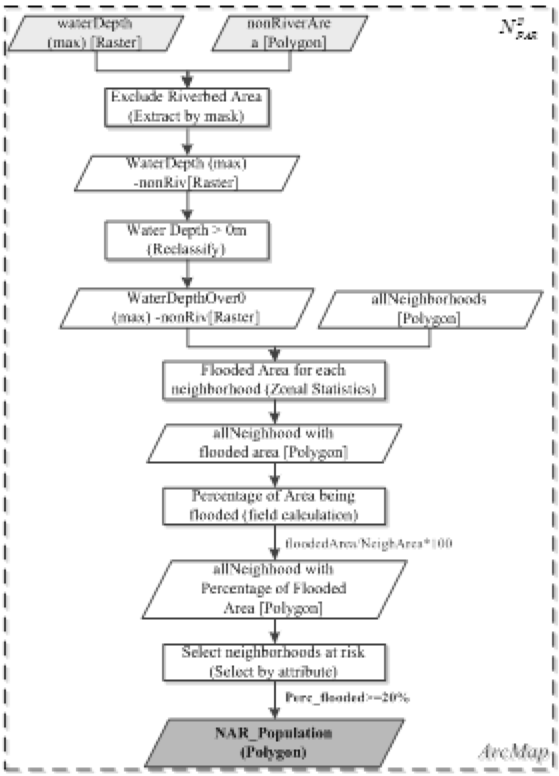


Fig. 11 Flowchart of Identification of PAR in GIS

Participation Share Estimation

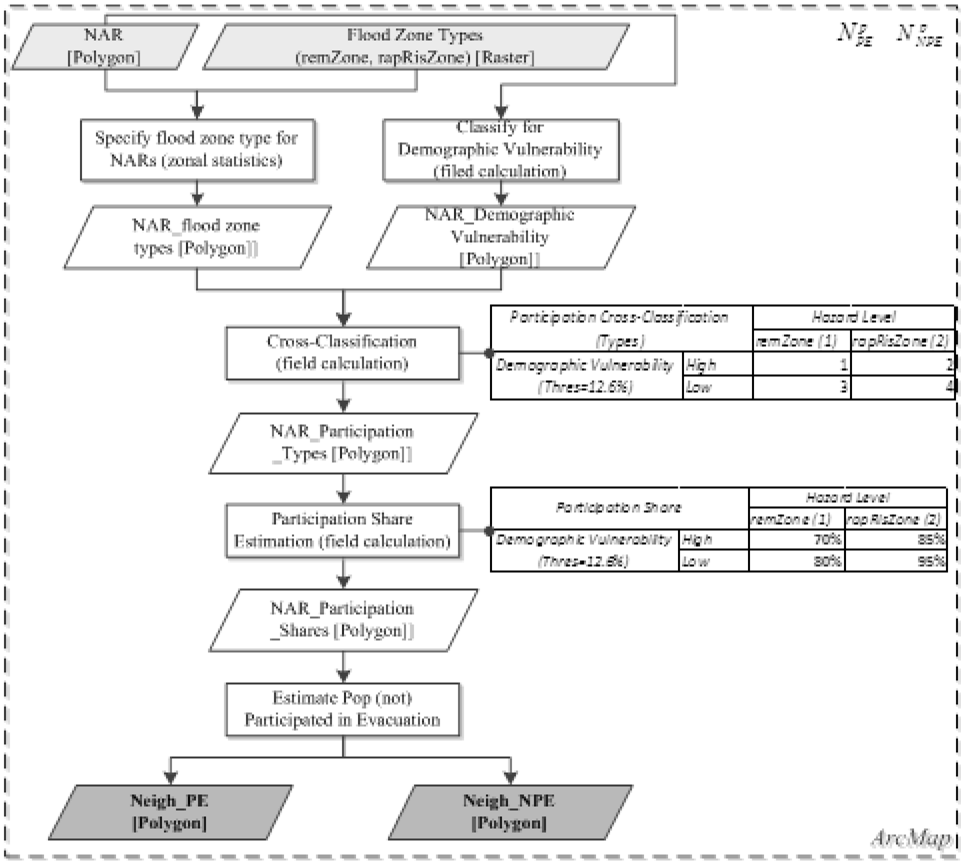


Fig. 12 Flowchart of Share of Participants Estimation in GIS

Departure Pattern Simulation

First, the starting time of departure are assigned with regard of specification from different scenario profiles, as shown in Fig. 13.

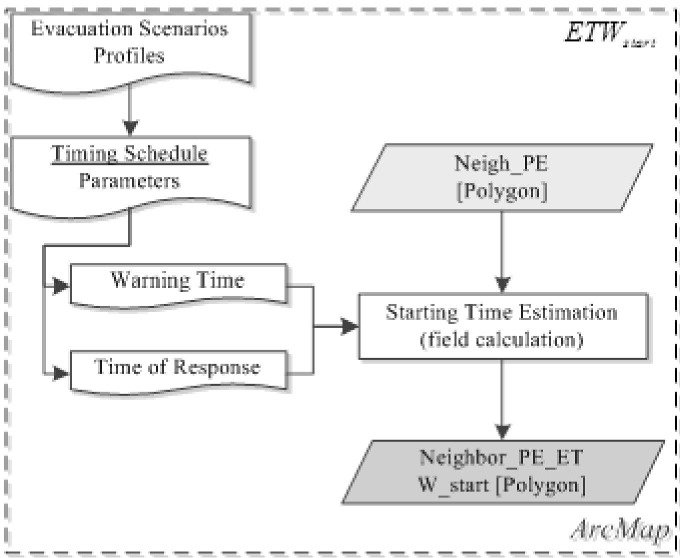


Fig. 13 Flowchart Departure Starting Time Assignment

Second, the ending time is determined by taking several temporal variables including starting time of departure (Fig. 13), full-departure time (Fig. 14) and time failing to departure.

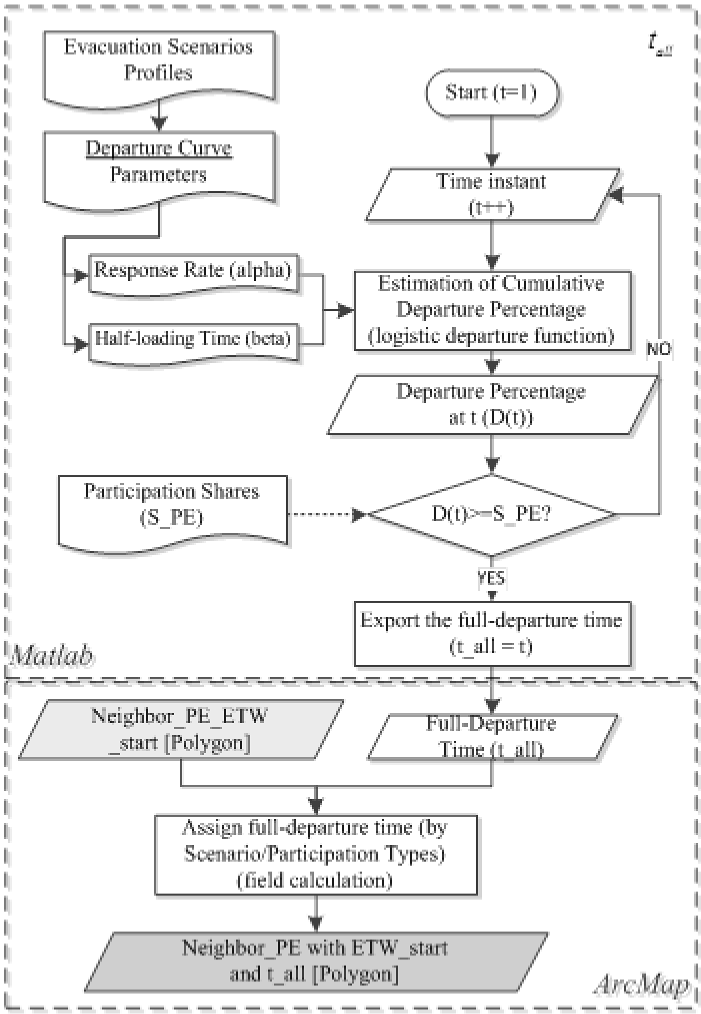


Fig. 14 Flowchart of Identification of Full-Departure Time

The workflow shown in Fig. 14 to identify the full-departure time is realized by MatLab scripting as shown in the following codes.

```
% This program is developed by Hong You for identification of Full-Departure Time
(t_all)
% Date: 2012-12-8

clear all
clc
echo off
warning off all

%Set values of parameters of departure curve
%Initializing alpha and beta arrays (for remaining zones (1) and zones with rapid
rising water (2)):
alpha = zeros(4,1);
beta = zeros(4,1);
%Assign values for both flood zone types
alpha(1,1)=input('set ALPHA value of departure curve for remZone: ');
alpha(2,1)=input('set ALPHA value of departure curve for rapRisZone: ');
alpha(3,1)=alpha(1,1);
alpha(4,1)=alpha(2,1);

beta(1,1)=input('set BETA value of departure curve for remZone: ');
beta(2,1)=input('set BETA value of departure curve for rapRisZone: ');
```

```
beta(3,1)=beta(1,1);
beta(4,1)=beta(2,1);

%Set the starting time of Departure Time Window (ETW) for both flood zone types
ETW_start =zeros(4,1);
ETW_start(1,1)=input('set ETW starting time for remZone: ');
ETW_start(2,1)=input('set ETW starting time for rapRisZone: ');
ETW_start(3,1)=ETW_start(1,1);
ETW_start(4,1)=ETW_start(2,1);

%Set the share of participation in evacuation as boundary condition for
%full-departure time identification (t_all)
SPE=zeros(4,1);
%four types of participation zone types
%1=high demographic vulnerability/remZone;
%2=high demographic vulnerability/rapRisZone;
%3=low demographic vulnerability/remZone;
%4=low demographic vulnerability/rapRisZone
SPE(1,1)=input('set participation share for High Demographic Vulnerability/remZone:
');
SPE(2,1)=input('set participation share for High Demographic
Vulnerability/rapRisZone: ');
SPE(3,1)=input('set participation share for Low Demographic Vulnerability/remZone:
');
SPE(4,1)=input('set participation share for Low Demographic Vulnerability/rapRisZone:
');

%Intializing array of full-departure times for 4 types of participation
%zones
t_all = zeros(4,1);

%Find the full-departure times for 4 types of participation zones
for i=1:4
    for t=ETW_start(i,1):beta(i,1)*3
        Et=1/(1+exp(-1*alpha(i,1)*(t-ETW_start(i,1)-beta(i,1))));
        if Et>=SPE(i,1);
            t_all(i,1)=t;
            break;
        end
    end
end

% In Command Window display the full-departure times for all 4 types of
participation zones
fprintf('\nThe Results of Full-Departure Time Identification:\n\n');
fprintf('Full-departure Time for High Demographic Vulnerability/remZone:%d
h.\n',t_all(1,1));
fprintf('Full-departure Time for High Demographic Vulnerability/rapRisZone:%d
h.\n',t_all(2,1));
fprintf('Full-departure Time for Low Demographic Vulnerability/remZone:%d
h.\n',t_all(3,1));
fprintf('Full-departure Time for Low Demographic Vulnerability/rapRisZone:%d
h.\n',t_all(4,1));
```

The estimation "time failing to route" for every neighbourhood is facilitated by a geoprocessing model in ArcGIS, as shown in Fig. 15.

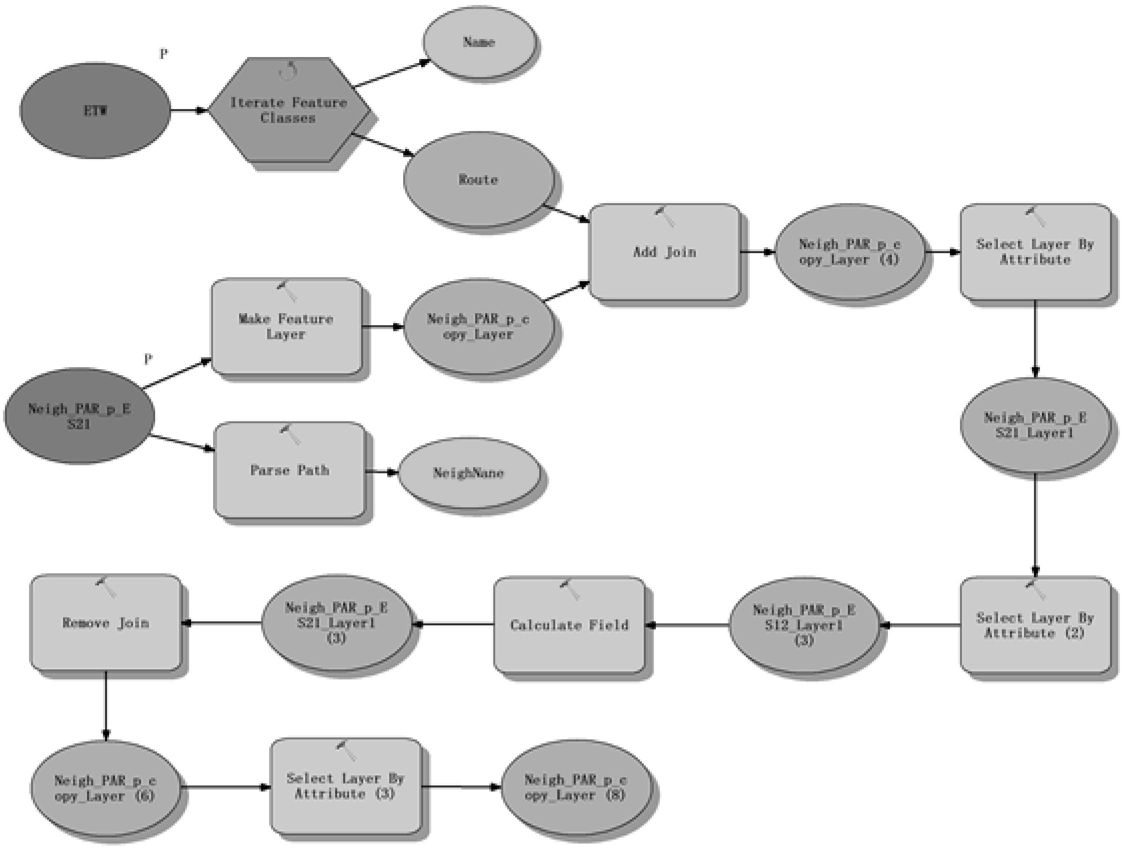


Fig. 15 Geoprocessing model of Identification of Time Failing to Route

The ending time of departure (ETW_end) is determined by comparing starting time of departure, full-departure time, time failing to route and time to flooding. The whole process to determine ending time of departure is explained by the following Fig. 16.

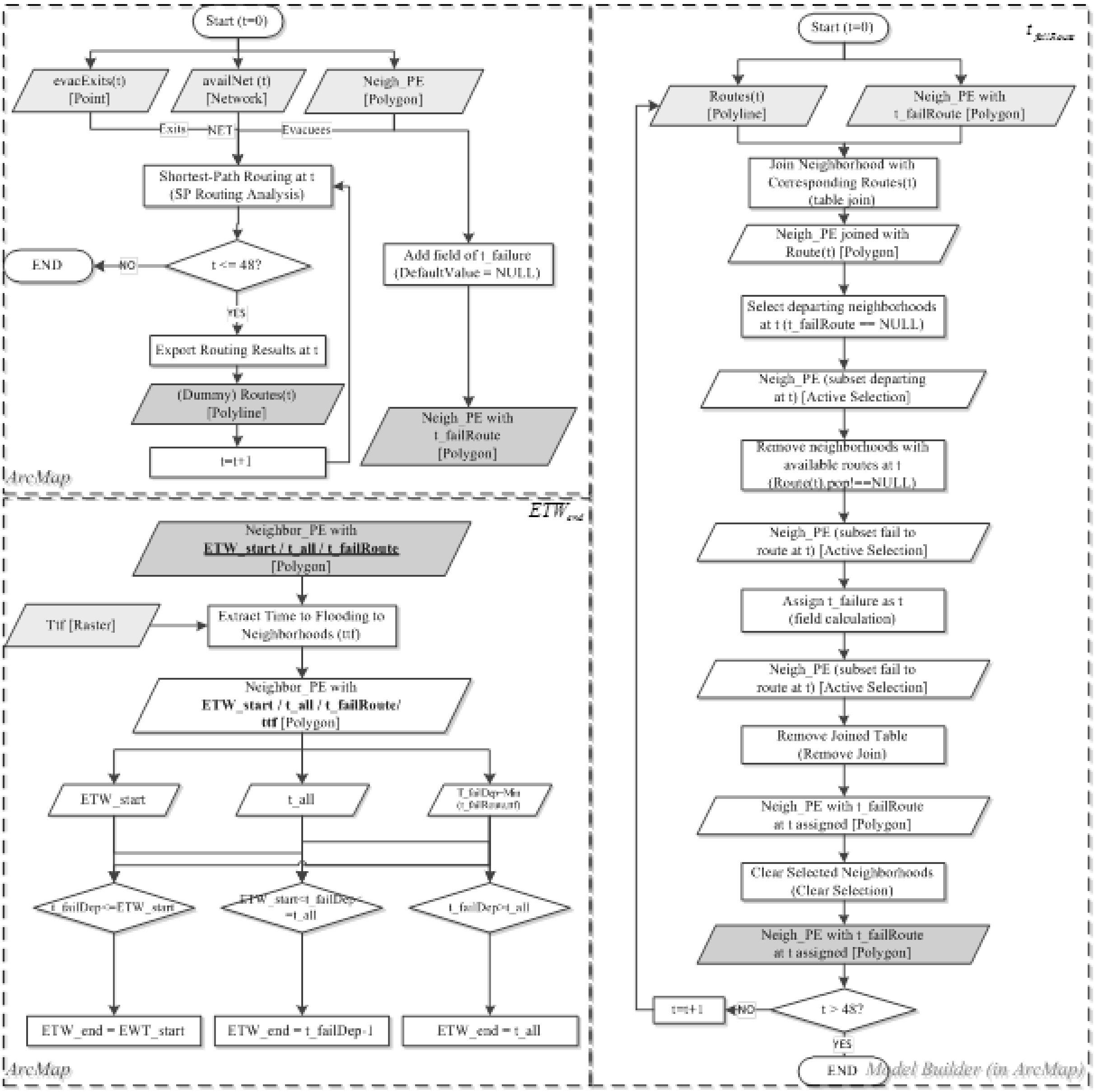


Fig. 16 Flowchart of Identification of Ending Time of Departure

The number of departing vehicles over time is estimated by applying specified departure curves over the estimated participants, as shown in Fig. 17.

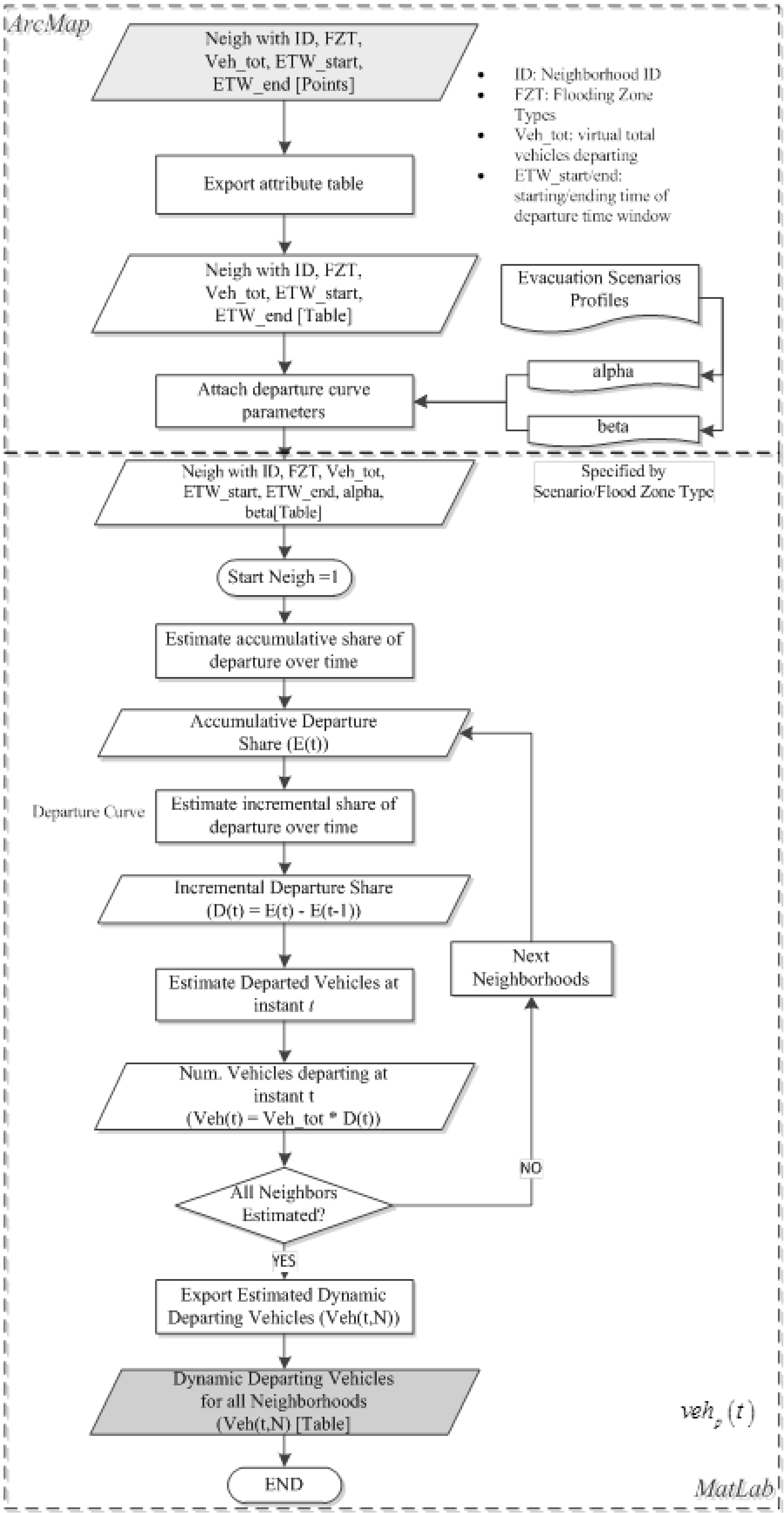


Fig. 17 Flowchart of Estimation of Departing Vehicles Over Time

The workflow in Fig. 17 is realized by a MatLab scripting programme as shown below.

```
%This program is developed by Hong You for the purpose of estimation of
%departed vehicles over time using specified departure curve (logistic
%form)
%Date: 2012-12-23

clear all
clc
echo off
warning off all

fileName = input('type in the file name: ','s');
scenarioIndex = input('type in the index of the evacuation scenario: ','s');

%import the rawdata which has been processed and exported from ArcGIS about
%Timing schedule of departure
%The departure timing schedule data includes neighbourhood ID, starting and
%ending time points of departure windows, total number of vehicles
%participated in evacuation and flooding zone types (FZT) which would be
%used for specification of departure curve parameters (alpha and beta)
[rawdata VAR_case]=xlsread(fileName);   %the rawdata should be specified for each
evacuation scenario

n = size(rawdata,1);    %get the number of neighbourhoods (num. of rows)
%Retrieve the extreme value from starting/ending time of departure time
%window as the boundary of analytical time span
tmin = min(rawdata(:,4));   %lower bound of time span: mininum starting time
tmax = max(rawdata(:,5));   %upper bound of time span: maximum ending time +1

%extract data for estimation (total vehicles departed, timing arrangements,
%and parameters of departure curve (alpha, beta)
ID = rawdata(:,1);
Veh_tot = rawdata(:,3);
ETW_start = rawdata(:,4);
ETW_end = rawdata(:,5);
alpha = rawdata(:,6);
beta = rawdata(:,7);

%Initialize the target variables to be estimated: the cumulative share of
%departure overtime, incremental share of departure and departed vehicles
%at each time instant
Et=zeros(n,tmax-tmin+1);    %the cumulative share of departure over time span
Dt=zeros(n,tmax-tmin+1);    %incremental share of departure over time span
Veh=zeros(n,tmax-tmin+1);   %departed vehicles over time span

%build up the header (field names) of departure data matrix
NID={'Neigh_Code'}
for t=tmin:tmax
    Header{t-tmin+1}=strcat('Veh_',num2str(t));
end

%Calculate the cumulative share of departure over time for all
%neighbourhoods
for i = 1:n
    if ETW_start(i,1) == ETW_end(i,1);  %for neighbourhoods not possible to find any
route out over time
        Et(i,:)=0;
        Dt(i,:)=0;
        Veh(i,:)=0;
    else
        Et(i,ETW_start(i,1)-tmin+1) = 1/(1+exp(-1*alpha(i,1)*(0-beta(i,1))));
        Dt(i,ETW_start(i,1)-tmin+1) = Et(i,ETW_start(i,1)-tmin+1);
        Veh(i,ETW_start(i,1)-tmin+1) = Veh_tot(i,1)* Dt(i,ETW_start(i,1)-tmin+1);

        for t = ETW_start(i,1)+1:ETW_end(i,1)
```

```
            Et(i,t-tmin+1) = 1/(1+exp(-1*alpha(i,1)*(t-ETW_start(i,1)-
beta(i,1))));    %estimate cumulative share of departre over time using logistic
function
            Dt(i,t-tmin+1) = Et(i,t-tmin+1) - Et(i,t-tmin);  %estimate incremental
share of departure
            Veh(i,t-tmin+1) = Veh_tot(i,1)*Dt(i,t-tmin+1); %estimate departed
vehicles within time window
        end
    end
end

%export the estimation results (departed vehicles) with neighbourhood ID to
%external XLS file
xlswrite(strcat('EST_Veh_',scenarioIndex),NID,'sheet1','A1');
xlswrite(strcat('EST_Veh_',scenarioIndex),ID,'sheet1','A2');
xlswrite(strcat('EST_Veh_',scenarioIndex),Header,'sheet1','B1');
xlswrite(strcat('EST_Veh_',scenarioIndex),Veh,'sheet1','B2');

fprintf('Estimation Complete!');
```

After the departure pattern (departing vehicles over time) is estimated, the final step of Evacuation Demand module is to estimate to population not successfully departing, as shown in Fig. 18.

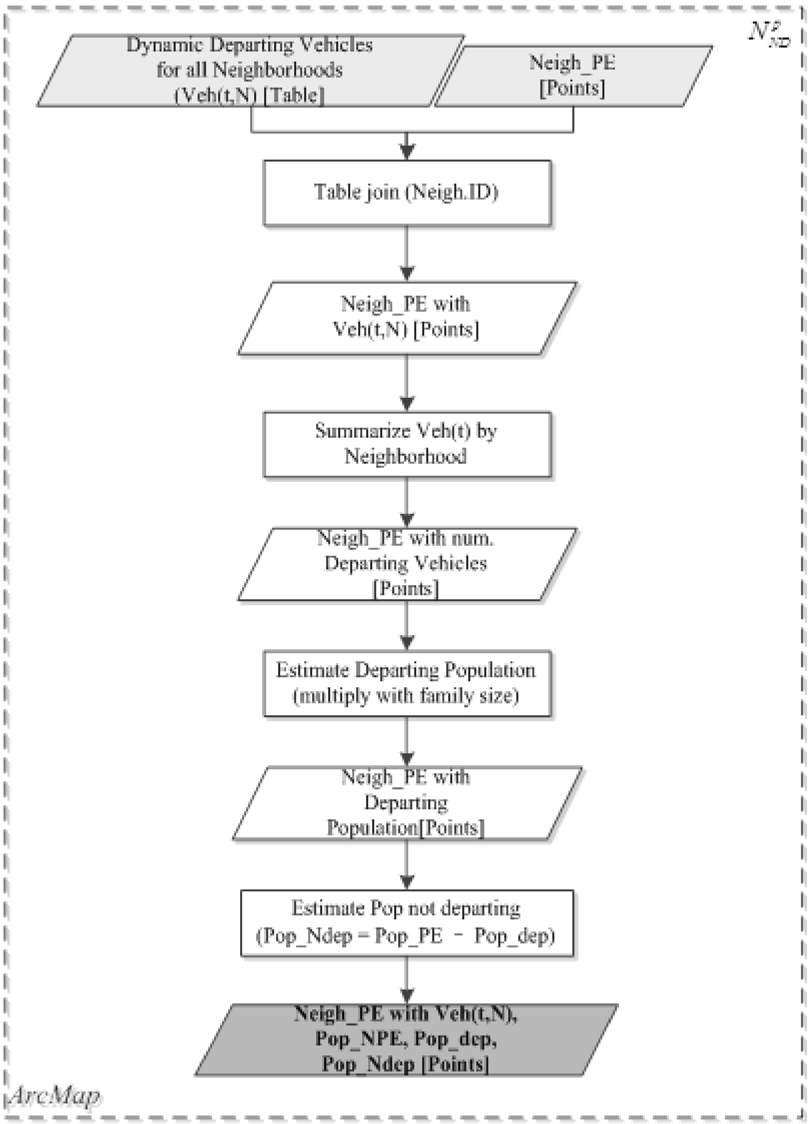


Fig. 18 Flowchart of Estimation of Population Not Departing

B3. Implementation of Evacuation Routing Module

The workflow of evacuation routing in ArcGIS is presented by Fig. 19.

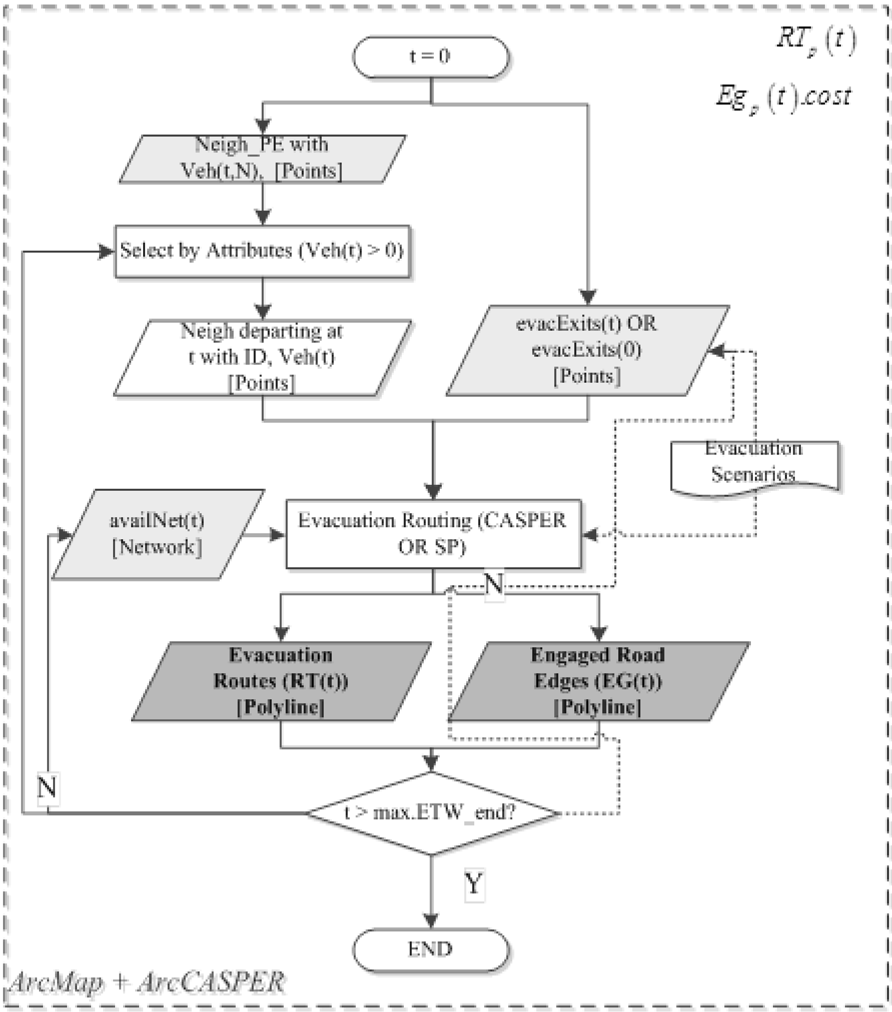


Fig. 19 Flowchart of Evacuation Routing

The workflow in Fig. 19 is carried out by ArcCASPER with its interface shown in Fig. 20.

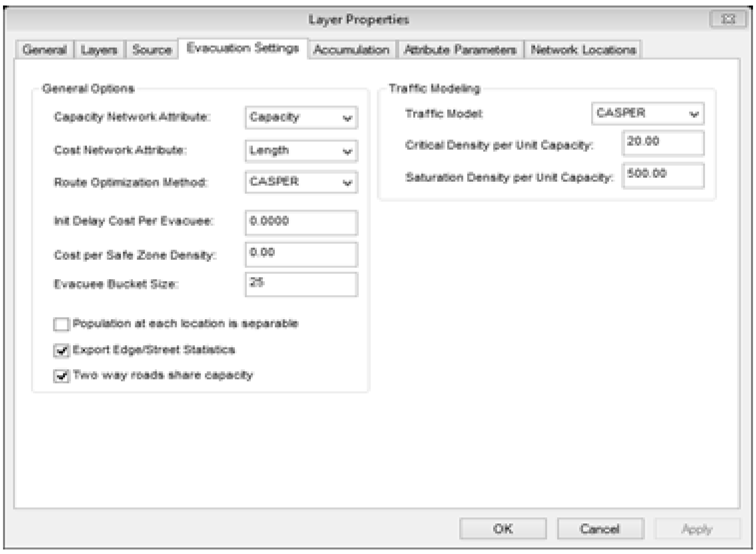


Fig. 20 Graphic User Interface of ArcCASPER in ArcGIS

B4. Implementation of Exposure Estimation Module

Estimation population exposed at home (Home-based Exposure)

The population exposed in flood at home are estimated following the workflow shown in Fig. 21.

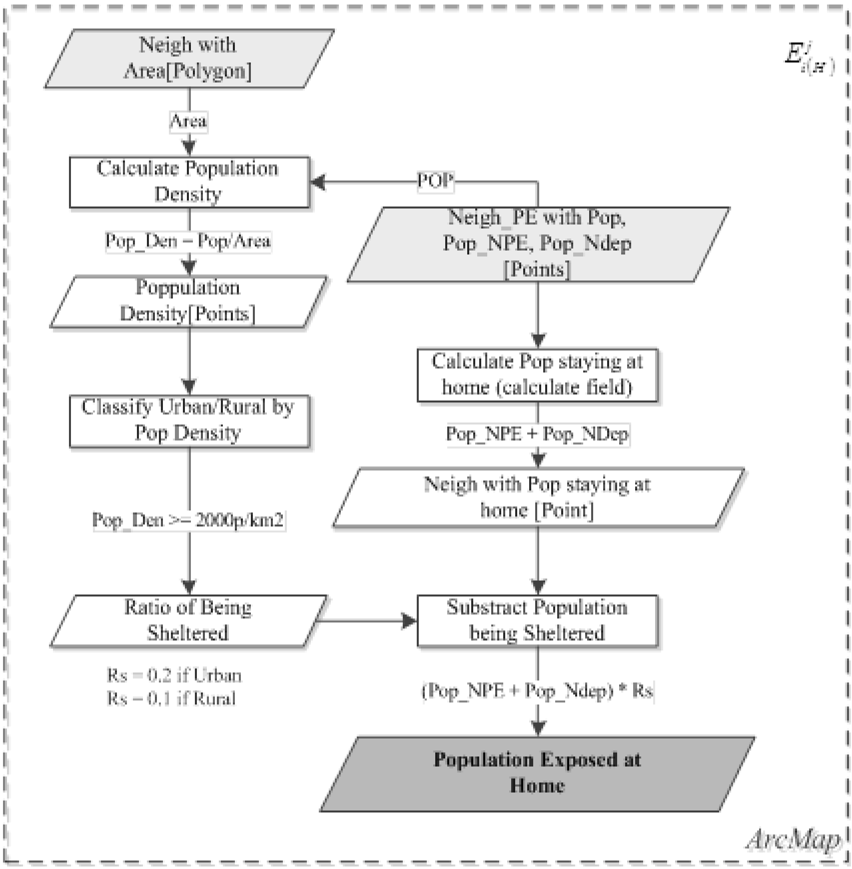


Fig. 21 Flowchart of Estimation of Exposed Population (home-based exposure)

Simulation population exposed on evacuation routes (En-route Exposure)

As discussed in the sub-section "Mathematical Description" and in Appendix A "**Mathematical description of EMS data structure and en-route exposure identification**", the workflow to build EMS data structure from evacuation routing outputs are illustrated in Fig. 22.

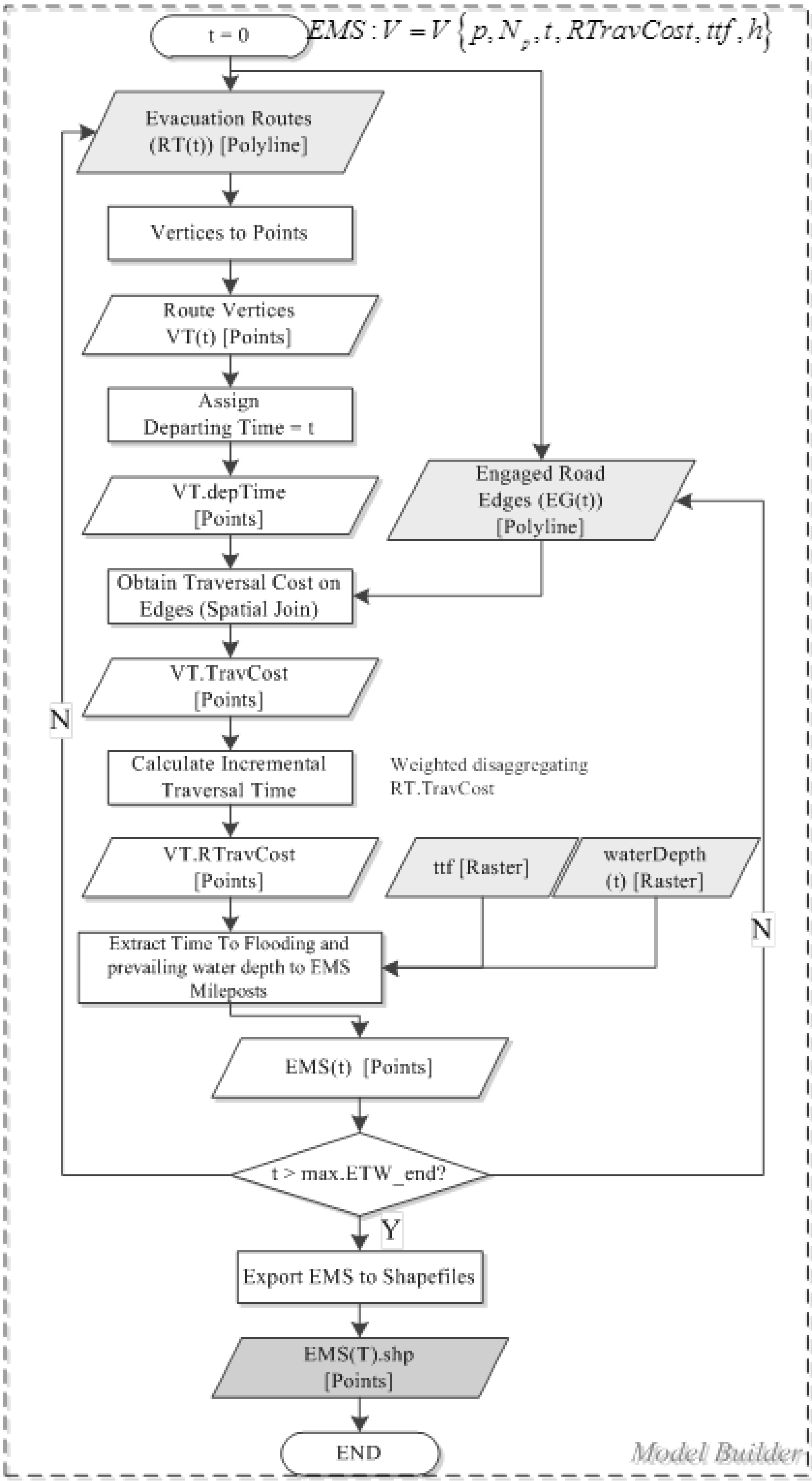


Fig. 22 Flowchart of Building EMS in ArcGIS

The workflow shown in Fig. 22 is realized in ArcGIS by a geoprocessing model demonstrated in Fig. 23.

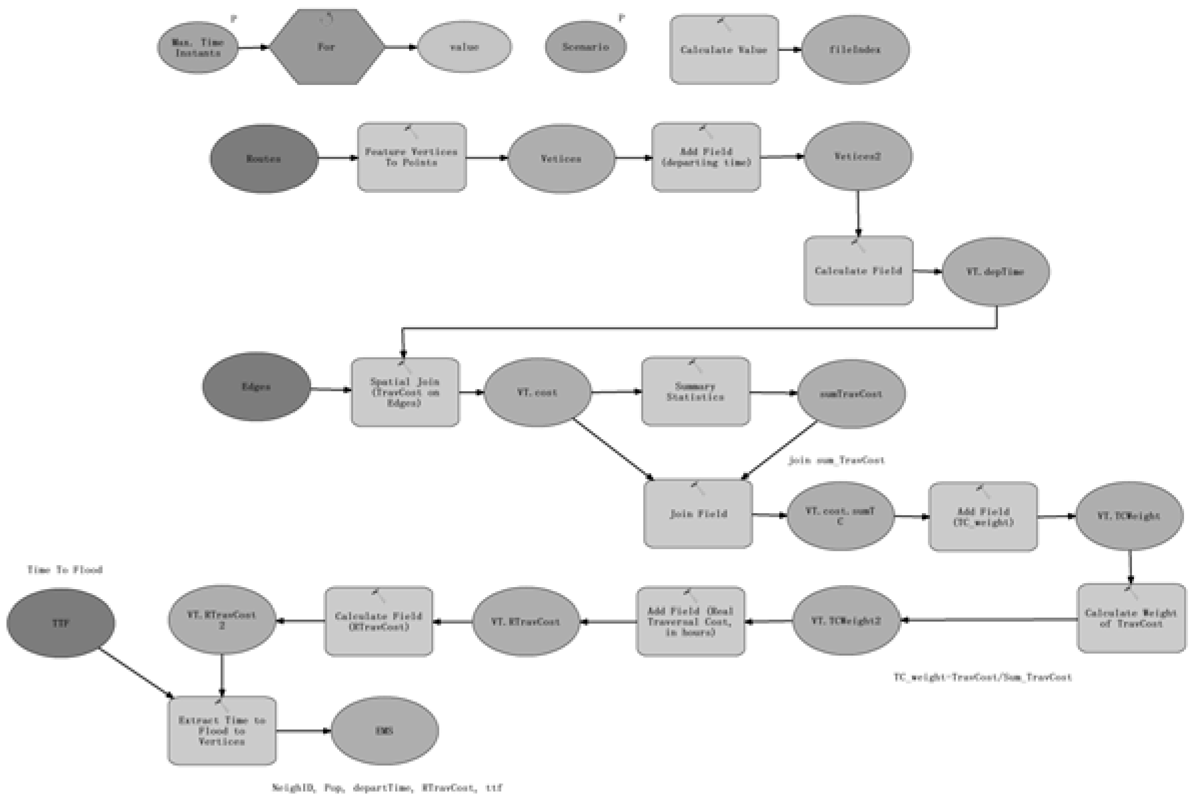


Fig. 23 Geoprocessing Model of EMS data building in ArcGIS

The EMS datasets (Shapefiles) generated by the model in Fig. 23 are imported in a MatLab scripting (as shown in Fig. 24) programme the workflow of which is illustrated in Fig. 25. This MatLab model would finalize the building of EMS data and identify the location and time of en-route exposure if there is any in case. The identification algorithm of this model is explained in Appendix A: **Mathematical description of EMS data structure and en-route exposure identification**.

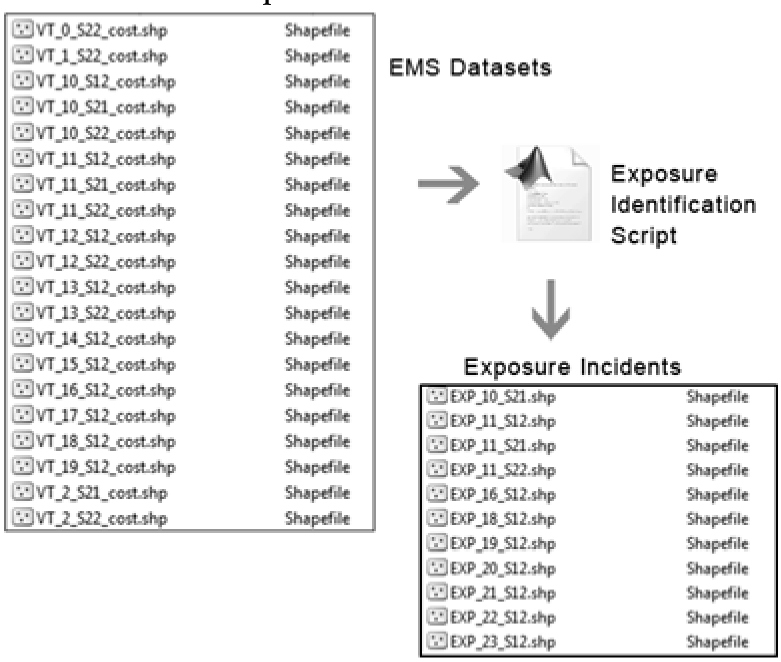


Fig. 24 Data Exchange and Workflow between ArcGIS and MatLab Workspace

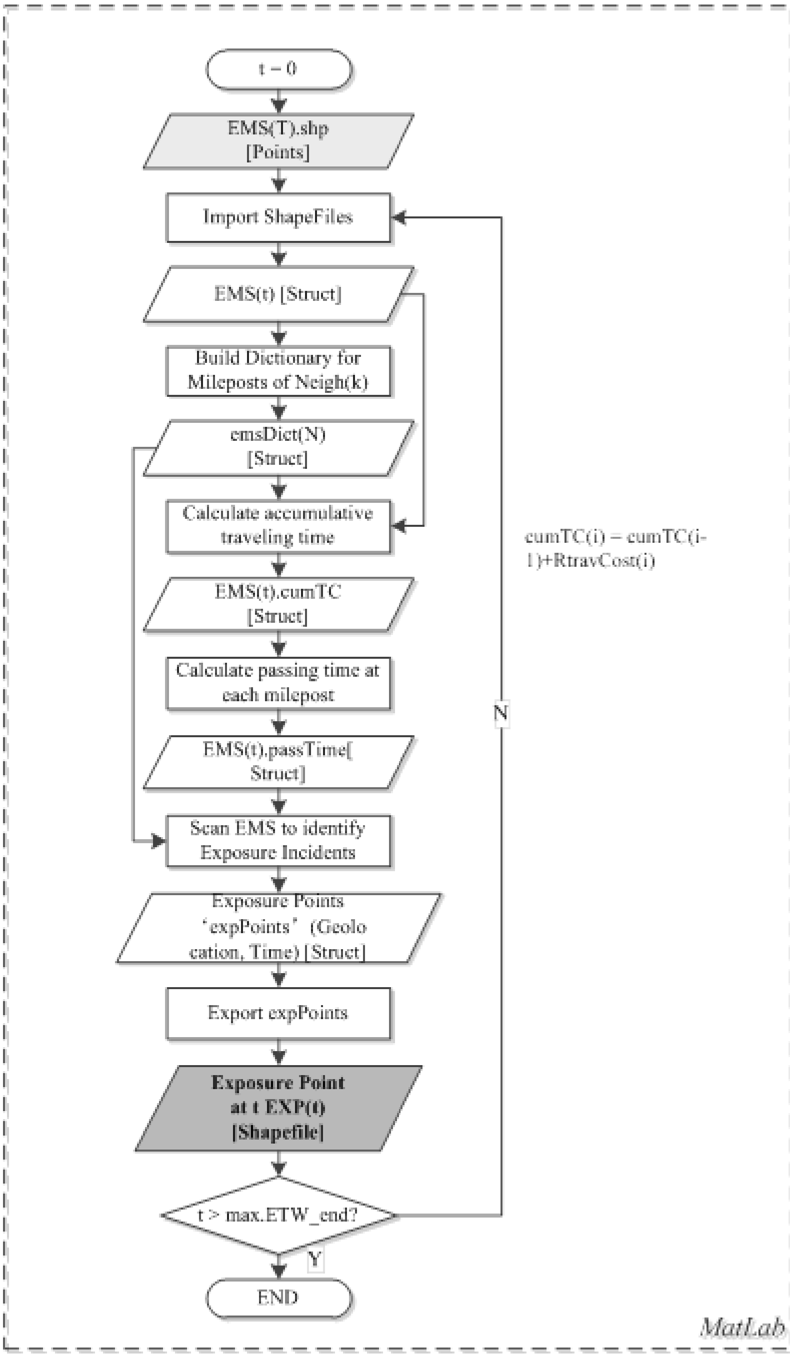


Fig. 25 Flowchart of EMS Manipulation and Exposure Identification

The workflow in Fig. 25 is realized by the scripting codes blow (MatLab script: EMS building and identification of en-route exposure incidents).

```
% This program is developed by Hong You for building up Evacuation Milepost
% Series (EMS)data structure from exported ESRI Shapefiles and
% identification of dynamic En-Route Exposure location
% Date: 2013.1.5

clear all
clc
echo off
warning off all

%% Set the data import parameters
```

```
cd('E:\Data_MSC\EMS');  %set working space
scenarioIndex = input('Please enter the index of Scneario: ','s');  % set index of
scenario
startFileIndex = input('Please enter the starting index of EMS Shapefiles: ');
endFileIndex = input('Please enter the ending index of EMS Shapefiles: ');

%% Building EMS data structure and identify En-Route Exposure Incidents
for i = startFileIndex:endFileIndex
    clear N S emsDict expPoints j k numExpPoints numNeighbor p shpFileName
    %% Import EMS Shapefiles one time for one time instant
    shpFileName = ['VT_', num2str(i), '_', scenarioIndex, '_cost.shp']; % Construct
name of Shapefile
    fprintf('\nImport EMS Shapfile: %s ...',shpFileName);
    S = shaperead(shpFileName);   %read in ShapeFile (EMS at instant i) and assign
to structure S
    N = size(S,1);  %get total number of mileposts of all neighbourhoods departing
at instant i
    fprintf('Data Import Completed!\n %d mileposts imported.\n',N);

    %% Build the emsDictionary for all mileposts of each neighbourhood
    p = 1;  % initialize the cursor of struct emsDictionary (emsDict)
    emsDict(p).ID = S(1,1).EvcName;   % retrieve ID of each neighbourhood
    emsDict(p).startPos = 1;   % initialize the starting position of the mileposts
of the 1st neighbourhood in EMS

    % scan through the EMS to specify neighbourhood ID, starting/ending
    % position of all neigborhoods in EMS
    for j = 1:N
        if S(j,1).EvcName == emsDict(p).ID;   % compare Neighbourhood ID of
mileposts with emsDictionary
        else
            % ID of milepost not equal to existing neighbourhood, move to
            % the next one
            emsDict(p).endPos = j-1;   % ending position for mileposts of current
neighbourhood
            p = p+1;    % move to the next neighbourhood
            emsDict(p).startPos = j;   % starting position for mileposts of the next
neighbourhood
            emsDict(p).ID = S(j,1).EvcName;   % retrieve Neighbourhood ID in EMS for
the next neighbourhood
        end
    end
    emsDict(p).endPos = N; % the ending position of mileposts for the last
neigborhood

    %% Calculate the cumulative traversal time between every two mileposts
    numNeighbor = size(emsDict,2); % get the number of neigborhoods
    % Calculate for each neighbourhood
    for k = 1:numNeighbor
        % generate a new field 'cumTC' for all mileposts to store values of
        % cumulative traversal time and initialize for the first milepost
        % of each neighbourhood
        S(emsDict(k).startPos,1).cumTC = S(emsDict(k).startPos,1).RTravCost;
        % go through EMS to calculate cumulative travel time for each
        % neighbourhood, startign from the 2nd milepost
        for j = emsDict(k).startPos+1:emsDict(k).endPos
            S(j,1).cumTC = S(j,1).RTravCost + S(j-1,1).cumTC;
        end
    end

    %% Calculate Passing Time at each milepost
    for j = 1:N
        % generate a new field 'passTime', passing time = departing time +
cumulative travel time
        S(j,1).passTime = S(j,1).depTime + S(j,1).cumTC;
    end
```

```
    %% Identify and Export En-Route Exposure Incidents
    % identify the EXP for each neighbourhood using indices in emsDictionary
    numExpPoints = 0;
    for k = 1:numNeighbor
        for j = emsDict(k).startPos:emsDict(k).endPos
            % if passing time is later than flooding, exposure identified
            if (S(j,1).passTime >= S(j,1).ttf)
                numExpPoints = numExpPoints + 1;
                expPoints(numExpPoints,1) = S(j,1);    % export the exposure
milepost to Geo-structre 'expPoints'
                %break     % Cursor j jumps to the end of milepost of neighbourhood
k,finish scanning
            end
        end
    end

    if numExpPoints > 0
        shapewrite(expPoints,strcat('EXP_',num2str(i),'_',scenarioIndex,'.shp'));
        fprintf('Exposure Identification Completed for time instant %d!\n %d
Exposure Incidents Identified!\n Check the results in the
file %s.\n',i,numExpPoints,strcat('EXP_',num2str(i),'_',scenarioIndex,'.shp'));
    else
        fprintf('Exposure Identification Completed for time instant %d!\n %d
Exposure Incidents Identified!\n',i,numExpPoints);
    end
end
```

B5. Implementation of Victim Estimation Module

```
% This program is developed by Hong You to estimate mortality rate for each
% neighbourhood using mortality function proposed by Jonkmann(2008). The
% mortality function is specified by different flood zone types (FZT:
% remaining zone and zones with rapid rising water). The water depth level
% is aggregated at neighbourhood level with MEAN statistics.
% Date: 2013-1-14

clear all
clc
echo off
warning off all

%% Import EXCEL spreadsheet data of water depth and flooding zone type
cd = 'E:\Data_MSC\Victim_Estimation';   % set the workingspace direction
[rawdata varCase] = xlsread('neigh_hmax_stats.xls');    % import xls data
N = size(rawdata,1);    % the number of neighbourhoods

%% Estimate Mortality Function
mort = zeros(N,1);
for i = 1:N
    if rawdata(i,4) == 1    % mortality for remaining zones
        mort(i,1) = cdf('normal', log(rawdata(i,3)), 7.6, 2.75);
    elseif rawdata(i,4) == 2    %mortality for zones with rapid rising water
        mort(i,1) = cdf('normal', log(rawdata(i,3)), 1.46, 0.28);
    end
end

%% Export mortality rate estiamted
varCase{5} = 'mortality';
xlswrite('mortality.xls',varCase,'sheet1','A1');
xlswrite('mortality.xls',rawdata,'sheet1','A2');
xlswrite('mortality.xls',mort,'sheet1','E2');
fprintf('Mortality Estimation Completed! Check the file: %s.\n','mortality.xls');
```

APPENDIX C: DATA PROCESSING AND ORGANIZATION

C1. Settings of Flood Scenarios

The flooding scenario "A1b" is characterized by 3 aspects: Topography, Inlet location and initiation types. In the selected scenario for this study, topography is specified as type A: current situation, in which all remnants of existing dike elements and modern linear landscapes are kept as they are, shown as Fig. 26.

Fig. 26 Topography A: Current Situation[57]

There are overall 5 inlets locations specified, as shown in figure below. They are Weurt, Deest and Druten along river Waal, Overasselt and Batenburg along river Maas. Choice of inlets locations is mainly based on three principles:

- Locations are scattered along rivers from quite some distance so as to get distinctive variance between scenarios
- Locations are not too far downstream otherwise inlet position comes to be in low elevation that maximum volume of water inside the dike-ring area is not sufficient for the water of the river to influence.
- They are positioned in a way that no buildings directly locate behind the inlet.

Weurt is selected as the location analysed in this study because in 1805, a recorded dike breach really occurred here (Hesselink, et al., 2003), as shown in the historical map Fig. 28.

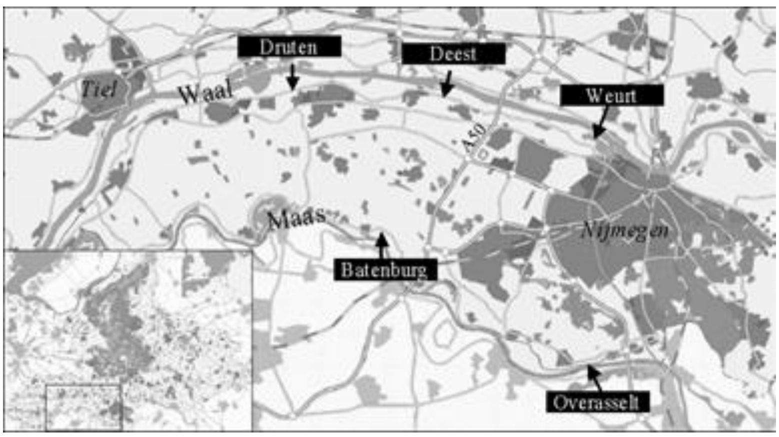


Fig. 27 Five Inlet Locations along River Waal and River Maas[58]

[57] Source: Alkema & Middelkoop, 2005

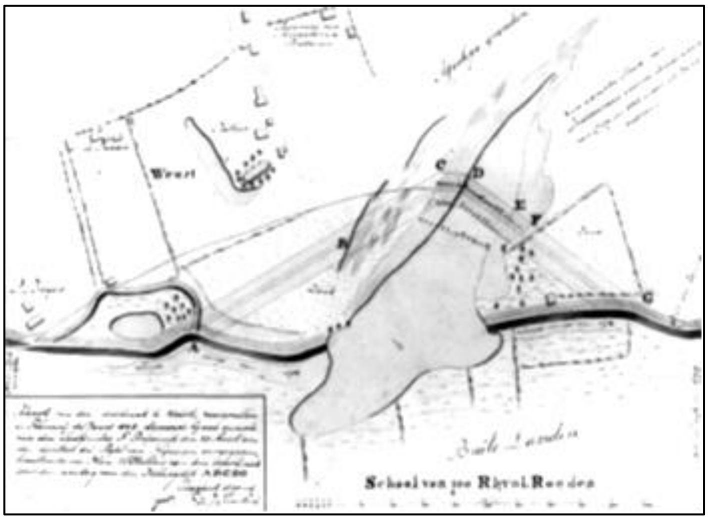


Fig. 28 Historical Map Showing Scour hole formed after the 1805 dike breach[59]

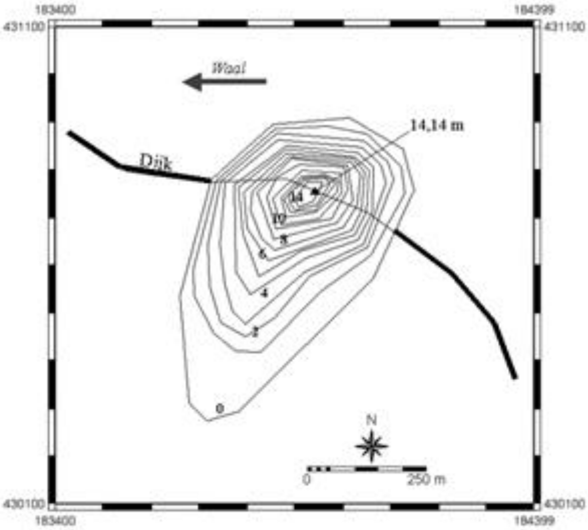


Fig. 29 Width and Depth at the Breach Weurt[60]

Finally, the breach in the Waaldijk (dikes along river Waal) at Weurt is a reconstruction of the historical breach incident in 1805. In the morning of February 13, an accumulation of ice floes in river Waal deterred the flow of water and caused a rapid rising of river level, then at 5:00 AM, a major river dike broke and flushed away 190m-wide section of the dike (Hesselink, et al., 2003). The breach profile is constructed based on Hesselink et al.'s thesis data, shown in Fig. 29. It is assumed that the formation of the breach lasts for 3 hours after which the shape of breach no longer changes (Alkema & Middelkoop, 2005).

C2. Organization of flood characteristics datasets in ArcGIS

Different from normal raster dataset, Raster Catalog can contain a pool of interrelated flooding datasets in a uniform data scheme. As shown in Fig. 30, each row in a Raster Catalog represents flood characteristics

[58] Source: D. Alkema, 2003.
[59] On the map, a plan for repair of the dike breach is plotted over the dike breach scour hole. Note that south is up. Source: Hesselink, A. W., et al. (2003).
[60] Source: Alkema & Middelkoop, 2005.

at specific time. As highlighted in Fig. 30, the most important properties, time can be easily manipulated in a classical relational database fashion.

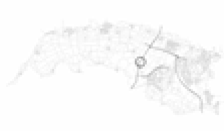
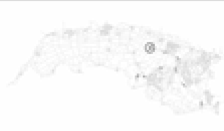
Contents | Preview | Description

OBJECTID *	Shape *	Raster	Name	Shape_Length	Shape_Area	Time_ST	Time_END
4	Polygon	<Raster>	h_raw_005	114900	752023125	2007/2/13 5:00:00	2007/2/13 6:00:00
5	Polygon	<Raster>	h_raw_006	114900	752023125	2007/2/13 6:00:00	2007/2/13 7:00:00
6	Polygon	<Raster>	h_raw_007	114900	752023125	2007/2/13 7:00:00	2007/2/13 8:00:00
7	Polygon	<Raster>	h_raw_008	114900	752023125	2007/2/13 8:00:00	2007/2/13 9:00:00
8	Polygon	<Raster>	h_raw_009	114900	752023125	2007/2/13 9:00:00	2007/2/13 10:00:00
9	Polygon	<Raster>	h_raw_010	114900	752023125	2007/2/13 10:00:00	2007/2/13 11:00:00
10	Polygon	<Raster>	h_raw_011	114900	752023125	2007/2/13 11:00:00	2007/2/13 12:00:00
11	Polygon	<Raster>	h_raw_012	114900	752023125	2007/2/13 12:00:00	2007/2/13 13:00:00
12	Polygon	<Raster>	h_raw_013	114900	752023125	2007/2/13 13:00:00	2007/2/13 14:00:00
13	Polygon	<Raster>	h_raw_014	114900	752023125	2007/2/13 14:00:00	2007/2/13 15:00:00
14	Polygon	<Raster>	h_raw_015	114900	752023125	2007/2/13 15:00:00	2007/2/13 16:00:00
15	Polygon	<Raster>	h_raw_016	114900	752023125	2007/2/13 16:00:00	2007/2/13 17:00:00
16	Polygon	<Raster>	h_raw_017	114900	752023125	2007/2/13 17:00:00	2007/2/13 18:00:00
17	Polygon	<Raster>	h_raw_018	114900	752023125	2007/2/13 18:00:00	2007/2/13 19:00:00
18	Polygon	<Raster>	h_raw_019	114900	752023125	2007/2/13 19:00:00	2007/2/13 20:00:00
19	Polygon	<Raster>	h_raw_020	114900	752023125	2007/2/13 20:00:00	2007/2/13 21:00:00
20	Polygon	<Raster>	h_raw_021	114900	752023125	2007/2/13 21:00:00	2007/2/13 22:00:00
21	Polygon	<Raster>	h_raw_022	114900	752023125	2007/2/13 22:00:00	2007/2/13 23:00:00
22	Polygon	<Raster>	h_raw_023	114900	752023125	2007/2/13 23:00:00	2007/2/14
23	Polygon	<Raster>	h_raw_024	114900	752023125	2007/2/14	2007/2/14 1:00:00
24	Polygon	<Raster>	h_raw_025	114900	752023125	2007/2/14 1:00:00	2007/2/14 2:00:00

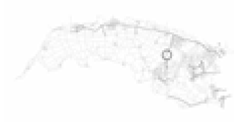
Fig. 30 Snapshot of Data structure of Raster Catalog used for organizing water depth data

C3. Specification of road attributes by road types

Tab. 3 Road Attributes Specification and Google Street View Images

Road Types	Total Length (km)	Lanes	Speed (km/h)	Sample | Street View[61]	
highway	75.9	3	80		
highway linking	23.9	3	40		
truck	18.6	2	80		
primary	81.3	2	60		
primary linking	0.7	2	30		

[61] Source: Google© Street View Screenshots.

secondary	90.5	2	40		
secondary linking	0.0	1	20		
tertiary	255.9	1	30		
tertiary linking	0.1	1	15		
unclassified	1115.8	1	30		

C4. Organization of datasets about dynamic availability of road network and exits

Road network data with different availability properties over time are stored in Geodatabase in two different forms: 1) independent time-sliced dataset which is used for efficient evacuation routing analysis, as shown in Fig. 31 and 2) aggregated temporal data that amalgamate all time-sliced datasets, as shown in Fig. 32. The second form is used for data visualization.

Name	Type
availNet_00	File Geodatabase Feature Class
availNet_01	File Geodatabase Feature Class
availNet_02	File Geodatabase Feature Class
availNet_03	File Geodatabase Feature Class
availNet_04	File Geodatabase Feature Class
availNet_05	File Geodatabase Feature Class
availNet_06	File Geodatabase Feature Class
availNet_07	File Geodatabase Feature Class
availNet_08	File Geodatabase Feature Class
availNet_09	File Geodatabase Feature Class

Fig. 31 Snapshot of Time-Sliced Network datasets

OBJECTID *	Shape *	TYPE	NAME	ONEWAY	LANES	OW	Speed	TT	Time_ST	Time_END
22481	Polyline	unclassified	Goudwerf	OK	1	0	30	.164946	2007/2/13 1:00:00	2007/2/13 1:00:00
22482	Polyline	unclassified	Augustuslaan	OK	1	0	30	.179580	2007/2/13 1:00:00	2007/2/13 1:00:00
22483	Polyline	primary_link		FT	2	1	30	.522890	2007/2/13 1:00:00	2007/2/13 1:00:00
22484	Polyline	unclassified	Mertenkamp	OK	1	0	30	.109471	2007/2/13 1:00:00	2007/2/13 1:00:00
22485	Polyline	tertiary	Wilhelminalaan	OK	1	0	30	.250429	2007/2/13 1:00:00	2007/2/13 1:00:00
22486	Polyline	unclassified	Disselboom	OK	1	0	30	.109488	2007/2/13 1:00:00	2007/2/13 1:00:00
22487	Polyline	tertiary	Hadrianussingel	OK	1	0	30	.074715	2007/2/13 1:00:00	2007/2/13 1:00:00
22488	Polyline	unclassified	Gaffel	OK	1	0	30	.019061	2007/2/13 1:00:00	2007/2/13 1:00:00
22489	Polyline	unclassified	Weurtseweg	OK	1	0	30	.481136	2007/2/13 1:00:00	2007/2/13 1:00:00
22490	Polyline	unclassified	Octopusstraat	OK	1	0	30	.061051	2007/2/13 1:00:00	2007/2/13 1:00:00
22491	Polyline	unclassified	De Ruyterstraat	OK	1	0	30	.396626	2007/2/13 1:00:00	2007/2/13 1:00:00
22492	Polyline	tertiary	Laan 1945	OK	1	0	30	.115858	2007/2/13 1:00:00	2007/2/13 1:00:00
22493	Polyline	unclassified	Wethouder Broekmanstraat	OK	1	0	30	.107265	2007/2/13 1:00:00	2007/2/13 1:00:00
22494	Polyline	secondary	Schoenaker	FT	2	1	40	.056689	2007/2/13 1:00:00	2007/2/13 1:00:00
22495	Polyline	unclassified	Roskam	OK	1	0	30	.111800	2007/2/13 1:00:00	2007/2/13 1:00:00
22496	Polyline	tertiary	Hadrianussingel	OK	1	0	30	.075163	2007/2/13 1:00:00	2007/2/13 1:00:00
22497	Polyline	secondary	Schoenaker	FT	2	1	40	.059492	2007/2/13 1:00:00	2007/2/13 1:00:00
22498	Polyline	secondary		FT	2	1	40	.035245	2007/2/13 1:00:00	2007/2/13 1:00:00
22499	Polyline	unclassified	Wethouder Broekmanstraat	OK	1	0	30	.023552	2007/2/13 1:00:00	2007/2/13 1:00:00
22500	Polyline	secondary		FT	2	1	40	.030183	2007/2/13 1:00:00	2007/2/13 1:00:00
22501	Polyline	tertiary	Hadrianussingel	FT	1	1	30	.060463	2007/2/13 1:00:00	2007/2/13 1:00:00
22502	Polyline	unclassified	Polstraat	OK	1	0	30	1.195282	2007/2/13 1:00:00	2007/2/13 1:00:00
22503	Polyline	primary	Van Heemstraweg	OK	2	0	60	.160736	2007/2/13 1:00:00	2007/2/13 1:00:00
22504	Polyline	unclassified	Kavelweg	OK	1	0	30	1.438112	2007/2/13 1:00:00	2007/2/13 1:00:00
22505	Polyline	tertiary	Jonkerstraat	OK	1	0	30	.134296	2007/2/13 1:00:00	2007/2/13 1:00:00

Fig. 32 Snapshot of Data structure of Dynamic Network Availability

OBJECTID *	Shape *	exitID	Time_ST	Time_END	availability
1	Point	1	2007/2/13	2007/2/13 3:00:00	1
2	Point	4	2007/2/13	2007/2/13 6:00:00	1
3	Point	6	2007/2/13	2007/2/13 20:00:00	1
4	Point	9	2007/2/13	2007/2/13 23:00:00	1
5	Point	11	2007/2/13	2007/2/14 3:00:00	1
6	Point	12	2007/2/13	2007/2/14 2:00:00	1
7	Point	14	2007/2/13	2007/2/13 23:00:00	1
8	Point	15	2007/2/13	2007/2/14 3:00:00	1
9	Point	21	2007/2/13	2007/2/15	1
10	Point	23	2007/2/13	2007/2/15	1
11	Point	24	2007/2/13	2007/2/15	1
12	Point	25	2007/2/13	2007/2/13 4:00:00	1
13	Point	27	2007/2/13	2007/2/15	1
14	Point	29	2007/2/13	2007/2/15	1

Fig. 33 Snapshot of Data structure of Dynamic Exit Availability

APPENDIX D: ANIMATIONS AND WEB APPLICATIONS

D1. Demonstrative Animations (Hyperlinks)

In order to better visualize the modelling process and offer more interpretable results for a wider range of audiences, animations of the major modelling outputs are generated using temporal GIS functionality of ArcGIS 10.1. Animations can be accessed freely via YouTube videos.

1) Animation of **water depth change** over time in flood (within 120 hours):
http://youtu.be/hcjXTAVJ_P8

2) Animation of **flood velocity** over time (within 120 hours):
http://youtu.be/tJOMnmhTFUA

3) Animation about **dynamic availability of road networks and evacuation exits** (within 48 hours):
http://youtu.be/g0gKaYSijZY

4) Animation about **departing vehicles over time** in Scenario S12:
http://youtu.be/ZxH51HR-3Lo

5) Animation about **departing vehicles over time** in Scenario S21:
http://youtu.be/GQbeRtfZl3Y

6) Animation about **departing vehicles over time** in Scenario S22:
http://youtu.be/hhxaPMNyFVc

7) Animation depicting **evacuation routing simulation** for Scenario S12:
http://youtu.be/UlL2tQSUKTU

8) Animation depicting **evacuation routing simulation** for Scenario S21:
Part 1: http://youtu.be/lZNbsWUfV6s

Part 2: http://youtu.be/EU1Z5TDpwP0

9) Animation depicting **evacuation routing simulation** for Scenario S22:
Part 1: http://youtu.be/FDPY63VdEMM

Part 2: http://youtu.be/tWhGUXK43EE

D2. Web Site and Web Applications (Hyperlinks)

In order to explore the possibility of placing the modelling framework proposed in this study as an efficient media/interface between modelling experts, decision makers and the public. Web applications based ESRI ArcGIS online services are developed to serve the broader purposes of models discussed in the sub-section "Rethinking about Functions of Modelling". Here are the links to the online applications.

1) Web Site (with essence of this study): **"Flood Risk at ITC"**: http://itcfloodresearch.weebly.com/
2) Web Applications: "**Estimation of Victims in Flood: Scenario Comparison**"
http://www.arcgis.com/apps/Compare/storytelling_compare/index.html?appid=fbbb84f6ed114318b83530e3f75de722

3) Web Application: "**Modelling Results Overview: Flood Hazard, Social Vulnerability and Victim Estimations**"
http://www.arcgis.com/apps/Compare/storytelling_tabbed/index.html?appid=fcf7d4721add43538b1c321a9a6e250b