Traffic Management During Flood Evacuations

Estimating Emergency Evacuation Time for Maastricht: Implications for Urban Safety Planning

CTB3000-16: Bachelor's Thesis

Emma van Wely

Delft University of Technology

Traffic Management During Flood Evacuations

Estimating Emergency Evacuation Time for Maastricht: Implications for Urban Safety Planning

by

Emma van Wely

5478642

Examiner 1:	Y. Yuan
Examiner 2:	S. Calvert
Supervisor:	S. Mahesh
Project Duration:	April, 2025 - June, 2025
Faculty:	Faculty of Civil Engineering, Delft

Cover: [7]
Style: TU Delft Report Style, with modifications by Daan Zwaneveld

TU Delft

Preface

This report marks the final step in completing my bachelor's degree in Civil Engineering at the Technical University Delft. The topic of evacuation planning caught my interest because of its mix between infrastructure, human behaviour and emergency logistics. After the 2021 floods in Limburg, I became curious about how cities like Maastricht would handle a full evacuation in practice.

The research process was challenging at times, especially in balancing realistic assumptions with theoretical modelling. However, it also taught me a lot, not just about traffic flow and planning, but also about working independently, setting priorities and translating complex problems into practical insights.

I would like to thank my examiners Y. Yuan, S. Calvert and my supervisor S. Mahesh for their guidance and constructive feedback. I also want to thank Adam Pel for helping me understand the practical aspects of emergency planning.

Emma van Wely
Delft, June 2025

Summary

This research focuses on the question: *"How long would it take to evacuate the population of Maastricht during a large scale flood, and is this feasible within the available time window, based on road capacity and assisted transport demand?"* The study approaches this from a traffic engineering perspective, using a scenario based model to estimate clearance times for all districts under both best-case and worst-case assumptions.

The analysis distinguishes between two main groups: self-evacuating residents (using private vehicles) and those requiring assisted evacuation (via trains, buses or ambulances). Input variables include car ownership per district, population size and density, road layout and capacity and the spatial distribution of critical facilities such as hospitals and prisons.

The simulation results show large differences in clearance times across the city. In the best-case scenario, with high car sharing rates and efficient resource use, most districts can evacuate within three hours. In the worst-case scenario, where assisted transport demand is high and no operational optimisations are in place, several areas exceed nine hours, and some reach up to eleven. Especially in districts Centrum and Zuidoost, clearance times are long due to a combination of low car access, vulnerable populations and limited road options.

The results were evaluated using the evacuation timeline model from Opper (2004), which splits the available time into four phases: response (6 hours), warning and preparation (3 hours), evacuation movement (En) and a safety margin (1–2 hours). This is then compared to the available evacuation time Ea, which is the time available between warning and flooding of the streets. In this study, Ea was estimated at 12 hours, leaving about 8 hours for people to evacuate. Several districts exceed this limit in both scenarios, indicating that full evacuation may not be feasible everywhere under current conditions.

Additional analysis using volume-to-capacity (v/c) ratios revealed key traffic bottlenecks, especially on the A2 southbound corridor and at bridges connecting the east and west banks of the city. These bottlenecks further reduce effective clearance time for some districts. The study also showed that demand for assisted transport is concentrated in a few high-risk zones, putting additional strain on limited resources.

These findings were used to develop practical recommendations. Key strategies include early coordination with public transport operators, pre-allocation of vehicles to vulnerable districts, the use of contra-flow or phased departure strategies to reduce peak congestion and the promotion of neighbourhood level car sharing. The study also highlights the need to test current plans through realistic drills and simulations, especially given the narrow time window and high dependency on coordination across multiple actors.

In conclusion, while a full preventive evacuation of Maastricht is theoretically possible under ideal circumstances, it is highly sensitive to delay, uncertainty and unequal resource distribution. The results shift the focus from purely technical modelling to practical feasibility and operational planning. With better coordination, clear prioritisation and targeted improvements, the city can increase its evacuation readiness, but under current assumptions, several neighbourhoods remain at risk of not evacuating in time.

Contents

1 Introduction

In December 1993, the Meuse River overflowed near Maastricht, especially in the neighbourhoods of Itteren and Borgharen. On December 20th, the river reached a record height of around 45.9 meters above NAP. As a result, about 12,000 people were evacuated and nearly 6,900 homes were affected. The flooding came quickly, leaving little time to prepare or respond [25, 10].

A more recent example occurred in 2021, after heavy rainfall in Germany, where more than 55 people had already died. On July 15th, at around 18:00, the municipality of Maastricht issued an urgent evacuation advisory to approximately 10,000 residents. Later that evening, municipal vehicles drove through neighbourhoods using loudspeakers to repeat the evacuation message. The flood was expected to reach the city between 02:00 and 03:00 in the morning, giving residents less than 24 hours to leave their homes [34].

The Meuse River flows directly through Maastricht. In recent years, climate change and increasing rainfall have made the river more likely to flood. In the past, only specific parts of the city had to evacuate, often with very short notice. But what if a much larger flood occurs in the future, affecting the entire city? How much time would be needed to evacuate everyone in time? And is it even feasible?

1.1. Problem statement

According to climate projections by the Royal Netherlands Meteorological Institute and Wageningen University, peak discharges of the Meuse River may increase by up to 20% by 2025 and 40% by 2100, significantly raising flood risk in Maastricht [38]. While smaller scale evacuations have occurred before, it remains unclear whether a full evacuation of the city is feasible, especially under time pressure, with limited infrastructure and many residents needing assistance. Without clear estimates, emergency services lack the information needed to prepare for a worst-case scenario.

1.2. Research objective and questions

The goal of this research is to give a first, structured estimate of how long it would take to evacuate all residents of Maastricht in case of a major flood. This is done from a traffic engineering perspective, focusing on road capacity, population distribution and the availability of assisted transport. The estimate is based on simplified traffic models and public data, using logical assumptions to keep the analysis realistic but doable. Rather than aiming for full simulation, this study provides insight into where the pressure points are, which areas are most vulnerable and what that means for emergency planning.

The main research question is:
"How long would it take to evacuate the population of Maastricht during a large scale flood, and is this feasible within the available time window, based on road capacity and assisted transport demand?"

To answer this question step by step, the following subquestions are used:

1. *What is the structure and capacity of the road network in and around Maastricht?*

2. *What is the distribution of the population across Maastricht, and what proportion requires assisted evacuation?*
3. *How many transport resources are available for assisted evacuation, and what is their capacity?*
4. *What are the expected evacuation times per neighbourhood for both self evacuating and assisted groups, based on transport capacity?*
5. *Where are the main traffic bottlenecks and risk zones during evacuation, and how do they impact overall evacuation performance?*
6. *Based on the analysis, what practical and location specific recommendations can be made to the municipality to reduce evacuation time and improve safety, especially in districts with high vulnerability or capacity gaps?*

1.3. Research strategy and orientation

This research used a practical and clear step-by-step approach to estimate how long it would take to evacuate Maastricht during a large flood. The subquestions were divided into three logical steps:

1. Understanding the current situation (road network, population and available transport);
2. Analysing the evacuation itself (evacuation time and bottlenecks);
3. Reflecting on possible improvements based on the results.

To carry out the analysis, several tools and data sources were used. Road and elevation data from OpenStreetMap and the Nationaal Wegenbestand (NWB) were processed in QGIS to map road types, locations and flood risk. Demographic information and car ownership data were taken from CBS StatLine and the neighbourhood level datasets from the Wijk- en Buurtkaart. These were used to estimate how many people could evacuate on their own and how many would need help. Traffic flow and transport capacity were calculated in Excel, using simplified models. For assisted evacuation, public information about buses, trains, ambulances and special locations like hospitals and prisons was used to estimate transport capacity under different scenarios.

The analysis followed two main frameworks: the three-layer model, which looks at who moves, over what infrastructure and how traffic behaves, and the evacuation timeline by Opper (2004), which breaks the process into time phases like warning, response and movement. [35]

The research focused on reliable public data and clear assumptions. Only the parts of Maastricht that are at risk of flooding were included, see Appendix A for an overview of the neighbourhoods and districts of Maastricht. The methods and choices made during this research were regularly discussed with external expert Dr. Adam Pel. He is an assistant professor in transport modelling at TU Delft and also works as a traffic analyst at Fileradar. With a PhD in evacuation modelling and experience in traffic simulation, network resilience and data driven analysis [37], his feedback helped to keep the research realistic, relevant to the context, and in line with current practices in traffic engineering.

1.4. Analytical framework

The three-layer model splits the evacuation problem into three components:

1. *Travel demand* – who needs to move and from where;
2. *Transport infrastructure and services* – what transport systems are available;
3. *Traffic flow* – how movement takes place during evacuation.

This structure is commonly used in evacuation planning and was selected based on expert advice from Dr. Adam Pel and supported by literature on traffic based evacuation modelling [36]. In this research, the model helps answer subquestions 1 to 5: road structure (1), population spread (2), transport availability (3), estimated evacuation times (4) and traffic flow risks (5).

In addition, the evacuation timeline model by Opper (2004) is used to divide the process into five time phases: prediction, response, warning, movement and safety buffer [35]. This is mainly applied in subquestion 4 to check whether full evacuation can be completed within the available warning time.

Together, these two frameworks allow both a spatial and temporal analysis of the evacuation process. A more detailed explanation of how they are applied is provided in Chapter 3.

1.5. Scientific and societal relevance

This research is relevant for both scientific and practical reasons. From a scientific perspective, it contributes to the field of traffic engineering and evacuation modelling by applying a structured framework to a real urban area with limited evacuation time. It shows how simplified models can be used to estimate evacuation feasibility in a data driven but accessible way.

From a societal perspective, the study supports flood preparedness in Maastricht, where recent events have shown the urgency of large scale evacuation planning. The results are especially relevant for local authorities, emergency services and public transport providers, who need insight into where the biggest risks are and how much time is realistically needed to evacuate the city safely.

1.6. Stakeholder context

Evacuating a city is not only a technical challenge, but also a coordination problem. Although stakeholders are not modelled in detail, their roles are crucial for understanding where capacity or timing issues may arise, especially in relation to assisted transport, road use and communication. In the context of this study, their influence is particularly relevant to be able to give fitting recommendations per stakeholder. In Figure 1.1 an overview of the power and interest per stakeholder is given.

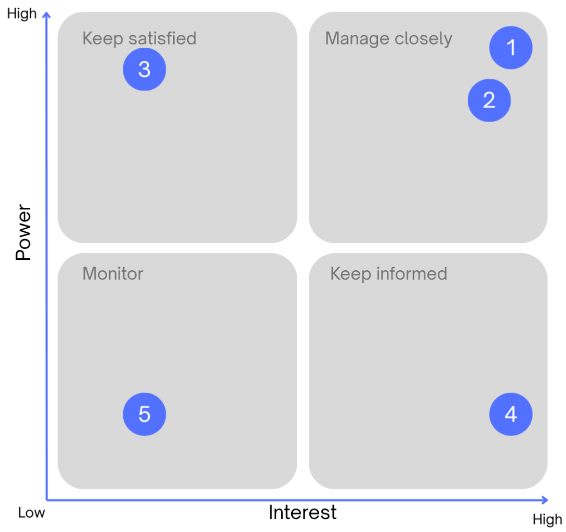

Figure 1.1: Power/interest matrix stakeholders

The most relevant actors are:

1. *Municipality of Maastricht* [15]
   Issues evacuation orders, manages local roads and communicates with the public. Their response speed directly impacts the response time (R) in the Opper timeline. If decisions are delayed or infrastructure is not prepared (like no contra-flow), districts may miss the window for movement.
2. *Veiligheidsregio Zuid-Limburg (VRZL)* [42]
   Coordinates regional emergency services (police, ambulance, fire brigade). Plays a central role in mobilising resources during the first hours of the timeline. Delays in coordination or lack of integration with municipal plans can reduce the effectiveness of both warning (W) and evacuation (En) phases.
3. *Public Transport Operators (Arriva, NS)*

Provide buses and trains used in assisted evacuation. Their availability and response time determine whether assisted evacuees can be moved within the narrow time window. Without prearranged agreements, capacity may fall short or arrive too late to meet demand.

4. *Healthcare and Care Institutions*
   Responsible for evacuating patients or residents with mobility or medical needs. Their ability to prepare and link with ambulance services affects assisted evacuation pressure in critical districts like Zuidoost. Unprepared facilities can cause severe local delays.
5. *Residents*
   Their behaviour shapes the effectiveness of self-evacuation. If large numbers of residents leave too late or do not cooperate, congestion increases and the risk of exceeding the available movement time grows.

1.7. Structure of the report

This report is structured as follows:

- Chapter 1 - Introduction
  This chapter introduces the research topic, explains the relevance of flood evacuation planning in Maastricht and presents the research question, subquestions and analytical framework.
- Chapter 2 - Theoretical Framework
  This chapter provides the background information on the road network in Maastricht, the population distribution, car ownership and assisted evacuation needs, based on literature and data sources.
- Chapter 3 - Methodology
  This chapter describes the design of the research, analytical methods (the three layer model and the Opper timeline), stakeholders, data sources and limitations.
- Chapter 4 - Model Inputs and Intermediate Results
  This chapter summarises the key datasets used in the analysis and presents the assumptions made regarding population, traffic flow, vehicle availability, departure timing and assisted transport options. These form the input for answering subquestions 2, 3 and 4.
- Chapter 5 - Results
  This chapter presents the estimation time estimates per area of Maastricht, identifies bottlenecks and includes both spatial and time based analyses using maps and simplified models.
- Chapter 6 - Discussion
  This chapter interprets the results in relation to the research question, it discusses the limitations and uncertainties and reflects on the existing flood preparedness.
- Chapter 7 - Conclusion and Recommendations
  This chapter summarizes the main findings, answers the research question and proposes recommendations to reduce evacuation time and improve safety for vulnerable districts.

2 Theoretical framework

This chapter provides background information that helps to understand the key factors that influence flood evacuations. The theories and concepts discussed here are important to explain why evacuating a city like Maastricht is challenging. The topics relate to several subquestions of this research: for example, understanding flood risk and population spread helps with subquestion 2, while road capacity and traffic behaviour are important for subquestions 1 and 5. The role of public transport is linked to subquestions 3 and 6. By exploring these topics first, the next chapters can build on this knowledge and use it to make realistic assumptions in the analysis.

2.1. Flood risk and vulnerability in Maastricht

Maastricht is located in the south of the Netherlands, along the river Meuse. Because of its location and the way the city is built, Maastricht faces a high risk of flooding. The city lies in a narrow river valley surrounded by hills, which limits how floodwater can spread out. This increases the impact of extreme river discharge. In the past, the Meuse has caused several major floods, leading to large scale evacuations and major damage to infrastructure [39]. More recently, the 2021 floods affected parts of Limburg and once again showed the need for strong and reliable flood planning [13].

Because of climate change, these types of flood events are expected to happen more often and become more severe. According to the Dutch Meteorological Institute (KNMI), the Netherlands will likely experience more extreme rainfall and higher river discharges in the coming decades, possibly going beyond what current flood defences can handle [20]. While the Meuse is not a tidal river and is therefore less influenced by sea level rise, it is very sensitive to heavy rainfall in upstream areas in Belgium and France. This makes Maastricht especially at risk for flooding during the winter months.

The layout of the city also makes evacuation more difficult. The historic centre has many densely built neighbourhoods with narrow streets and few open spaces. This can block both spontaneous and organised evacuations [8]. In addition, Maastricht has a relatively high number of elderly residents [15]. These residents are more likely to need help evacuating because of limited mobility or because they do not own a car [23].

Important infrastructure such as hospitals, bridges and main roads are often located in low areas. This makes them vulnerable during a flood and increases the chance of delays in emergency response and higher risks for people who need help [11]. That is why both the physical flood risk and the location of vulnerable residents need to be taken into account when preparing for a large scale evacuation in Maastricht.

2.2. Principles of evacuation planning

Good evacuation planning is important to reduce the number of casualties and the disruption caused by flood emergencies or other dangerous situations. This is especially relevant in low lying delta areas like the Netherlands, where there is limited infrastructure and where a threat can develop quickly. In those cases, fast and well prepared evacuation strategies are needed. The main goal of an evacuation is to move people out of the danger zone, or, if that is not possible, to bring them to a safer location nearby [21].

Evacuation plans often include three basic strategies:

- Preventive evacuation: people leave the area before the danger arrives;
- Vertical evacuation: people move to higher floors within the danger zone;
- Shelter-in-place: people stay indoors at a safe and elevated location [22].

Each of these strategies needs different types of preparation and infrastructure. The choice depends on how much time there is before the flood and how fast decisions can be made and put into action [6].

One of the biggest challenges is the mismatch between the time that is available, from the moment a warning is given until the flood arrives, and the time that is needed to evacuate safely. If there is not enough time, a full preventive evacuation may no longer be possible [35, 6]. In those cases, a combination of strategies is often needed, especially in areas with limited road capacity or with vulnerable residents, such as elderly people or those living in dense urban neighbourhoods [21, 27].

Several researchers recommend using evacuation timelines to plan the process. These timelines help show the different phases, such as prediction, warning and traffic movement, and how they depend on each other. They can also be used to test how well an evacuation might work under time pressure, and where the main bottlenecks in the system are [35].

There are two key concepts that are important to understand when planning evacuations:

- Lead time is the time between the moment an evacuation is ordered and when the flood reaches the area. If this time is short, it becomes harder to move everyone, especially those who need help.
- Bottlenecks are places in the road network where traffic exceeds the road's capacity. These are often narrow bridges or busy intersections. Such bottlenecks can have a big impact on how successful an evacuation will be [36].

Lastly, any evacuation plan must take into account both people who can leave with their own car (self-evacuating), and people who cannot leave on their own and need help, such as the elderly or disabled. Research shows that usually 10–15% of the population needs some form of assisted transport, such as buses or ambulances [23, 27].

2.3. Macroscopic traffic flow and road capacity

In evacuation planning, it is important to know whether the road network can handle the number of people who need to leave in a short amount of time. This section explains how traffic flow theory can be used to estimate road capacity during emergency situations, such as flooding. It also discusses typical capacity assumptions and the effect of bottlenecks on evacuation performance.

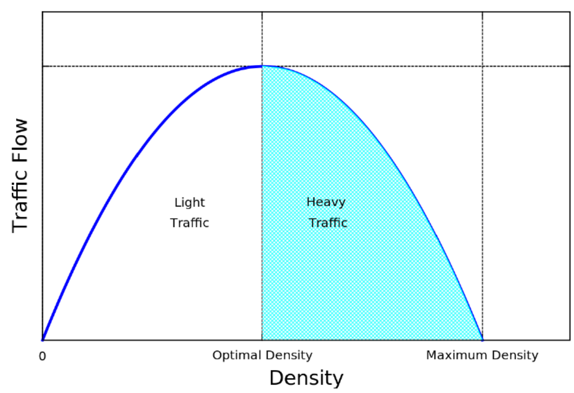

Figure 2.1: Flow-density diagram [40].

At a macroscopic level, traffic flow is often described using the formula $Q = k \times v$, where Q is the traffic flow (vehicles per hour), k is the density (vehicles per kilometre), and v is the speed (kilometres per hour). This relationship helps estimate how many vehicles can pass through a road section during evacuation [31].

However, in emergency situations, traffic does not behave as usual. For flood evacuations, it is common to use a reduced road capacity of 600 vehicles per hour per lane. This lower number takes into account poor weather, driver stress, and unfamiliarity with routes [35]. This goes for last minute evacuation, in this research people evacuate before the disaster hits.

This lower value is also used in Dutch evacuation studies. Even under ideal conditions, a full preventive evacuation of provinces such as South Holland cannot be done within 24 hours because of limited infrastructure. For instance, the MADAM simulation model shows that evacuating 80% of the population in North and South Holland takes more than 72 hours, even with advanced traffic management [22].

Road capacity depends not only on the roads themselves, but also on how traffic is managed and how people behave. Bottlenecks can appear both inside and outside the evacuation area, for example at intersections, merge points, or rural-to-urban transitions. These bottlenecks can lower the actual flow far below the calculated maximum [22].

One way to increase road capacity is to use contra flow: temporarily using inbound lanes for outbound evacuation. This can double capacity in theory, but it is difficult to organise and only useful for short distances [35].

To get a better understanding of evacuation times, macroscopic traffic simulation models are often used. These models simulate how traffic flows through a full road network and can adjust variables like speed, density and capacity depending on the situation. For example, during wildfires, roads that are blocked by smoke or fire are downgraded in real time. A similar approach applies to flood evacuations, where panic, poor visibility and partial flooding can all reduce traffic flow [17].

In summary, although macroscopic traffic models are simplified, they offer a useful framework to analyse evacuations. They show how physical road limits, environmental conditions and human behaviour all influence how quickly people can be evacuated. That is why realistic flow estimates, bottleneck analysis and alternative strategies are essential when full evacuation may not be possible.

2.4. Role of public transport in emergency evacuations

Public transport is crucial for evacuating vulnerable groups such as the elderly, people with disabilities, and residents without access to private vehicles [22]. Buses, ambulances, and trains help support these groups during emergencies.

However, capacity is limited. Due to congestion, delays, and boarding times, most vehicles can only make one or two trips during the warning phase [35]. Exercises like Waterproef have shown that public transport alone is insufficient; it can only complement private transport, not replace it [22].

Additional challenges include staff shortages, complex coordination, and incomplete registries of people needing assistance [23]. Some regions respond by using local shelters or vertical evacuation to shorten travel distances [22].

In conclusion, while public transport is essential for assisted evacuation, it must be combined with other strategies to ensure everyone can evacuate in time.

2.5. Summary

This chapter gave an overview of the most important concepts related to flood evacuation. It showed that Maastricht is vulnerable to flooding because of its location, road network and population structure. The literature explains that evacuation is strongly influenced by time pressure, road capacity and the number of people who need help leaving the area. Traffic flow models and evacuation timelines can help estimate how long an evacuation might take and where the main bottlenecks will occur. However, the theory also shows that public transport has limited capacity and must be combined with other strategies. The next chapter builds on these theoretical insights to explain how the evacuation model was designed. It shows how the concepts from this chapter are translated into practical assumptions, data inputs and simplified calculations to estimate evacuation times for different parts of Maastricht.

3
Methodology

In this chapter, the methodology is presented that was used to answer the central research question: *"How long would it take to evacuate the population of Maastricht during a large scale flood, and is this feasible within the available time window, based on road capacity and assisted transport demand?"*

To answer this question in a clear and structured way, the research is divided into six subquestions. Each subquestion focuses on a different part of the overall problem: understanding the existing road network, estimating how many people need to evacuate, identifying who needs transport support, calculating how long the evacuation would take, identifying possible bottlenecks and finally proposing improvements. Together, these subquestions build up the evacuation analysis step by step.

This chapter begins with an explanation of the overall research design. Then, the two analytical frameworks are introduced, followed by the assumptions made in the model. After that, each subquestion is discussed in more detail, along with the methods and data used to answer them. Finally, the chapter closes with an overview of data collection and the limitations of the research.

3.1. Research design

This thesis applies a quantitative, scenario based approach to estimate how long it would take to evacuate the entire population of Maastricht during a major flood. From a traffic engineering perspective, the study uses simplified models and public data on road capacity, population and transport availability.

The analysis assumes a scenario in which the full city must be evacuated before road access is lost, based on a fixed cut-off moment from the evacuation timeline framework. The scope is limited to Maastricht itself, so cross-border effects and detailed behavioural responses are excluded.

To reflect behavioural uncertainty, two simplified scenarios are included: one where residents without a car can share transport (best-case), and one where all require assistance (worst-case). The city is analysed at neighbourhood level to assess local feasibility within the available time window.

3.2. Analytical framework

To structure the evacuation analysis, this study combines a spatial and a temporal framework. Together, they link population, infrastructure, traffic flow and time constraints into one integrated approach.

3.2.1. Three layer spatial model

The first framework is a simplified three-layer spatial model, based on evacuation and transport planning principles [36]. It divides the evacuation problem into three components:

1. *Travel demand*
   This layer analyses how many people need to evacuate and from where. It includes population data, car ownership, and the share of residents needing assistance because they cannot evacuate independently.

2. *Transport infrastructure and services*
   This layer examines the available road network and public transport options. Road type and number of lanes are estimated. The evacuation routes are estimated using Google Maps, by determining the largest streets per neighbourhood.
3. *Traffic Flow*
   This layer focuses on how people move during evacuation. A simplified macroscopic formula is applied: $Q = k \times v$, where Q is traffic flow (vehicles/hour), k is density (vehicles/km), and v is speed (km/hour) [9, 31]. In this study, this relation is used to estimate how many vehicles can pass a road section per hour, based on assumed speeds and densities.

Each subquestion in the research relates to one or more of these layers:

- Layer 1 (*Travel demand*): subquestions 2, 3 and 4;
- Layer 2 (*Transport infrastructure and services*): subquestions 1, 3 and 5;
- Layer 3 (*Traffic Flow*): subquestions 4 and 5.

3.2.2. Evacuation timeline (Opper, 2004)

The second framework is a timeline based model developed by Opper (2004) [35]. It breaks the evacuation process into several time dependent phases:

1. *Prediction (P)* — when a reliable flood forecast becomes available;
2. *Response (R)* — when authorities begin decision making and mobilisation;
3. *Warning (W)* — when the population is alerted and prepares to leave;
4. *Evacuation (En)* — the time needed to move everyone out;
5. *Safety margin (S)* — a buffer to account for delays and disruptions.

In this study, the durations for response and warning are based on literature: 6 hours for response and 3 hours for warning and behavioural preparation. The different phases can flow into each other, they don't necessary happen in an order without overlap, especially looking at the Warning and Evacuation phases, people can already evacuate during the Warning phase. [35]. The evacuation time (En) is not fixed but calculated per neighbourhood based on population and road capacity.

These components together form the total required time for a successful evacuation. This is compared to the available time (Ea), defined as the window between the moment a reliable flood warning can be issued and the moment evacuation becomes impossible, for example, when access roads are flooded. Ideally, this value is based on detailed hydraulic modelling. However, in this study Ea is estimated from historical flood events. If the total required time exceeds Ea, evacuation is considered infeasible for that area under the given scenario.

3.2.3. Combined application in this research

By combining the spatial and temporal frameworks, this study analyses both *how much needs to be moved* and *how much time is available to do so*.

Table 3.1: Combined analytical framework: three-layer model and Opper timeline

Framework Component	Description	Related SQ(s)	Chapter(s)
Three-Layer Spatial Model			
Travel Demand	Who evacuates, from where	SQ2, SQ3, SQ4	Ch. 4.4, 4.5
Infrastructure	Road network and transport systems	SQ1, SQ3, SQ5	Ch. 4.3, 5.2
Traffic Flow	How movement occurs on the network	SQ4, SQ5	Ch. 5.1, 5.2
Opper Timeline Model			
Response (R)	Decision-making and mobilisation	–	Ch. 4.6.2
Warning (W)	Alerting population and preparation	–	Ch. 4.6.2
Movement (En)	Actual evacuation movement	SQ4	Ch. 5.1, 5.3
Safety Margin (S)	Buffer for disruptions and delays	SQ5, SQ6	Ch. 5.3, 6, 7

The three-layer model provides a neighbourhood level view of population, infrastructure and capacity. The evacuation timeline then helps assess whether the calculated evacuation durations fit within the available window before flooding.

Table 3.1 presents the combined analytical framework used in this study. It shows how both the spatial layers and the time phases are connected to specific subquestions and chapters in the report.

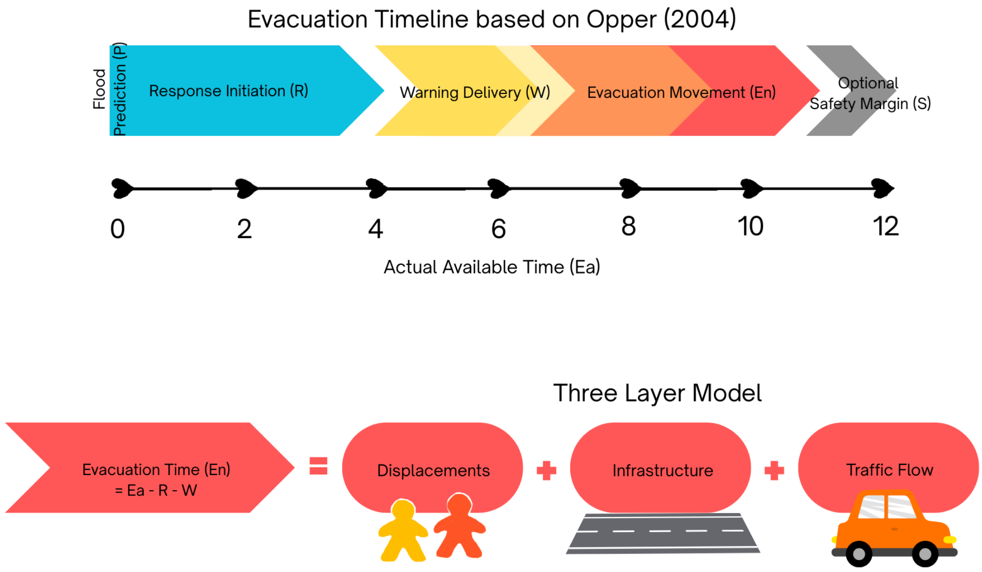

Figure 3.1: Combined use of timeline and three-layer model [35, 36]

3.3. Modelling assumptions

Because of the limited scope and time frame of this research, several simplifying assumptions were made. These assumptions reduce the complexity of the model, but they are still based on logic, literature and expert input. Below, each assumption is explained, along with its consequences for the analysis and modelling approach.

- Full compliance: all residents follow evacuation orders.
- Two behavioural scenarios: best-case (car sharing) and worst-case (full assisted transport demand).
- Fixed transport capacity: no dynamic scheduling or failures.
- Evacuation ends at city boundary; external network not modelled.
- Infrastructure remains functional until the cut-off moment.
- Only flood-prone neighbourhoods are included.
- Static macroscopic modelling: no dynamic traffic behaviour or route choice is simulated.
- Full compliance: all residents evacuate as instructed, without delay or refusal.
- Behavioural scenarios: best-case (car sharing) and worst-case (full assisted transport demand).
- Fixed vehicle supply: no operational disruptions in bus, train, or ambulance availability.
- No flood progression: roads are assumed usable until a fixed cut-off point.
- No external network effects: evacuation ends at the city boundary.
- Use of public datasets with estimations where data is missing.
- Only flood-prone neighbourhoods included; higher elevation areas are excluded.
- Evacuation routes selected manually based on major roads.

- Uniform departure window per neighbourhood; no staggered scheduling is applied.

These assumptions simplify the model but still allow a meaningful estimate of evacuation feasibility. The effects of these simplifications on the results are discussed in Chapter 6.

3.4. Methodological approach per subquestion

This section describes the specific method used to answer each subquestion.

Subquestion 1

"What is the structure and capacity of the road network in and around Maastricht?"

To answer this question, open source road data from OpenStreetMap will be imported into QGIS. The roads in Maastricht will be classified by type (residential, arterial, highway), number of lanes and their connection to key exit routes for certain neighbourhoods. This classification is then exported to Excel to calculate an estimated road capacity.

The capacity per road is calculated using:

$$Q_{\text{segment}} = k \times v \tag{3.1}$$

$$Q_{\text{total}} = Q_{\text{segment}} \times n \tag{3.2}$$

Where Q_{segement} is in veh/h/lane and n is the number of lanes. This gives an estimated flow per exit route, which is used as input for calculating clearance times in subquestion 4. This analysis relates to Layer 2 and Layer 3 of the three layer model.

Subquestion 2

"What is the distribution of the population across Maastricht, and what proportion requires assisted evacuation?"

First, the district boundaries are defined using QGIS data and verified with municipal maps. Then, CBS neighbourhood data is used to estimate the number of residents per neighbourhood, combined with data on car ownership and average household size.

To estimate how many residents are likely to self-evacuate, it is assumed that one vehicle serves one household, and that each vehicle carries the average number of household members in that neighbourhood. This assumption reflects household-based evacuation behaviour observed in flood scenarios [22].

The following formula is used to calculate the share of residents able to evacuate independently:

$$P_{\text{self}} = \min\left(1, \frac{H \times N_{\text{vehicles}}}{P_{\text{total}}}\right) \tag{3.3}$$

$$P_{\text{assisted}} = 1 - P_{\text{self}} \tag{3.4}$$

- P_{self}: proportion of the population that is able to evacuate using private vehicles;
- H: average household size in the neighbourhood;
- N_{vehicles}: number of registered vehicles;
- P_{total}: total number of residents in the neighbourhood.

It is important to note that not all residents aged 65 and older are automatically classified as assisted evacuees. While age is a known risk factor for limited mobility, the model assumes that elderly people living in multi person households or those with access to a private vehicle can self evacuate. Only residents without a vehicle (under the best- and worst-case assumptions) and without household support are included in the assisted evacuation group. Public sources are also used to locate specific facilities such as hospitals and prisons. These are added as fixed points of assisted evacuation demand.

This analysis corresponds to Layer 1 of the three layer model and directly supports subquestions 3 and 4.

Subquestion 3

"How many transport resources are available for assisted evacuation, and what is their capacity?"

This subquestion focuses on identifying the available transport resources for residents who cannot evacuate independently, such as those without access to a private vehicle, elderly residents or people living in care facilities.

Public sources are used to estimate the number of transport vehicles that could be used in an evacuation, including:

- Public buses (Arriva) for elderly, the hospital and the prison;
- Trains for general public without a car;
- Ambulances operated by the regional safety services.

For each vehicle type, the following characteristics are estimated:

- The number of vehicles available in the Maastricht area;
- The number of people each vehicle can carry per trip;
- An estimated round trip time, based on the distance to an determined evacuation location.

This gives the *per-trip capacity* per vehicle type, expressed as:

$$C_{\text{per\_trip}} = N_{\text{vehicles}} \times P_{\text{vehicle}} \tag{3.5}$$

With the estimated roundtrip time and the number of buses, train and ambulances, an estimation of the evacuation time per neighbourhood can be calculated to answer subquestion 4. This can be done by the best- and worst-case scenario.

This analysis relates to Layer 1 and Layer 2 of the three layer model.

Subquestion 4

"What are the expected evacuation times per neighbourhood for both self-evacuating and assisted groups, based on transport capacity?"

For each neighbourhood, the evacuation time is estimated separately for self-evacuating residents and for those requiring assisted transport. This is done by selecting the main exit roads that residents are expected to use and calculating the available capacity of those routes.

For self-evacuating residents, per road segment Formula 3.1 is used, using the estimations made for subquestion 2. The total capacity of the roads is then calculated using Formula 3.2.

The self evacuation time per neighbourhood is then calculated using:

$$T_{\text{selfstreet}} = \frac{N_{\text{vehicles}}}{Q_{\text{total}}} \tag{3.6}$$

This gives an evacuation time per evacuation street. For each neighbourhood the street with the longest evacuation time determines the total evacuation time. In formula form:

$$T_{\text{self}} = \max(T_{\text{selfstreet}}) \tag{3.7}$$

For assisted groups, the evacuation time per neighbourhood is calculated using the total assisted transport capacity estimated in subquestion 3:

$$T_{\text{vehicle}} = \frac{N_{\text{assisted}}}{B \times C} \times \frac{T_{\text{roundtrip}}}{60} \tag{3.8}$$

Where:

- T_{vehicle}: evacuation time in hours for either bus, train or ambulance;
- N_{assisted}: number of residents needing either bus, train or ambulance evacuation;
- B: number of vehicles allocated to the neighbourhood;
- C: carrying capacity per vehicle per round trip;
- $T_{\text{roundtrip}}$: roundtrip time in minuted, based on safe location per district.

The values of k and v are specified in Chapter 4, based on assumptions from literature and expert input. The resulting evacuation times are later compared to the available movement time window in the conclusion of this thesis.

This analysis applies all three layers of the spatial model and provides the core time estimates needed for the overall evaluation.

Subquestion 5
”Where are the main traffic bottlenecks and risk zones during evacuation, and how do they impact overall evacuation performance?”

Using QGIS, the road network is mapped along with elevation data and key structural bottlenecks. Roads are assigned flow capacity values and expected volumes are estimated from population data. A simplified bottleneck analysis is performed using volume-to-capacity (v/c) ratios:

$$v/c = \frac{V_{\text{expected}}}{Q_{\text{segment}}} \tag{3.9}$$

During peak rush hour about 58% of Dutch people are on the roads in a 3 hour window [19], for this analysis it is estimated that 70% of private vehicles will depart within the most critical 4 hour window. Thus, the expected volume during the peak hour is approximated as:

$$V_{\text{expected}} = \frac{N_{\text{vehicles}} \times 0.7}{4} \tag{3.10}$$

Maps are generated to highlight high v/c zones using colour coding (e.g., green < 0.8, red > 2.0). This is based on the best- and worst-case scenario of car sharing. The best being that only buses and ambulances will be used for the hospital and prison and the worst being that more buses need to be used for assisted evacuation. These bottlenecks are later used to explain delays and vulnerabilities in subquestion 4 and inform recommendations in subquestion 6.

A best- and worst-case scenario will also be calculated, whether car sharing is happening or not. This is determined with formulas:

$$T_{\text{best}} = T_{\text{self}} \tag{3.11}$$

$$T_{\text{worst}} = \max(T_{\text{self}},\ T_{\text{bus}},\ T_{\text{train}},\ T_{\text{facilities}}) \tag{3.12}$$

Subquestion 6
”Based on the analysis, what practical and location specific recommendations can be made to the municipality to reduce evacuation time and improve safety, especially in districts with high vulnerability or capacity gaps?”

This subquestion explores practical improvements based on the results of the previous analyses. Rather than modelling these in detail, the suggestions are qualitatively assessed for feasibility and relevance. To maintain a clear structure and align with the stakeholder roles introduced earlier, the recommendations are grouped per actor, such as the municipality, public transport operators and emergency services. The goal is to provide concise, location specific suggestions that support coordinated evacuation planning.

3.5. Data collection

To answer the research question and subquestions, both spatial and statistical data have been collected from open and official sources. All key datasets are already available and have been processed for use in this research.

Spatial data:
The road network of Maastricht has been obtained from OpenStreetMap and imported into QGIS. The roads are classified by type, number of lanes, and connectivity. The data was downloaded in shapefile format and cleaned to remove small local roads that are not relevant for evacuation. Elevation data was used to identify flood prone districts and to exclude high elevation areas from the evacuation model.

Demographic data:
Population data per district, household size and car ownership rates have been collected from CBS StatLine and the Wijk- en Buurtkaart. These data are available in CSV format and have been combined in Excel with neighbourhood shapefiles to match population data to spatial zones.

Transport resources:
Information on available public transport was collected from websites of operators such as Arriva and NS and from publicly available municipal and provincial planning documents. When exact numbers were not available, realistic estimates were made based on literature, expert advice and comparable evacuation studies.

Fallback for missing data:
If data was incomplete or unavailable, values were estimated using documented assumptions, expert input (e.g. from Dr. Adam Pel) or logical reasoning based on known parameters. These cases and the assumptions made are described in Chapter 4.

All data have been processed and stored in standard formats (e.g. .csv, .shp, .xlsx), allowing easy integration between QGIS for spatial analysis and Excel for quantitative modelling.

4

Model inputs and intermediate results

This chapter presents the key input values, assumptions and intermediate results used to estimate evacuation times. It combines public data (e.g. population, road network, vehicle availability) with simplified assumptions (e.g. flow capacity, vehicle occupancy), structured per subquestion.

Where relevant, both best- and worst-case scenarios are included to reflect uncertainty. Intermediate outcomes such as the number of self-evacuating residents or transport resources are shown to support the calculations in the next chapter.

4.1. Used data sources

Appendix B provides an overview of the main data sources used in this research. The table shows where the input data comes from, what it is used for and how it is processed into model ready values. The sources include open datasets, official planning documents and expert input. Most data has been collected in digital format and integrated in QGIS and Excel for further processing. Where exact numbers were not available, assumptions were made based on literature and logical reasoning. These cases are further explained in the next sections.

4.2. District selection based on flood risk

This section defines which areas of Maastricht are included in the analysis. The selection is based on elevation and historical flood levels, which together determine which neighbourhoods are considered at risk.

An elevation map was created in QGIS using open elevation data. All areas located below 50 metres above NAP were identified. NAP (Normaal Amsterdams Peil) is the standard Dutch reference level for elevation, which approximates sea level. The 5 metre threshold is based on the highest recorded flood levels of the Meuse near Maastricht. In 1993, the river peaked at 45.50 metres above NAP, and in 2021 at around 45.70 metres [18, 4]. To stay on the safe side, a 4 metre buffer was added to account for future uncertainties and to reflect an extreme flood scenario. This threshold serves as a conservative modelling boundary.

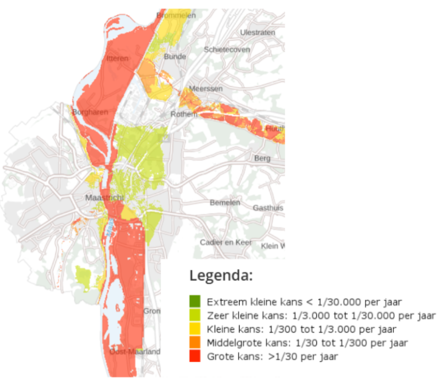

Figure 4.1: Flooding hazard areas map [5].

As an additional check, the elevation based flood zone was compared with reference flood maps from the *Atlas Leefomgeving*, a national environmental map portal developed by Dutch authorities. Figure 4.1 shows that the areas at highest risk lie along the river, which matches the QGIS elevation based selection.

Appendix C shows which districts are included in the analysis. Two districts, Buitenwijk West and Buitenwijk Zuid-West, are excluded, as most of their area lies above 50 metres NAP and they are considered safe zones. Residents in those areas are assumed not to require evacuation via the main road network.

This selection determines the spatial scope of the evacuation problem and directly relates to Layer 1 (*travel demand*) of the three layer model. Only neighbourhoods within the identified flood prone zone are included in the evacuation time calculations.

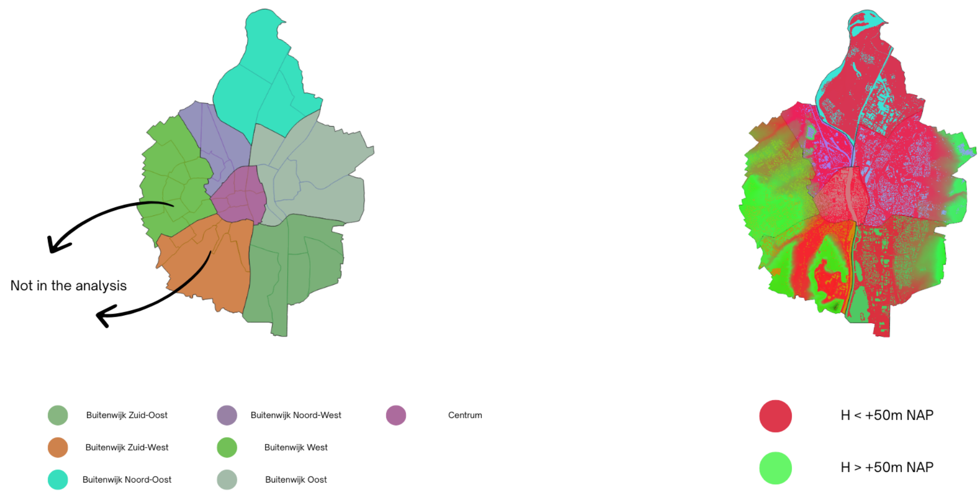

Figure 4.2: Elevation Maps with districts Maastricht

4.3. Road network and transport infrastructure

This section provides the spatial data and modelling assumptions used to answer Subquestion 1: *"What is the structure and capacity of the road network in and around Maastricht?"*

The road data is used to estimate the available evacuation capacity per neighbourhood. This includes the number and type of road segments, their classification and the assumptions made to calculate potential vehicle flow during emergency evacuation.

The road network used in this research is based on the Nationaal Wegenbestand (NWB), an official national dataset maintained by Rijkswaterstaat and made available through the PDOK platform. The NWB contains detailed spatial and functional information for all road segments in the Netherlands.

4.3.1. Road type classification

Each road segment in the NWB dataset includes a *BST_code*, which identifies the functional road type. These codes were used to group roads into relevant categories for evacuation modelling. Non motorised infrastructure such as footpaths, bicycle lanes and parking areas were excluded, since they are not suitable for evacuation by car or bus. The cleaned network was used to define both the spatial coverage and flow capacity of the road system for each neighbourhood. The main categories included:

- *HR (Hoofdrijbaan)* — Main carriageways, typically multi-lane and high capacity;

- *RB (Rijbaan)* — Urban and residential roads, often lower speed and fewer lanes;
- *PR (Provinciale weg)* — Regional/provincial roads outside the city core;
- *OPR / AFR* — On-ramps and off-ramps connecting arterial roads;
- *VBK, VBD, VBR* — Various connectors between urban or regional segments.

These functional types help indicate which segments are likely to support higher traffic volumes. In Appendix D there is an overview of the infrastructure with and without neighbourhoods.

4.3.2. Spatial coverage

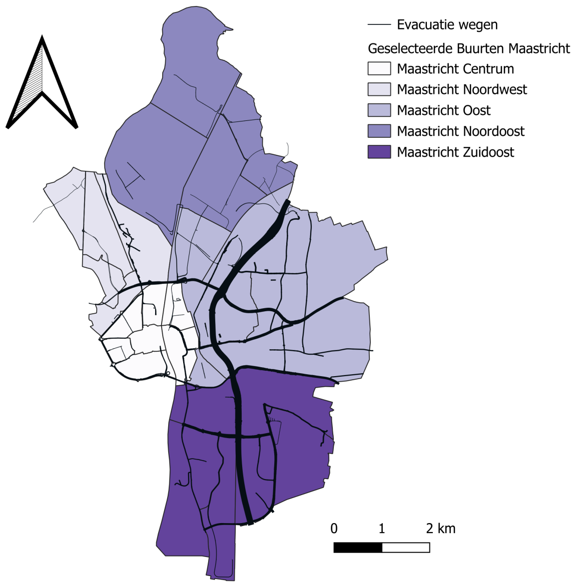

Figure 4.3: Estimated evacuation routes

The filtered dataset includes a total of 4435 road segments within the five selected districts. The distribution of road types varies significantly between areas. A detailed breakdown of road segments by BST code and district is provided in Appendix E. A spatial map of the streets used as evacuation routes is shown in Figure 4.3, where the thickness of the line depends on how many cars will need to use it. And in Appendix F and overview of the streets used as evacuation routes per neighbourhood is given.

4.3.3. Flow estimations

Using Formulas 3.1 and 3.2 the capacity per evacuation street is determined. These values are used in Chapter 5 to calculate estimated evacuation times per neighbourhood. In table 4.1 the assumptions used per functional road category (BST-code) is shown, based on Dutch evacuation modelling guidelines and traffic engineering sources.

These assumptions follow constrained flow evacuation models as described in [22]. Mass evacuation traffic consistently performs below standard Highway Capacity Manual (HCM) expectations, this means below standard capacities [44]. The result is a full capacity map of all motorised road segments in the flood prone area. A colour coded visualisation of the calculated Q_{segment} values is shown in Figure 4.4.

Table 4.1: Capacity estimation assumptions per road type

BST Code	Road Type	v [km/h]	k [veh/km]	n [lanes]
HR	Main carriageway (Hoofdrijbaan)	70	20	2–4
PR	Provincial road (Provinciale weg)	60	20	1–2
RB	Urban road (Rijbaan)	30	25	1
OPR/AFR	On/off-ramps	40	20	1
VBK/VBD/VBR	Connecting roads	30	25	1

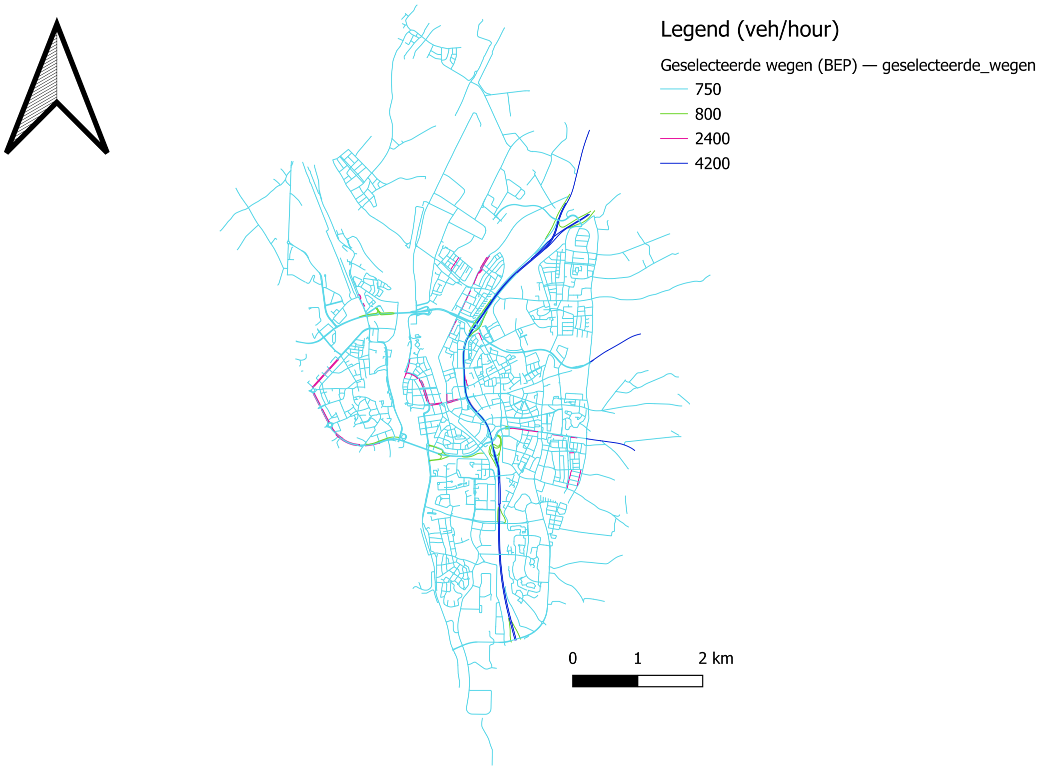

Figure 4.4: Estimated segment flow capacity (Q_{segment}) in veh/h per segment

4.4. Population and vehicle ownership per neighbourhood

This section presents the input data and intermediate calculations used to answer Subquestion 2: *”What is the distribution of the population across Maastricht, and what proportion requires assisted evacuation?”*

The goal is to estimate, for each district and neighbourhood, how many residents are likely to self evacuate and how many will require assisted evacuation. The analysis is based on demographic and vehicle ownership data from the 2022 *Wijk- en Buurtkaart* and *CBS StatLine*. The year 2022 was selected because it is the most recent dataset that includes both population and car registration figures per neighbourhood.

4.4.1. Method and data processing

For each flood prone district, data on total population, residents aged 65+, average household size and the number of registered vehicles were processed in Excel. These variables were used to estimate self-evacuation potential and assisted transport needs using Formulas 3.3 and 3.4.

Car ownership is a key predictor of independent evacuation capacity [22, 26], while the proportion of residents aged 65+ indicates potential vulnerability. Appendix G includes the vehicle-to-senior ratio to help identify districts with higher assisted transport demand.

4.4.2. Results per district

Based on the values in Appendix G, the estimated share of residents who can self evacuate versus those who require assisted evacuation is shown in Table 4.2.

Table 4.2: Estimated self evacuating and assisted population per district in Maastricht

District	Population	Self evac.	Assisted evac.
Centrum	20235	35%	65%
Buitenwijk Noordwest	2130	80%	20%
Buitenwijk Oost	30235	67%	33%
Buitenwijk Noordoost	2690	100%	0%
Buitenwijk Zuidoost	20815	78%	22%

In districts where the number of vehicles is more than half the total population, the self evacuating share is capped at 100%.

In some neighbourhoods, the number of residents aged 65 and older exceeds the estimated number of people needing assisted evacuation. This is because the model assumes that elderly residents with access to a private car and sufficient mobility can self evacuate, especially when they live in multi person households. In these cases, the 65+ group is not automatically treated as dependent on assisted transport.

4.4.3. Special facilities: MUMC+ and PI Maastricht

Two specific facilities were included in the assisted evacuation planning due to their population, vulnerability, and logistical complexity:

- *Maastricht University Medical Centre+ (MUMC+)* is located in the Randwyck neighbourhood. The hospital has approximately 715 clinical beds, including intensive care and acute care units. For this study, it is conservatively estimated that 100 patients will require evacuation by ambulance, based on national guidance for medical evacuations and expert consultation [30].
- *PI Maastricht* is a penitentiary institution located in Limmel. The prison has capacity for approximately 240 detainees [14]. Due to security and logistical protocols, these evacuations must be treated separately from regular assisted transport.

Both institutions are considered fixed points of assisted evacuation demand and are included in the planning of transport resources in Section 4.5.

4.5. Assisted transport: vehicles and scenarios

This section supports Subquestion 3: *"How many transport resources are available for assisted evacuation, and what is their capacity?"*

Some residents cannot evacuate on their own and require assisted transport. This section defines which types of vehicles are used, which groups they serve, and what modelling assumptions apply.

4.5.1. Types of vehicles and target groups

Three transport modes are considered for assisted evacuation:

- *City buses* — for residents without private vehicles, prioritising elderly, disabled and detainees;
- *Trains* — for residents near stations without car access;
- *Ambulances* — for immobile or medically dependent individuals.

City buses are operated by Arriva, with 14 routes and an estimated 2.5 buses per route, yielding 35 buses in total [29]. Each is assumed to carry 40 seated passengers, based on mixed vehicle types

[3]. Of these, 28 are allocated to the general population and 7 to institutional locations (hospital and prison).

Maastricht has three train stations: Centraal (NS and Arriva), Noord and Randwyck (Arriva only) [28, 33]. NS trains at Centraal can carry approximately 613 passengers (413 seated + 200 standing) [43]; Arriva trains accommodate up to 225 passengers (150 seated + 75 standing) [41]. Based on departures between 6:00–9:00 AM [32, 2], estimated availability is:

- Centraal: 2 NS + 10 Arriva trains
- Noord: 4 Arriva trains
- Randwyck: 6 Arriva trains

For hospital evacuations, 10 ambulances are available [1], each transporting 1–2 patients per trip.

Table 4.3 summarises the assumed capacities.

Table 4.3: Assumed vehicle capacity per transport type

Vehicle Type	Target Group	Estimated Capacity
City bus	Elderly, disabled, detainees	~40 passengers
Train	General public without vehicle	~225–613 passengers
Ambulance	Medically dependent persons	1–2 patients

Round trip times for all modes were estimated using Google Maps, based on the shortest safe route from each neighbourhood to an evacuation destination and back. Appendix H provides an overview of the assigned destinations per district.

4.6. Evacuation timeline assumptions

This section provides the time assumptions used in the evacuation timeline model, which supports Subquestion 4: *"What are the expected evacuation times per neighbourhood for both self evacuating and assisted groups, based on transport capacity?"*

To estimate whether a full evacuation is possible within the time available, this study follows the phased timeline method developed by Opper (2004). This method breaks down the evacuation process into sequential stages and assigns estimated durations to each step. These assumptions are used to calculate the available window for movement before flooding makes the roads impassable.

Applicability to the Dutch context

Although Opper's study is based on Australian case studies, the timeline structure and time ranges are considered transferable to Dutch evacuation planning. This is supported by Dutch evacuation expert Dr. Adam Pel, who suggested the use of this evacuation planning tool. The fixed durations for decision making, warning and movement align with evacuation studies conducted for flood prone regions in the Netherlands [22]. Moreover, the timeline allows for adjustments based on national response times or local warning infrastructure, which keeps the model context sensitive.

Time estimates

Based on the timeline structure, given in Chapter 3.2.3, estimations for the duration of each phase can be determined. The estimated duration for each phase is based on Opper (2004) and supported by Dutch guidelines. Table 4.4 summarises the key components.

Within the warning phase, two key behavioural components are recognised:

- *WAF (Warning Acceptance Factor)* — estimated at 1 hour. This is the time people need to receive and mentally process the warning message.
- *WLF (Warning Lead Factor)* — estimated at 1 hour. This is the time people need to get ready, pack essentials and prepare to leave.

Table 4.4: Evacuation timeline assumptions based on Opper (2004) [35]

Timeline Step	Description	Time Estimate
Response time (R)	Decision-making and emergency mobilisation	6 hours
Warning and preparation (W)	Sending alerts and personal preparation	3 hours
Evacuation time (En)	Time needed for evacuating the area	Variable (Chapter 5)
Available time (Ea)	Time between warning and route closure	12 hours

These factors reflect typical human response behaviour in flood situations and are supported by international studies on evacuation dynamics. Even if the warning is technically issued, these behavioural steps must still be completed before movement can begin [35].

During the 1993 Meuse flood, evacuation activities in Maastricht began approximately 12 hours before peak discharge [12, 24]. Assuming that access remained open until close to the peak, this study adopts a conservative estimate of 12 hours for Ea. This is the time remaining to complete the evacuation of people (traffic movement), after warnings have started being delivered, before evacuation routes are cut by flooding [35].

Safety margin

In addition to the formal timeline phases, a safety margin of 1 to 2 hours is included in the planning. This margin accounts for real world disruptions such as traffic congestion, infrastructure issues or people leaving later than expected. This safety margin is added after calculating the expected evacuation time and is treated as a separate buffer. It is not intended to cover modelling or data uncertainty, but rather to reflect operational unpredictability.

Opper (2004) refers to this as the Traffic Safety Factor (TSF) and notes that it should scale with the base evacuation time, for example, 1 hour buffer for 1 hour of travel, or up to 3.5 hours for longer or more complex evacuations. This approach is also consistent with Dutch evacuation planning practices [22]. For this research a constant of 2 hours is used for the safety factor.

Lead time and total time requirement

The lead time in this study refers to the available window between the moment a reliable flood prediction is made and the point at which evacuation routes are no longer usable. This is not a clear sum up of al the phases, because some phases blend in with each other, such as warning time and evacuation time [35].

To determine whether evacuation is feasible, the total required time is calculated by summing all relevant phases:

$$T_{\text{required}} = T_{\text{evacuation}} + T_{\text{safety}} \tag{4.1}$$

As seen in Table 4.4, the non movement phases already consume 9 hours. As Opper (2004, p. 13) notes:

> *"The time allowance for decision making, resource mobilisation and warning cannot be safely reduced below a planning figure of nine hours."*

[35, p. 13]

The calculated total time (T_{required}) is then compared to the estimated available time (Ea). If it exceeds Ea, full evacuation is considered unfeasible under the given scenario:

$$T_{\text{required}} = En + S \leq Ea \tag{4.2}$$

4.7. Conclusion

This chapter has outlined all relevant input data and modelling assumptions used to support the evacuation time analysis. The intermediate results provide a district and neighbourhood level overview of population distribution, road capacity and available transport resources. These inputs are used in the next chapter to calculate estimated evacuation durations and to assess which neighbourhoods face the highest risk of delay or capacity shortfall.

5 Results

This chapter presents the results of the evacuation analysis of Maastricht. Based on the inputs and assumptions outlined in Chapter 4, estimated evacuation times are calculated for each neighbourhood under both self-evacuation and assisted transport scenarios. The outcomes are used to identify which districts can be cleared efficiently and which areas face critical delays due to road capacity limits or limited transport resources.

Section 5.1 discusses evacuation times per neighbourhood, including both private vehicle use and assisted modes such as buses and ambulances. Section 5.2 provides a visual and quantitative analysis of traffic bottlenecks using volume-to-capacity (v/c) ratios. Section 5.3 determines the evacuation time per district in the best- and worst-case scenario. Finally, Section 5.4 highlights vulnerable districts and suggests where strategic improvements may be most effective.

5.1. Evacuation time estimations per neighbourhood

This section presents the results for Subquestion 4: *”What are the expected evacuation times per neighbourhood for both self-evacuating and assisted groups, based on transport capacity?”*

The results are gathered using the estimations made surrounding the evacuation routes and capacity in Chapter 4.

5.1.1. Self-evacuation time per neighbourhood

To calculate the self-evacuation time per neighbourhood the Formulas 3.6 and 3.7 are used. The table of the resulting evacuation times per neighbourhood are shown in Appendix I. In Figure 5.1 a histogram of the evacuation times per neighbourhood are shown, coordinated per district in the colours used in Appendix I. Values vary between less than 2 hour in some low density or well connected neighbourhoods, up to over 11 hours in areas with many vehicles and limited access roads, mostly areas where the exit road was the A2.

Districts with large populations but limited road access, such as Centrum, have some of the longest estimated evacuation times, up to 11.4 hours. In contrast, smaller or less densely populated neighbourhoods closer to exit routes, such as Meerssenhoven, Amby and Lanakerveld show evacuation times under 3 hours.

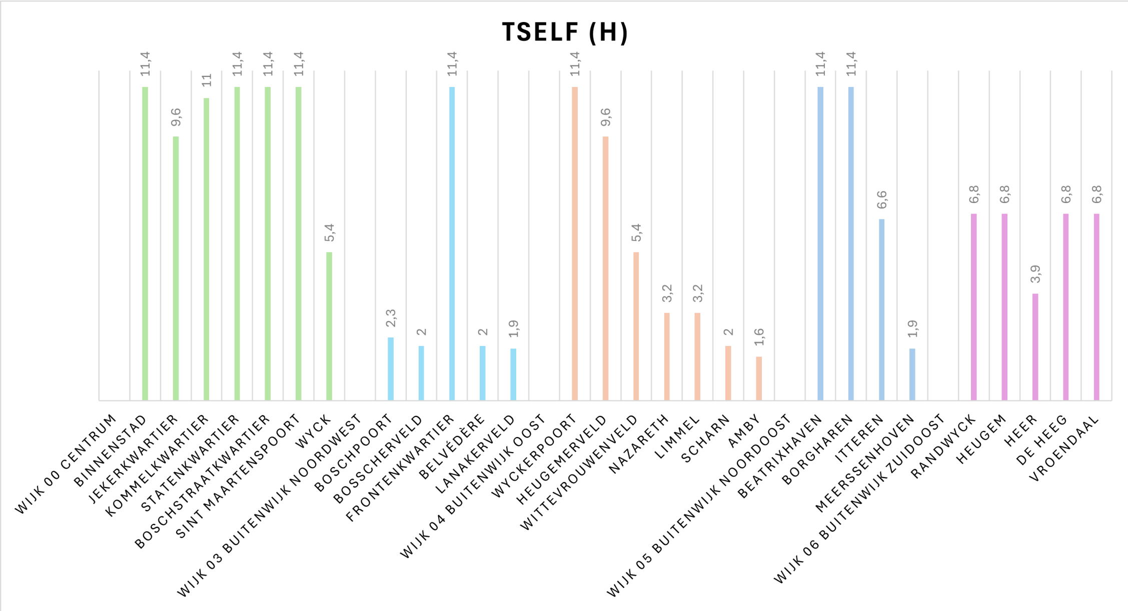

Figure 5.1: Histogram of the evacuation times per neighbourhood

5.1.2. Assisted evacuation time per neighbourhood

In this section the assisted evacuation time per mode of transport per neighbourhood is calculated. This is done with the estimations made in Chapter 4 surrounding evacuation locations and the calculations where made with the Formula 3.8.

Estimated bus evacuation times

The assisted group that evacuates by bus consists of residents without access to a private vehicle, with priority given to elderly individuals (65+). Institutional populations (MUMC+ and PI Maastricht) are handled separately.

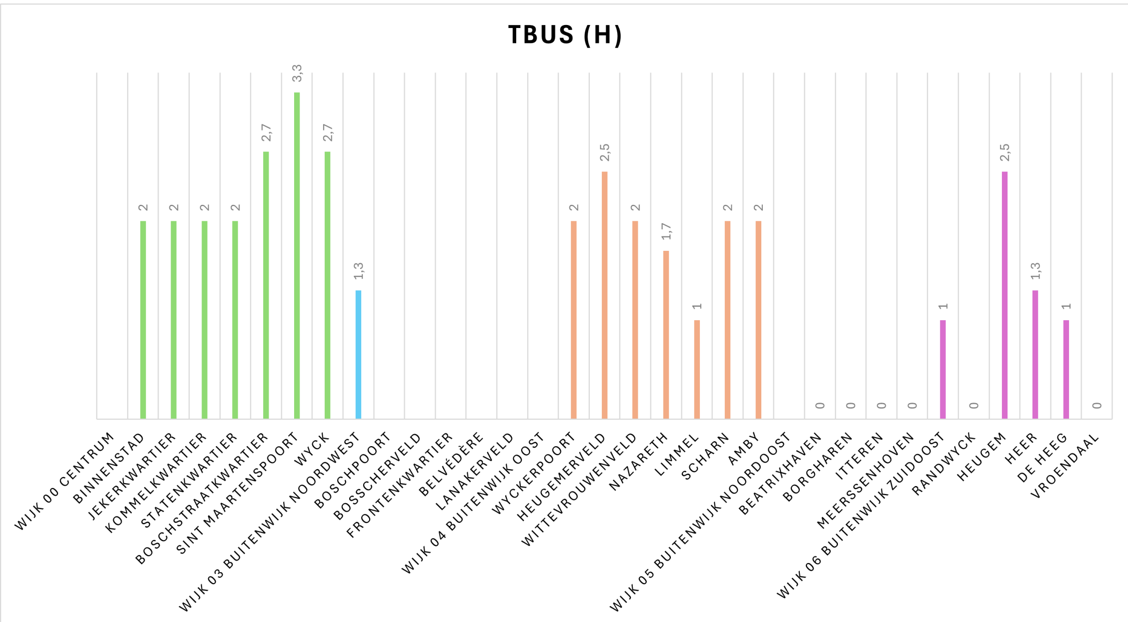

Figure 5.2: Histogram of the assisted evacuation times per neighbourhood by bus

In total, 28 city buses were assumed to be available for evacuation purposes, apart from the prison buses. These buses were proportionally allocated across neighbourhoods based on the number of assisted evacuees aged 65 or older.

To ensure each neighbourhood with assisted demand is served, fractional results from the proportional distribution were rounded to the nearest whole number. In cases where rounding led to a total of fewer than 28 buses, one additional bus was manually assigned to under served areas until the total equalled 28.

The tables in Appendix J present the estimated bus evacuation times per neighbourhood. The district Noordoost isn't calculated, because as seen in Chapter 4, there are no assisted evacuees in that district. In Figure 5.2 the estimated assisted evacuation time by bus is shown through a histogram per neighbourhood.

Most neighbourhoods fall within a range of 1 to 3 hours, with higher values in densely populated districts with more elderly residents and fewer buses per capita, such as Sint Maartenspoort, Wyck and Scharn. Neighbourhoods with no assigned buses (shown as 0 hours) either had no eligible assisted evacuees or were served by trains or ambulances instead.

Estimated train evacuation times

Figure 5.3 shows the estimated train based evacuation time per district. This is based on an estimation of round trip time to large train stations outside of Maastricht. This concerns the assisted evacuees without private vehicles who are assigned to trains instead of buses. The analysis is done at district level rather than neighbourhood level.

Each district is connected to their nearest station as follows:

1. Centrum –> Maastr. Centraal;
2. Noordwest –> Maastr. Noord;
3. Oost –> Maastr. Centraal;
4. Noordoost –> Maastr. Noord;
5. Zuidoost –> Maastr. Randwyck.

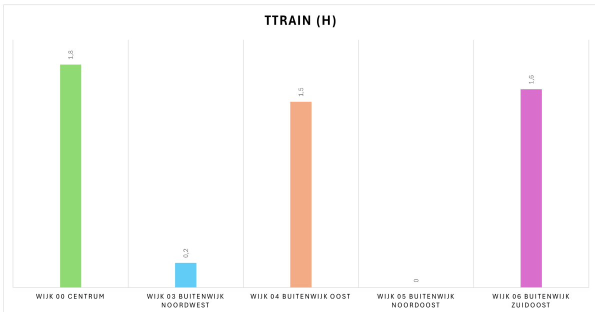

Figure 5.3: Histogram of the assisted evacuation times per district by train

Centrum, Zuidoost and Oost show the longest durations, with 1.8, 1.6 and 1.5 hours hours, while Noordwest is completed in less than 1 hour due to a much smaller group and direct connection to Maastricht Noord. No train based evacuees are assigned in Noordoost, so the time remains 0.

Estimated special facilities evacuation times

Table 5.1 summarises the respective evacuation needs of the special facilities, while Table 5.2 presents the estimated evacuation durations based on available transport resources and round-trip times.

For MUMC+ calculations result in a total ambulance based evacuation time between 4.14 and 8.33 hours, depending on whether one or two patients are transported per trip. For buses, four are allocated, resulting in a total evacuation duration of 3.2 hours.

Since no ambulance transport is required for PI Maastricht, evacuation is conducted using three dedicated buses. With a round-trip time of 20 minutes, the estimated bus evacuation duration for this group is 0.67 hours.

These calculations indicate that institutional evacuations, while representing a small share of the total population, require dedicated logistics due to fixed locations and limited specialised vehicles. In particular, the hospital evacuation involves stricter timing and higher resource demand, which may significantly impact assisted transport capacity in surrounding areas.

Table 5.1: Special facilities

Institution	Population	Ambulance pop.	Bus pop.
MUMC+	715	100	615
PI Maastricht	240 (from Limmel)	0	240

Table 5.2: Evacuation times special facilities

Institution	Namb.	Nbus	RT Amb. (min)	RT Bus (min)	Tamb. (h)	Tbus (h)
MUMC+	10	4	50	50	4.14 - 8.33	3.2
PI Maastricht	0	3	-	20	-	0.67

5.2. Bottlenecks and risk zones

This section together with Section 5.4 answer Subquestion 5: *"Where are the main traffic bottlenecks and risk zones during evacuation, and how do they impact overall evacuation performance?"*

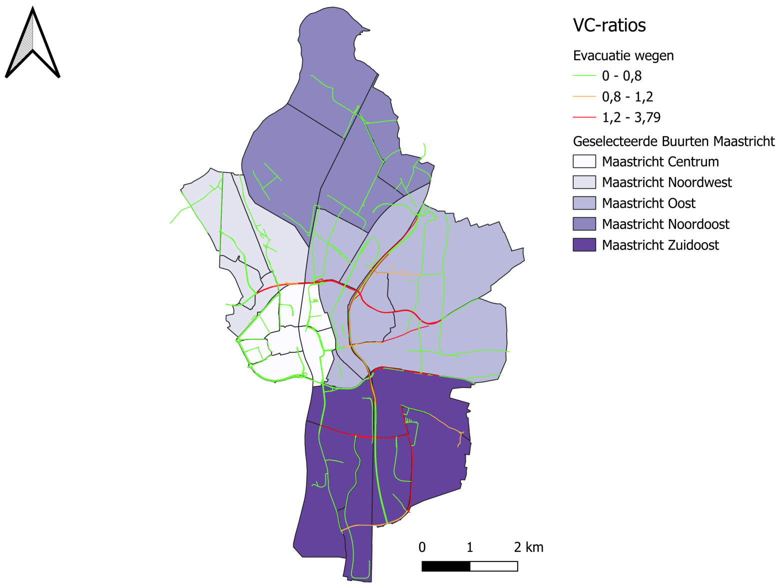

Figure 5.4: VCratio map with the districts

Figure 5.4 and Appendix K show the volume-to-capacity (v/c) ratios, calculated with Formulas 3.9 and 3.10, across Maastricht's evacuation network. These indicate how heavily road segments are loaded, using traffic flow estimates divided by road capacity.

Routes are colour-coded: green (v/c < 0.8) for free flow, orange (0.8–1.2) for moderate load, and red (v/c > 1.2) for overcapacity. Major bottlenecks appear on the A2 southbound, the John F. Kennedy Bridge and exit routes in Oost and Zuidoost.

The map overlays district boundaries to highlight local risk differences. Areas like Noordwest and parts of Centrum show low stress, but districts such as Zuidoost and Oost face high congestion, as many other areas rely on the same exit roads. For instance, Centrum itself has green roads, but still contributes to overload on the A2 corridor. Comparing it to Figure 4.3 it is suggested that the roads with the most cars on them form the biggest bottlenecks.

These findings suggest the need for targeted traffic strategies in high-risk areas, such as contra-flow lanes or staggered departures to reduce peak pressure on critical routes.

5.3. Best- vs worst-case scenario

Table 5.3 compares the estimated evacuation times for each neighbourhood in both best- and worst-case scenarios, using Formulas 3.11 and 3.12. The best-case scenario assumes that most residents can self-evacuate using private vehicles, apart from the special facilities, supported by car sharing. The worst-case scenario assumes that all residents without access to a private car require assisted transport by bus, train or ambulance.

Train evacuation times were calculated at the district level and applied to neighbourhoods within that district that have assisted evacuees assigned to trains. Similarly, the evacuation time for special facilities, such as the hospital in Randwyck, was added as ($T_{\text{facilities}}$) and included in the best- or worst-case scenario if it exceeded the self-evacuation time.

In some neighbourhoods, such as Wyckerpoort and Scharn, the self-evacuation time is the longest component and therefore determines both the best- and worst-case duration. In others, such as Randwyck, the worst-case is determined by something else, the hospital. This comparison helps identify which areas are most at risk of delays under pressure and where assisted transport planning is most critical.

For a clear overview of which neighbourhoods require the most support, colours are added to the estimated evacuation times (best-case and worst-case). These colours are based on Opper's timeline structure, assuming a total available time (Ea) of 12 hours. The response time is about 6 hours but falls outside the scope of the Ea, then the warning time is 3 hours, which consists of a total of 2 hours WAF+WLF, see Chapter 4.6, and 1 hour combined with evacuation movement. This means that there is a window of 10 hours for evacuation and the safety factor, so 8 hours for the evacuation alone. This is summarized in Figure 5.5.

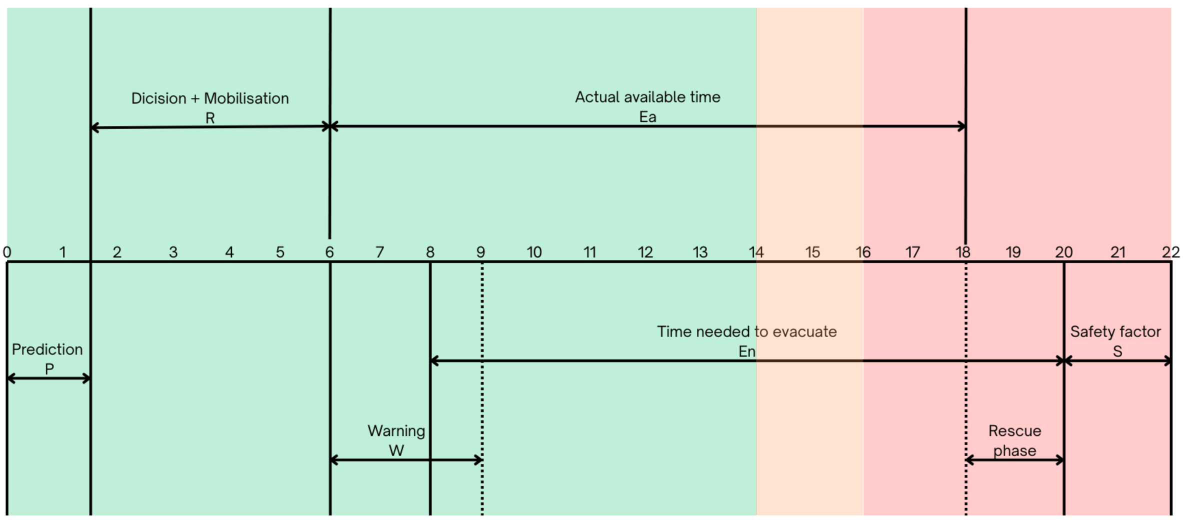

Figure 5.5: The evacuation timeline of Maastricht

Colour coordinated like:

- T_{evac} < 6 hours — Evacuation likely feasible with time to spare.
- 6 hours $\leq T_{\text{evac}}$ < 8 hours — Evacuation possible, but tight.
- T_{evac} > 8 hours — Evacuation exceeds available time window.

Table 5.3: Best- vs worst-case scenario evacuation times

Neighbourhood	T_{self} (h)	T_{train} (h))	$T_{\text{facilities}}$ (h)	T_{bus} (h)	T_{best} (h)	T_{worst} (h)
Wijk 00 Centrum	**-**	**1.8**	**-**	**-**	**-**	**-**
Binnenstad	11.4	-	-	2.0	11.4	11.4
Jekerkwartier	9.6	-	-	2.0	9.6	9.6
Kommelkwartier	11.0	-	-	2.0	11.0	11.0
Statenkwartier	11.4	-	-	2.0	11.4	11.4
Boschstraatkw.	11.4	-	-	2.7	11.4	11.4
Sint Maartenspoort	11.4	-	-	3.3	11.4	11.4
Wyck	5.4	-		2.7	5.4	5.4
Wijk 03 Noordwest	**-**	**0.2**	**-**	**1.3**	**-**	**-**
Boschpoort	2.3	-	-	-	2.3	2.3
Bosscherveld	2.0	-	-	-	2.0	2.0
Frontenkwartier	11.4	-	-	-	11.4	11.4
Belvédère	2.0	-	-	-	2.0	2.0
Lanakerveld	1.9	-	-	-	1.9	1.9
Wijk 04 Oost	**-**	**1.5**	**-**	**-**	**-**	**-**
Wyckerpoort	11.4	-	-	2.0	11.4	11.4
Heugemerveld	9.6	-	-	2.5	9.6	9.6
Wittevrouwenv.	5.4	-	-	2.0	5.4	5.4
Nazareth	3.2	-	-	1.7	3.2	3.2
Limmel	3.2	-	0.7	1	3.2	3.2
Scharn	2.0	-	-	2.0	2.0	2.0
Amby	1.6	-	-	2.0	1.6	2.0
Wijk 05 Noordoost	**-**	**-**	**-**	**-**	**-**	**-**
Beatrixhaven	11.4	-	-	-	11.4	11.4
Borgharen	11.4	-	-	-	11.4	11.4
Itteren	6.6	-	-	-	6.6	6.6
Meerssenhoven	1.9	-	-	-	1.9	1.9
Wijk 06 Zuidoost	**-**	**1.6**	**-**	**1.0**	**-**	**-**
Randwyck	6.8	-	4.2-8.3	-	6.8	8.3
Heugem	6.8	-	-	2.5	6.8	6.8
Heer	3.9	-	-	1.3	3.9	3.9
De Heeg	6.8	-	-	1.0	6.8	6.8
Vroendaal	6.8	-	-	-	6.8	6.8

In Wijk 00 Centrum, almost all neighbourhoods fall into the red category, with both best-case and worst-case evacuation times exceeding 8 hours. Especially the Boschstraatkwartier, Statenkwartier and Sint Maartenspoort show consistent delays in both scenarios, suggesting limited road capacity relative to demand.

In Wijk 03 Noordwest, the picture is more positive. All neighbourhoods except Frontenkwartier fall within the green category. This suggests that this district is well connected and has relatively low evacuation pressure.

Wijk 04 Oost shows more variation. Neighbourhoods like Wyckerpoort and Heugemerveld are in the red, while the others are all in the green. This implies that while the district has general access to transport infrastructure, some parts face localised bottlenecks.

In Wijk 05 Noordoost, the pattern is mixed: while Beatrixhaven and Borgharen have high estimated evacuation times, Meerssenhoven shows a very short evacuation time, suggesting strong self-evacuation capability and road availability.

Finally, in Wijk 06 Zuidoost, results are again mixed, but mostly orange. Only the neighbourhood Heer is in the green. Randwyck is the only neighbourhood in the red, but this neighbourhood contains the hospital, which partially explains longer assisted evacuation times.

5.4. Evacuation bottlenecks per district

This section presents a district level analysis of evacuation constraints based on worst-case scenario results. While overall evacuation times vary across Maastricht, nearly all districts include at least one neighbourhood that exceeds the 8 hour threshold. The analysis distinguishes between two main types of constraints: (1) capacity-related issues, such as limited outbound road access, and (2) mobility-related factors, including low car ownership or high demand for assisted transport.

Rather than repeating detailed results, this section identifies the dominant constraint type per district to support the interpretation of spatial differences in evacuation feasibility, providing input for the recommendations in Chapter 7.

Wijk 00 Centrum

In Wijk 00 Centrum, almost all neighbourhoods exceed the 8 hour evacuation limit in both scenarios, with times up to 11.4 hours. Most areas rely on a small number of outbound roads, including the A2 and Kennedy Bridge, leading to high congestion. Car ownership is relatively low, particularly in Binnenstad and Jekerkwartier, yet road saturation remains the dominant factor. The results suggest that infrastructure constraints are the main contributor to delays in this district.

Wijk 03 Noordwest

Most neighbourhoods in Wijk Noordwest remain under the 6 hour limit in both scenarios. An exception is Frontenkwartier, which reaches 11.4 hours, likely due to limited road access. Car ownership is high and assisted evacuation demand is low across the district. The results indicate a localised capacity issue in one neighbourhood, while the overall district shows no major constraints.

Wijk 04 Oost

Several neighbourhoods in Wijk Oost exceed the 8 hour threshold in the worst-case scenario, specifically Wyckerpoort and Heugemerveld. These areas show high population density and limited outbound routes. In addition, Oost has one of the highest assisted transport demands, due to a larger elderly population and lower car ownership. The results point to a combination of infrastructure and mobility constraints, with the latter being more pronounced.

Wijk 05 Noordoost

Evacuation times in most of Wijk Noordoost remain within the feasible window. However, Borgharen and Beatrixhaven exceed 11 hours evacuation times. These delays are not due to assisted transport, which is not required in this district, but rather linked to limited road access. Car ownership is high throughout the area. Constraints in this district appear to be specific to a few locations with reduced capacity.

Wijk 06 Zuidoost

In Wijk Zuidoost, several neighbourhoods have evacuation times near or above the 6–8 hour range. Randwyck presents additional complexity due to the presence of MUMC+, requiring ambulance and bus transport for over 700 people. Assisted evacuation demand is high and car ownership is relatively low in parts of the district. The results indicate that mobility constraints, especially related to institutional load, are a key factor in this area.

Summary

The worst-case scenario results show that all districts contain neighbourhoods with elevated evacuation times, but the nature of these constraints differs. In Centrum and parts of Noordoost, delays are primarily linked to limited road access. In Oost and Zuidoost, high assisted transport demand is a key factor, particularly in areas with low car ownership or institutional populations. In contrast, most neighbourhoods in Noordwest remain below the 6 hour threshold, except for one local outlier. The table below summarises the dominant constraints per district.

Table 5.4: Overview of dominant evacuation constraints per district

District	Capacity Constraint	Mobility Constraint	Primary Bottleneck
Centrum	High	Medium	Road capacity (congestion on exit routes)
Noordwest	Low	Low	Localised capacity (Frontenkwartier)
Oost	Medium	High	High assisted transport demand
Noordoost	Medium	Medium	Road access (Borgharen, Beatrixhaven)
Zuidoost	Medium	High	MUMC+ evacuation and elderly population

6 Discussion

This study aimed to provide a clear and structured first estimate of how long it would take to evacuate the entire city of Maastricht during a large scale flood. By combining spatial and time based modelling, the analysis looked at both the capacity of the road network and how the population is spread across the city. It also included two types of evacuees: people who can leave on their own, and those who need assistance.

6.1. Interpreting results through the analytical framework

To better understand the results, a combined analytical framework was used (see Table 3.1). This framework brings together the three-layer model (focusing on people, roads and traffic) with the evacuation timeline developed by Opper (2004), which breaks down the evacuation into different time phases. By linking each research question to one or more parts of this framework, the analysis shows how space and time together shape the outcome.

Travel demand layer

This layer focuses on how many people need to leave each area and how many of them need help to do so. The results show big differences between neighbourhoods. Districts like Centrum and Oost have both a high number of residents and low car ownership. In Zuidoost, the situation is even more complex due to the presence of MUMC+. These areas remain problematic even in the best-case scenarios. This confirms that understanding evacuation feasibility requires detailed, neighbourhood level analysis.

Infrastructure layer

This layer looks at the physical road network and its capacity. Some neighbourhoods have several ways to exit the city or access public transport, but others depend on just one or two main roads. The A2 and Kennedy Bridge act as major bottlenecks and become overloaded in almost every scenario. This shows that having enough vehicles is not enough: the physical infrastructure must also be strong and flexible enough to support evacuation.

Traffic flow layer

The traffic flow layer analyses how people move through the network once the evacuation starts. The results show that congestion builds up quickly, especially around major bridges and junctions. This congestion is mainly caused by private vehicles, as they make up the vast majority of traffic volume. The addition of assisted transport vehicles has little impact on overall flow, since their numbers are small compared to the number of cars. In fact, the model suggests that if more people used shared or public transport, total evacuation time would likely decrease.

Time based interpretation: the evacuation timeline

Looking at the results through the lens of the timeline model, a clear pattern emerges: while many neighbourhoods can be evacuated within the 8 hour window, several key areas exceed this limit, particularly Centrum, parts of Noordoost, parts of Oost, Frontenkwartier and Randwyck. This suggests that although large parts of the city might evacuate in time under favourable conditions, achieving a full, city wide evacuation within the available timeframe remains highly challenging and risky. The variation in clearance times highlights that even a few delayed districts could compromise the overall safety of the evacuation operation.

This suggests that changes are needed, especially in the infrastructure and traffic flow layers. Options include phased departures, promoting bus or train evacuations, temporary one-way routes (contra-flow), or local pick-up points to shorten travel time. The timeline model helps identify not just where congestion happens, but also when time becomes too short to evacuate everyone safely.

6.2. Limitations

Several limitations must be taken into account when interpreting these findings. Each limitation is linked to specific components of the analytical framework, either spatial (layer based) or temporal (timeline based), and influences the reliability of the outcomes.

Simplified modelling approach
A macroscopic and static modelling approach was used, applying the traffic flow formula $Q = k \times v$ to estimate segment capacity. This ignores dynamic behaviours such as re-routing, signal delays or incident based congestion.

- Effect: This may underestimate traffic build-up at critical points like the A2 or John F. Kennedy Bridge, leading to **evacuation times that are too optimistic**, especially during peak flows.

Behavioural assumptions
The model assumes full compliance: all residents evacuate as instructed. Two simplified behavioural cases (with or without car sharing) are included, but real world reactions are more unpredictable.

- Effect: Panic, refusal to evacuate or early departures may disrupt coordination. As a result, **the actual evacuation scenario could be very different from the models predictions.**

Geographic scope
The analysis is limited to the administrative boundaries of Maastricht, without accounting for down-stream effects on surrounding municipalities or on cross-border routes.

- Effect: Evacuation traffic may **encounter congestion or delays outside the city**, especially near safe zones or major highways, which are not modelled here.

No flood dynamics included
Flood progression is not simulated. It is assumed that during evacuation all the roads are still safe and available to drive on.

- Effect: In real flood scenarios, water may arrive in stages, cutting off specific districts or roads earlier than planned. The model **is not made to reflect on these time based road constraints.**

Static transport availability
The availability of buses, trains and ambulances is treated as fixed and uninterrupted. Operational issues such as delays, driver shortages or vehicle breakdowns are not included.

- Effect: This likely leads to an **overestimation of assisted transport capacity**, especially for vulnerable groups in districts like Zuidoost or for hospital evacuations.

Data limitations
Data on car ownership, elderly population and vehicle availability were drawn from public sources and generalised when necessary. Where specific data were missing, expert judgement and assumptions were applied.

- Effect: These assumptions may affect **district level accuracy**, especially in cases such as institutional populations, assisted evacuees percentages or informal car sharing practices.

Estimated actual available time (Ea)
The Ea value should be estimated by hydraulic calculations, but was based on historical values.

- Effect: The Ea value should be different per neighbourhood and can be longer or shorter depending on the place. This means that **the feasibility of evacuation per neighbourhood can differ completely.**

Selection of districts
Only districts identified as flood prone based on elevation and historical data were included.

- Effect: While this narrows the analysis to high risk areas, it may **underestimate total evacuation needs in future flood scenarios**, especially if infrastructure fails or water levels exceed current expectations.

Exclusion of high elevation neighbourhoods based on theoretical assumptions
Neighbourhoods at higher elevation or adjacent to safe zones were excluded from the analysis, under the assumption that evacuation toward higher ground is still possible.

- Effect: This assumption fits a dry weather, preventive evacuation model. However, in real flood events combined with heavy rainfall, such areas may **still become isolated or inaccessible**, especially if water flows down from hills. This may **underestimate the true number of evacuees** and the complexity of the evacuation strategy.

Subjective selection evacuation routes
The selection of evacuation routes per neighbourhood was done manually, based on the largest or most logical roads according to Google Maps.

- Effect: In reality, residents may use different or multiple routes based on familiarity, congestion or police direction. This assumption may lead to **overestimation of capacity per route** and **underestimation of congestion spreading** across the network.

No modelling of departure time distribution
All residents in a neighbourhood are assumed to evacuate in the same window, without modelling phased or staggered departures.

- Effect: This may **inflate peak demand on roads**, especially in densely populated areas. In practice, authorities may stagger departures to reduce overload, which this model does not simulate.

6.3. Implications for future research

This study provides a first approximation of city wide evacuation feasibility using a simplified and accessible modelling approach. However, several areas offer opportunities for further research to improve the accuracy, realism and policy relevance of flood evacuation analysis.

First, future studies could implement *dynamic traffic simulation models*, to capture route choice, vehicle interactions and time-varying congestion. This would allow more realistic modelling of departure waves, bottleneck evolution and adaptive routing.

Second, integrating *flood dynamics* into the model could improve the estimation of the actual available time per neighbourhood. Linking traffic modelling with hydraulic simulations would help identify when specific roads become unusable due to rising water levels.

Third, a *behavioural layer* could be added to account for factors such as evacuation delay, compliance uncertainty and response to official warnings. This would make it possible to test not just clearance times, but also the robustness of different communication and mobilisation strategies.

Finally, future research could expand the *geographic and institutional scope* of the analysis, for example by including cross-border evacuation routes, regional shelter capacity and coordination between neighbouring municipalities. This would help support integrated emergency planning at the regional level.

Together, these directions would support the development of more detailed and operational evacuation strategies for cities like Maastricht and beyond.

7

Conclusion and recommendations

Conclusion

This study investigated how long it would take to evacuate the population of Maastricht during a large scale flood, and whether this is feasible within the available time window, based on road capacity and assisted transport demand. Using a simplified traffic model, spatial population data, and the evacuation timeline by Opper (2004), clearance times were estimated per neighbourhood for both self-evacuating and assisted groups.

The evacuation timeline divides the process into four phases: response, warning and preparation, movement and a safety buffer. In this study, the response phase (around 6 hours) occurs before the official evacuation window begins. A total available time (Ea) of 12 hours is assumed. After reserving 2 hours as a safety margin and 2 hours for the WAF and WLF, 8 hours remain for the actual evacuation. Neighbourhoods requiring more than 8 hours cannot be fully evacuated in time, even under favourable conditions.

In the worst-case scenario, where all residents without a car require assisted transport, evacuation times increase only slightly. The main exception is Randwyck, where institutional transport demand (MUMC+) causes significant delays. Overall, the largest bottlenecks are caused by the self-evacuating group, especially in areas with high vehicle ownership and limited road access. Buses and trains appear more efficient for moving large groups within limited time.

The district level analysis in Chapter 5.4 shows that constraints vary by location. In Centrum, road capacity is the main limitation; in Noordoost, high private vehicle use leads to network congestion. Districts like Oost and Zuidoost face additional challenges due to low car ownership and high demand for assisted evacuation.

Estimated clearance times range from under 3 hours in well connected areas to over 11 hours in critical neighbourhoods. This means that a full preventive evacuation of Maastricht is only feasible under ideal conditions. In practice, several areas cannot be evacuated within the available time window unless major operational improvements are made.

In summary, a full evacuation is theoretically possible, but not realistically achievable without strong coordination and strategic planning. Future preparedness must focus on early mobilisation, targeted use of transport resources and tailored strategies for the most vulnerable districts.

Recommendations

This section answers Subquestion 6: *"Based on the analysis, what practical and location specific recommendations can be made to the municipality to reduce evacuation time and improve safety, especially in districts with high vulnerability or capacity gaps?"*

Based on the results and bottlenecks identified in Chapter 5.4, the following recommendations are provided. Each recommendation is linked to a key stakeholder and focuses on practical improvements within the strict time constraints of the evacuation timeline.

Municipality of Maastricht

- *Reallocate assisted transport to high risk districts*
  Prioritise Zuidoost (MUMC+) and Oost (elderly population) when assigning buses and ambulances. Consider pre-positioning vehicles near critical facilities.
- *Encourage local car sharing initiatives*
  Launch awareness campaigns in low car ownership areas to promote voluntary car sharing in advance. This can reduce pressure on public transport without major investment.
- *Support phased departure strategies*
  Coordinate timed evacuations in districts with limited road capacity to avoid peak congestion, especially where single exit routes are present.

Veiligheidsregio Zuid-Limburg (VRZL)

- *Implement dynamic traffic control*
  Prepare contra-flow plans, use traffic marshals and coordinate road use with municipal authorities to keep key routes operational during peak evacuation hours.
- *Coordinate integrated drills*
  Organise simulations that include multiple agencies to test real time coordination and ensure the warning and movement phases can be completed within the evacuation window.

Public transport operators (Arriva, NS)

- *Formalise emergency agreements*
  Define clear protocols with the municipality on how many buses and trains can be made available in crisis scenarios and under what timing and conditions.
- *Share real time data with emergency planners*
  Enable better transport planning by providing access to vehicle availability, departure frequencies and potential delays.

Healthcare and care institutions

- *Align facility evacuation plans with regional strategy*
  Ensure that hospitals and care homes (e.g. MUMC+) are linked to ambulance availability and evacuation priorities set by VRZL.
- *Pre-identify patient transport needs*
  Maintain updated lists of patients requiring specialised transport and communicate these early during warning phases.

Residents

- *Prepare in advance and follow official routes*
  Encourage households to make advance plans, especially in high risk districts. Compliance with routing and departure instructions is essential to avoid local congestion.
- *Participate in preparedness campaigns*
  Public engagement improves the overall resilience of the evacuation strategy and can reduce reliance on assisted transport.

These recommendations serve as a starting point for more detailed, operational planning. By addressing district level vulnerabilities and aligning stakeholder roles, Maastricht can improve its preparedness for future flood evacuations.

References

[1] Ambulancezorg Limburg. *Ambulancepost Maastricht*. Accessed: 2025-05-26. 2024. URL: https://www.ambulancezorglimburg.nl/locations/ambulancepost-maastricht?iframe=true.

[2] Arriva Nederland. *Arriva Reisplanner*. Geraadpleegd op 5 juni 2025. Arriva. 2025. URL: https://www.arriva.nl/plan-je-reis/reisplanner/.

[3] Arriva Touring. *Touringcars – Veilig, comfortabel en duurzaam op reis*. Accessed: 2025-05-26. 2024. URL: https://www.arrivatouring.nl/touringcars.

[4] Nathalie Asselman et al. *Juli 2021: Overstroming en wateroverlast in Zuid-Limburg – Eerste bevindingen voor Valkenburg, Geulmonding, Roermonding en Eygelshoven*. Tech. rep. 11207700-000-ZWS-0019. Deltares, 2022. URL: https://www.deltares.nl/publicaties.

[5] Atlas Leefomgeving. *Maps – Flood risk and environment*. Accessed on 12 May 2024. 2024. URL: https://www.atlasleefomgeving.nl/kaarten.

[6] A. Barendregt et al. "Determining the time available for evacuation of a dike-ring area by expert judgement". In: *Proceedings of ISSH – Stochastic Hydraulics* (2005).

[7] Maarten van de Biezen. *Maastricht - Luchtfoto met de Maas*. 2016. URL: https://www.hollandluchtfoto.nl/media/1c2c7858-3e79-4332-8665-3dc5b3537964-maastricht-luchtfoto-met-de-maas (visited on 04/28/2025).

[8] Bureau Europa. *The River*. Online. Tentoonstelling en rondleiding, 30 juni–14 augustus 2022. 2022. URL: https://www.bureau-europa.nl/en/the-river/?utm_source=chatgpt.com (visited on 06/14/2025).

[9] Wilco Burghout. "Hybrid microscopic-mesoscopic traffic simulation". PhD thesis. KTH Royal Institute of Technology, 2005.

[10] Consortium Grensmaas. *Hoogwater in Limburg*. Accessed 14 June 2025. 2021. URL: https://www.grensmaas.nl/actueel/hoogwater-in-limburg/ (visited on 06/14/2025).

[11] K. M. De Bruijn et al. "Towards a national flood risk analysis tool". In: *Journal of Flood Risk Management* 12.S2 (2019), e12516. DOI: 10.1111/jfr3.12516.

[12] Ministerie van Defensie. *Vervlogen tijden*. 2020. URL: https://magazines.defensie.nl/vliegendehollander/2020/01/07_vervlogentijden (visited on 04/24/2025).

[13] Deltares. *Watersnood 2021: Lessen uit Limburg*. Accessed 8 May 2025. 2022. URL: https://publications.deltares.nl/11207700_000_0019.pdf.

[14] Dienst Justitiële Inrichtingen. *Locaties PI Maastricht*. Accessed May 14, 2025. 2023. URL: https://www.dji.nl.

[15] Gemeente Maastricht. *Crisisbeheersingsplan Gemeente Maastricht*. Retrieved from https://www.gemeentemaastricht.nl. 2022.

[16] Gemeente Maastricht. *Stadsdelen en wijken in Maastricht*. Map image used in Figure **??**. 2024. URL: https://www.gemeentemaastricht.nl (visited on 05/10/2024).

[17] Paolo Intini et al. "Traffic modeling for wildland-urban interface fire evacuation". In: *Journal of Transportation Engineering, Part A: Systems* 145.3 (2019), p. 04019002. DOI: 10.1061/JTEPBS.0000221.

[18] Jurjen de Jong and Nathalie Asselman. *Analyse overstromingen Geulmonding – Watersysteemevaluatie Waterschap Limburg*. Tech. rep. 11207700-000-ZWS-0013. Deltares, 2022. URL: https://www.deltares.nl/publicaties.

[19] Kennisinstituut voor Mobiliteitsbeleid. *Zes vragen over de file*. https://www.kimnet.nl/actueel/nieuws/2020/01/21/zes-vragen-over-de-file. Geraadpleegd op 30 mei 2025. 2020. URL: https://www.kimnet.nl/actueel/nieuws/2020/01/21/zes-vragen-over-de-file.

[20] KNMI. *KNMI'23 Klimaatscenario's voor Nederland*. Accessed 8 May 2025. 2023. URL: https://www.knmi.nl/klimaatscenarios.

[21] B. Kolen and I. Helsloot. "Decision-making and evacuation planning for flood risk management in the Netherlands". In: *Disasters* 38.3 (2014), pp. 610–635. DOI: 10.1111/disa.12059.

[22] B. Kolen and I. Helsloot. "Time needed to evacuate the Netherlands in the event of large-scale flooding: strategies and consequences". In: *Disasters* 36.4 (2012), pp. 700–722. DOI: 10.1111/j.1467-7717.2012.01278.x.

[23] B. Kolen, I. Helsloot, and A. Scholtens. "Evacuatie bij overstromingen: leren van internationale ervaringen". In: *Tijdschrift voor Veiligheid* 12.3 (2013), pp. 5–21.

[24] Waterschap Limburg. *Well: Onze evacuatie*. URL: https://www.waterschaplimburg.nl/uwbuurt/artikel/verhalen-achter-dijk/verhalen-achter-dijk/well-onze-evacuatie/ (visited on 04/24/2025).

[25] Limburgs Museum. *Hoogwater 1993*. Accessed 14 June 2025. 2023. URL: https://onslimburgsmuseum.nl/collecties/hoogwater/hoogwater-1993 (visited on 06/14/2025).

[26] M. K. Lindell and C. S. Prater. "Critical behavioral assumptions in evacuation time estimate analysis for private vehicles". In: *Journal of Hazardous Materials* 150.1 (2007), pp. 1–6. DOI: 10.1016/j.jhazmat.2007.04.073.

[27] D. Lumbroso, K. Stone, and F. Vinet. "An assessment of flood emergency plans in England and Wales, France and the Netherlands". In: *Natural Hazards* 58.1 (2011), pp. 341–363. DOI: 10.1007/s11069-010-9671-0.

[28] Maastricht Bereikbaar. *Ik kom met de trein*. Accessed: 2025-05-26. 2024. URL: https://www.maastrichtbereikbaar.nl/hoe-reis-ik/ik-neem-het-openbaar-vervoer/ik-kom-met-de-trein.

[29] Maastricht Bereikbaar. *Ik neem de bus*. Accessed: 2025-05-26. 2024. URL: https://www.maastrichtbereikbaar.nl/hoe-reis-ik/ik-neem-het-openbaar-vervoer/ik-neem-de-bus.

[30] Maastricht UMC+. *Feiten & cijfers*. Accessed May 14, 2025. 2023. URL: https://www.mumc.nl/over-het-mumc/feiten-en-cijfers.

[31] Adolf D. May. *Traffic Flow Fundamentals*. Prentice Hall, 1990.

[32] Nederlandse Spoorwegen. *NS Reisplanner*. Geraadpleegd op 5 juni 2025. NS. 2025. URL: https://www.ns.nl/reisplanner/#/.

[33] Nederlandse Spoorwegen. *Reizigersgedrag Maastricht Noord*. Accessed: 2025-05-26. 2024. URL: https://dashboards.nsjaarverslag.nl/reizigersgedrag/maastricht-noord.

[34] NOS. *Liveblog Watersnood 16 juli*. 2021. URL: https://nos.nl/collectie/13869/liveblog/2389373-dringend-advies-maastricht-aan-10-000-mensen-ga-je-huis-uit-dodental-duitsland-boven-55 (visited on 04/24/2025).

[35] S. Opper. *The Application of Timelines to Evacuation Planning*. NSW State Emergency Service, 2004.

[36] A. J. Pel, M. C. Bliemer, and S. P. Hoogendoorn. "A review on travel behaviour modelling in dynamic traffic simulation models for evacuations". In: *Transportation* 39.1 (2012), pp. 97–123.

[37] Adam Pel. *Dr. Adam Pel – TU Delft Staff Page*. Accessed: 2025-05-07. 2024. URL: https://www.tudelft.nl/citg/over-faculteit/afdelingen/transport-planning/staff/persoonlijke-paginas/pel-aj.

[38] Wageningen University & Research. *Klimaatbestendigheid van Nederland: Verkenning van het kennisniveau en de kennisbehoefte.* 2014. URL: https://edepot.wur.nl/311280 (visited on 04/30/2025).

[39] Rijkswaterstaat. *Ruimte voor de rivieren*. Accessed 8 May 2025. 2020. URL: https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren.

[40] Martin Treiber and Arne Kesting. *Flow-Density Diagram of Road Traffic*. Figure retrieved from ResearchGate. 2004. URL: https://www.researchgate.net/figure/Flow-Density-Diagram-of-Road-Traffic-illustrating-how-the-optimal-density-point_fig6_228966705 (visited on 05/10/2024).

[41] Treinreiziger.nl. *Dit is de nieuwe Arriva-trein WINK voor Noord-Nederland*. Accessed: 2025-05-26. 2021. URL: https://www.treinreiziger.nl/dit-is-de-nieuwe-arriva-trein-wink-voor-noord-nederland/.

[42] Veiligheidsregio Zuid-Limburg. *Regionaal Risicoprofiel Zuid-Limburg 2023*. Retrieved from https://www.vrzl.nl. 2023.

[43] Wikipedia contributors. *Intercity Nieuwe Generatie*. Accessed: 2025-05-26. 2024. URL: https://nl.wikipedia.org/wiki/Intercity_Nieuwe_Generatie.

[44] Brian Wolshon. “Empirical Characterization of Mass Evacuation Traffic Flow”. In: *Transportation Research Record: Journal of the Transportation Research Board* 2041 (2008), pp. 38–48. DOI: 10.3141/2041-05.

A

Maastricht districts and neighbourhoods

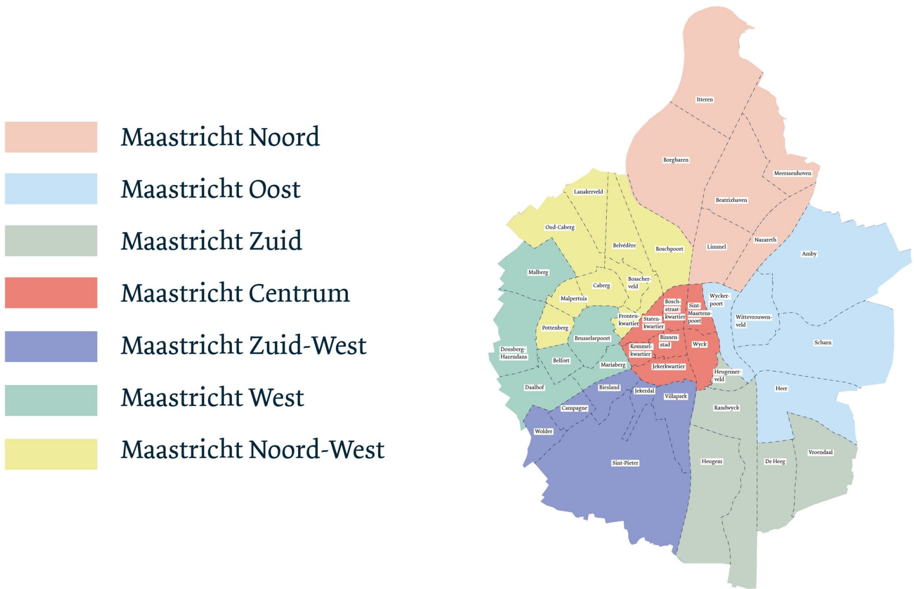

Figure A.1: Overview of the Maastricht districts and neighbourhoods [16]

B

Overview data sources

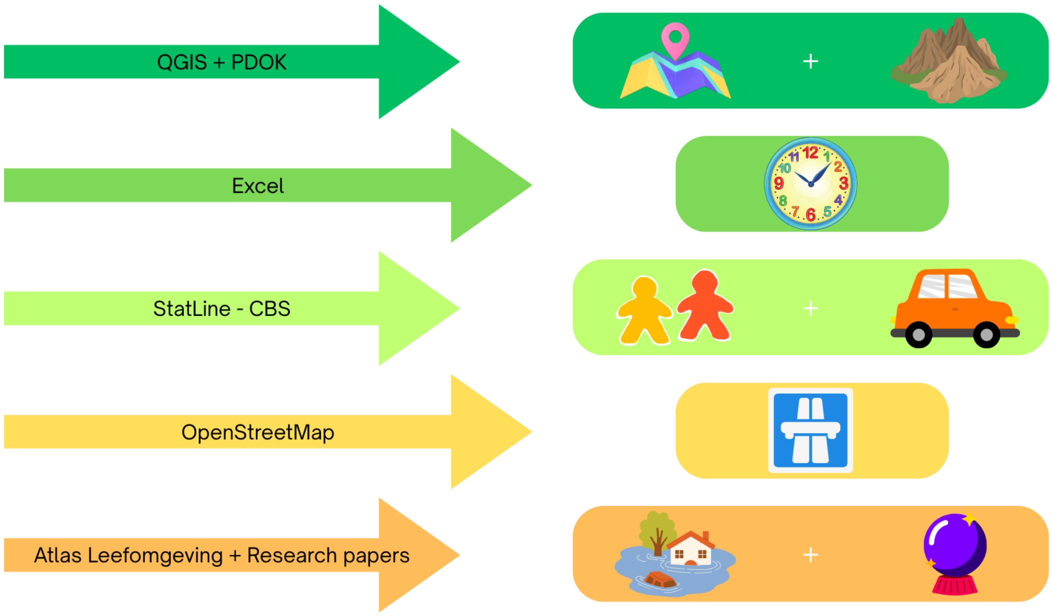

Figure B.1: Data sources overview

C
Selected districts with neighbourhoods

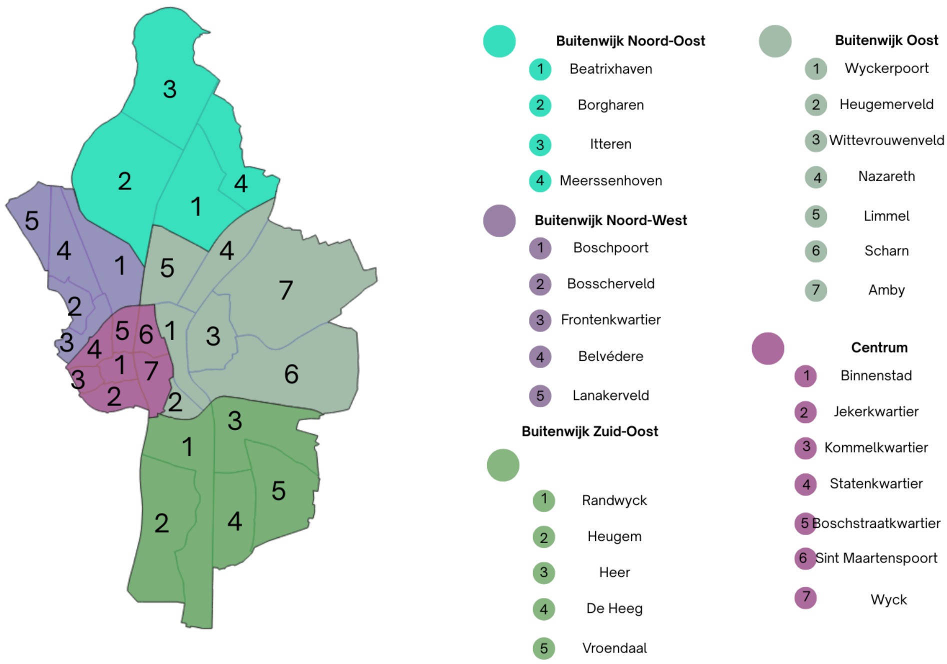

Figure C.1: Selected districts with neighbourhoods

D

Infrastructure maps

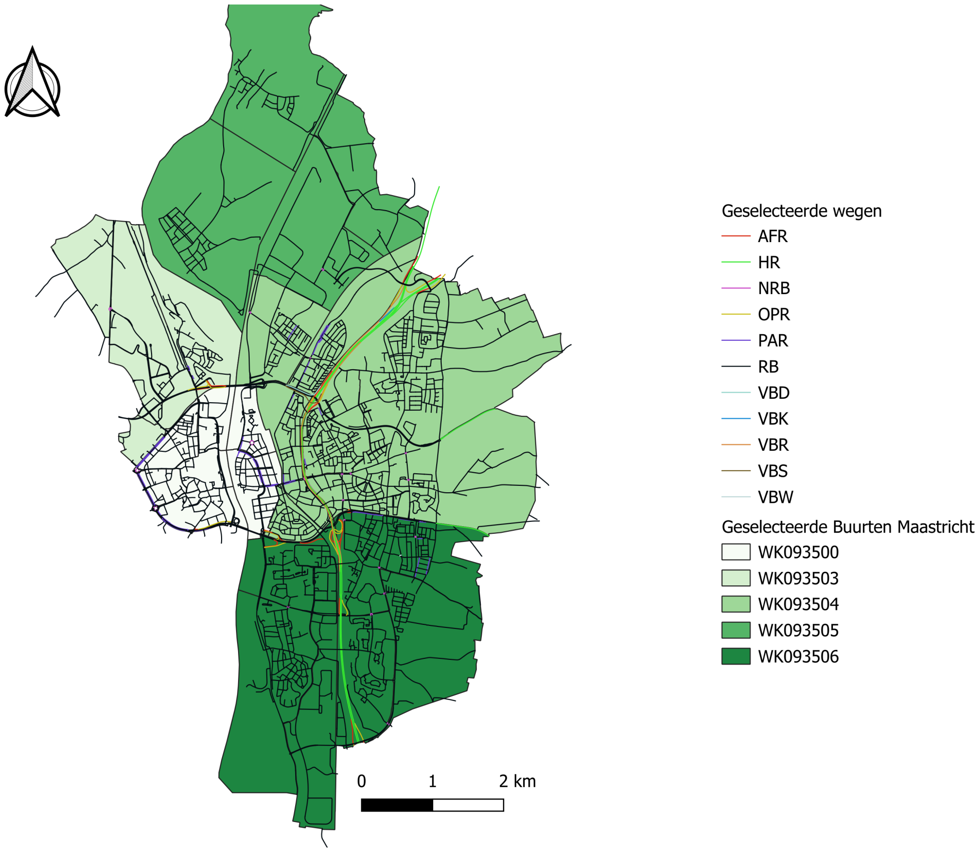

Figure D.1: Infrastructure map with neighbourhoods

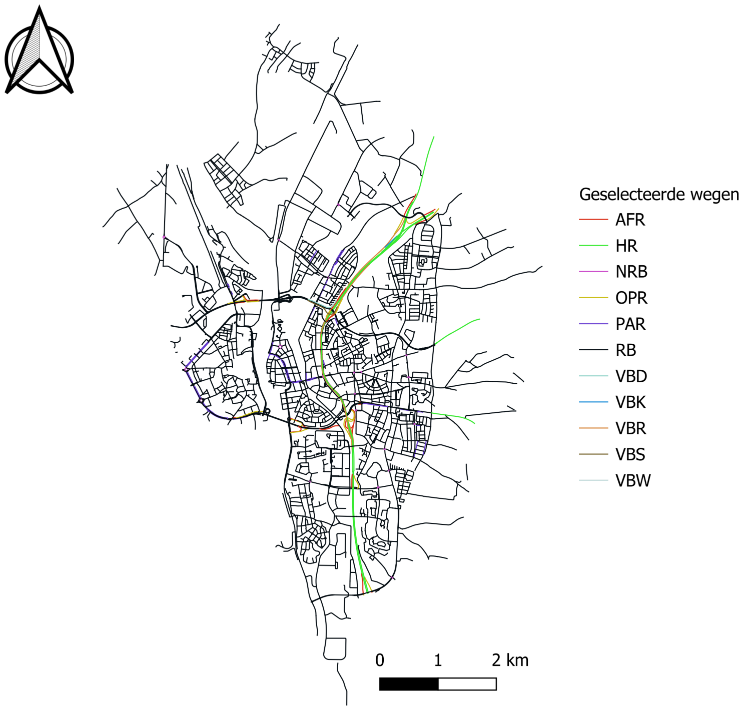

Figure D.2: Infrastructure map

E

Road segment count

Table E.1: Count of selected road segments per functional type (`bst_code`)

BST Code	Segment Count
AFR	38
HR	36
NRB	106
OPR	37
PAR	117
RB	4080
VBD	1
VBK	1
VBR	17
VBS	1
VBW	1

F

Evacuation routes and self evac. times

Wijken en buurten	Evacuation streets
Wijk 00 Centrum	
Binnenstad	Maasboulevard, Maasmolendijk, Boschstraat, Bosscherweg, Noorderbrug, Noorderbrugsingel
Jekerkwartier	Prins Bisschopsingel, Tongerseweg, john f. kennedybrug, john f. kennedysingel, Maasboulevard, A2
Kommelkwartier	Hertogsingel, Calvariestraat, Abtstraat, Tongersestraat, Tongerseweg, Brusselsestraat, Sint Servaasklooster
Statenkwartier	Statensingel, Frontensingel, Brusselsestraat, Bosscherweg, Noorderbrug, Capucijnenstraat, Viaductweg, A2
Boschstraatkwartier	Maasboulevard, Maasmolendijk, Boschstraat, Bosscherweg, Noorderbrug, Viaductweg, A2, Koningin Emmaplein, Sint Annalaan
Sint Maartenspoort	Franciscus Romanusweg, Sint Antoniuslaan, Wilhelminasingel, Noorderbrug, Viaductweg, A2
Wyck	Avenue Ceramique, Akerstraat, Wilhelminasingel, Scharnerweg, A2
Wijk 03 Buitenwijk Noordwest	
Boschpoort	Bosscherweg
Bosscherveld	Belvederelaan, Brusselseweg
Frontenkwartier	Statensingel, Noorderbrugsingel, Frontensingel, Noorderbrug
Belvédère	Brusselseweg, Belvederelaan
Lanakerveld	Zouwweg, Brusselseweg, Lanakerweg, Kantoorweg
Wijk 04 Buitenwijk Oost	
Wyckerpoort	A2, Scharnerweg, Meerssenerweg, Noormannensingel, Noorderbrug, Viaductweg
Heugemerveld	John f. Kennedysingel, john f. kennedybrug, Akersteenweg, Prins Bisschopsingel, Baron van Hövellstraat, Rijksweg
Wittevrouwenveld	Terblijterweg, Scharnerweg, Bergerstraat
Nazareth	A2, Meerssenerweg, Kasteel Neubourgweg, Kasteel Erensteinstraat, Severenstraat, Viaductweg
Limmel	Viaductweg, Borgharenweg, Willem Alexanderweg, Balije weg, A2, Noorderbrug
Scharn	Bemelerweg, Vijverdalseweg, Akkersteenweg, Weg van Heer naar Bemelen, Bergerstraat, Molenweg, Terblijterweg
Amby	Ambyerstraat Noord, Ambyerstraat Zuid, Severenstraat, Longinastraat, Terblijterweg, Bergerstraat, A2
Wijk 05 Buitenwijk Noordoost	
Beatrixhaven	Nieuwe Limmelderweg, Fregatweg, Galjoenweg, Klipperweg, Ambyerweg, Meerssenhoven
Borgharen	Daalstraat, Adam van Harenstraat, Trichtervoogdenstraat, Middenstraat, Sluisdijk, Borgharenweg, Noorderbrug, Viaductweg, Terblijterweg, Bergerstraat
Itteren	Op de Bos, Ruyterstraat, Geneinde, Klipperweg, Meerssenhoven
Meerssenhoven	Weert, Oude Steeg, A2, Fregatweg, Klipperweg
Wijk 06 Buitenwijk Zuidoost	
Randwyck	Habitatsingel, Molensingel, Hoge Weerd, Oeslingerbaan, Limburglaan, John f. kennedy brug, john f. kennedysingel, A2, Universiteitssingel
Heugem	Hoge Weerd, Köbbesweg, A2, Oeslingerbaan, Oude Maasstraat, Molensingel
Heer	Akersteenweg, Oeslingerbaan, Rijksweg, Veldstraat, Heerder Holstraat
De Heeg	Langendaal, Rijksweg, Maastrichterweg, Oeslingerbaan, Köbbesweg, A2
Vroendaal	Heerder Holstraat, Rijksweg, Köbbesweg, A2, Savelsbosch

Figure F.1: Estimated evacuation streets per neighbourhood

G

Neighbourhood data table

Wijken en buurten	Population	Population 65+	Mean household unit	Number of vehicles	Vehicle per 65+ resident	Vehicle per resident	Self evacuating	Assisted evacuation
Wijk 00 Centrum	20235	3820	1,3	5445	143%	27%	35%	65%
Binnenstad	2155	215	1,3	440	205%	20%	27%	73%
Jekerkwartier	1615	380	1,4	500	132%	31%	43%	57%
Kommelkwartier	2575	660	1,4	675	102%	26%	37%	63%
Statenkwartier	4660	650	1,3	1035	159%	22%	29%	71%
Boschstraatkwartier	1870	285	1,3	520	182%	28%	36%	64%
Sint Maartenspoort	2025	235	1,4	425	181%	21%	29%	71%
Wyck	5345	1395	1,4	1850	133%	35%	48%	52%
Wijk 03 Buitenwijk Noordwest	2130	515	1,8	950	184%	45%	80%	20%
Boschpoort	1565	385	1,8	685	178%	44%	79%	21%
Bosscherveld	40	15	1,6	25	167%	63%	100%	0%
Frontenkwartier	435	95	1,7	165	174%	38%	64%	36%
Belvédère	25	5	1,9	40	800%	160%	100%	0%
Lanakerveld	70	15	2	30	200%	43%	86%	14%
Wijk 04 Buitenwijk Oost	30235	5990	1,8	11315	189%	37%	67%	33%
Wyckerpoort	3860	870	1,6	1340	154%	35%	56%	44%
Heugemerveld	2805	480	1,7	930	194%	33%	56%	44%
Wittevrouwenveld	5530	810	1,8	1725	213%	31%	56%	44%
Nazareth	3105	570	1,7	1065	187%	34%	58%	42%
Limmel	1930	305	1,6	625	205%	32%	52%	48%
Scharn	6555	1350	1,8	2680	199%	41%	74%	26%
Amby	6450	1610	2,1	2955	184%	46%	96%	4%
Wijk 05 Buitenwijk Noordoost	2690	770	1,9	1600	208%	59%	100%	0%
Beatrixhaven	15	0	1,6	145	n.a.	967%	100%	0%
Borgharen	1740	515	1,9	910	177%	52%	99%	1%
Itteren	905	245	2	525	214%	58%	100%	0%
Meerssenhoven	20	10	1,3	15	150%	75%	98%	3%
Wijk 06 Buitenwijk Zuidoost	20815	4525	1,8	9040	200%	43%	78%	22%
Randwyck	2145	410	1,6	1025	250%	48%	76%	24%
Heugem	4380	975	1,8	1765	181%	40%	73%	27%
Heer	7310	1725	1,9	3115	181%	43%	81%	19%
De Heeg	5905	1120	1,9	2655	237%	45%	85%	15%
Vroendaal	1070	300	2,3	480	160%	45%	100%	0%

Figure G.1: Total table Chapter 4.4

Table G.1: Population, household size and vehicle availability per district in Maastricht

District	Population	65+	HH size	Vehicles	Veh./65+	Veh./res.
Centrum	20235	3820	1.3	5445	143%	27%
Buitenwijk Noordwest	2130	515	1.8	950	184%	45%
Buitenwijk Oost	30235	5990	1.8	11315	189%	37%
Buitenwijk Noordoost	2690	770	1.9	1600	208%	59%
Buitenwijk Zuidoost	20815	4525	1.8	9040	200%	43%

H

Evacuation destinations

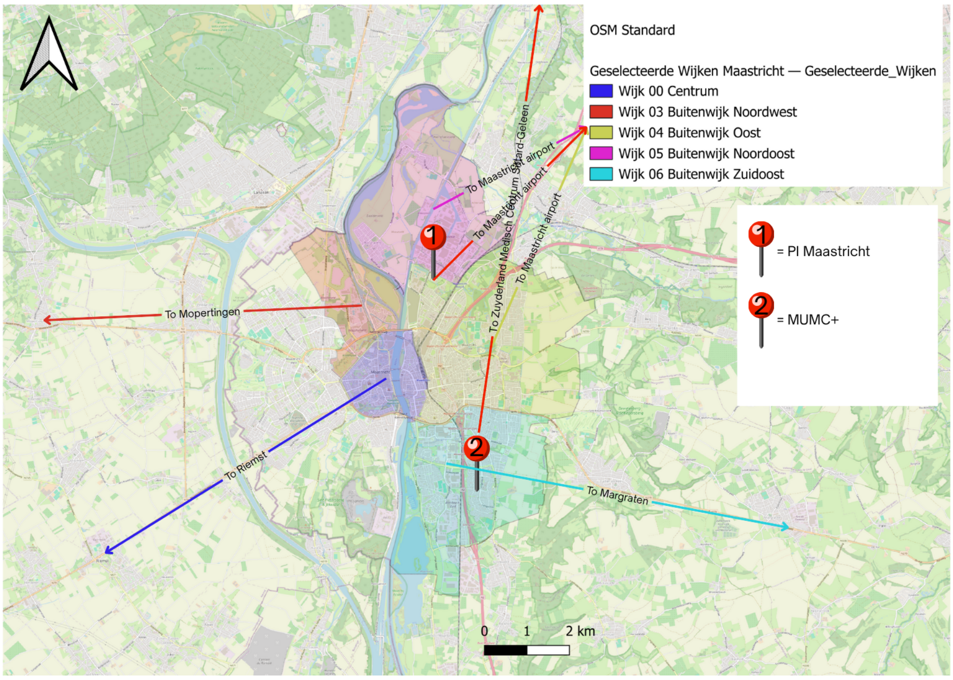

Figure H.1: Evacuation destinations

The trains go to the station of Sittard.

I

Estimated self evacuation time per neighbourhood

Districts and Neighbourhoods	Tself (h)
Wijk 00 Centrum	
Binnenstad	11,4
Jekerkwartier	9,6
Kommelkwartier	11
Statenkwartier	11,4
Boschstraatkwartier	11,4
Sint Maartenspoort	11,4
Wyck	5,4
Wijk 03 Buitenwijk Noordwest	
Boschpoort	2,3
Bosscherveld	2
Frontenkwartier	11,4
Belvédère	2
Lanakerveld	1,9
Wijk 04 Buitenwijk Oost	
Wyckerpoort	11,4
Heugemerveld	9,6
Wittevrouwenveld	5,4
Nazareth	3,2
Limmel	3,2
Scharn	2
Amby	1,6
Wijk 05 Buitenwijk Noordoost	
Beatrixhaven	11,4
Borgharen	11,4
Itteren	6,6
Meerssenhoven	1,9
Wijk 06 Buitenwijk Zuidoost	
Randwyck	6,8
Heugem	6,8
Heer	3,9
De Heeg	6,8
Vroendaal	6,8

Figure I.1: Estimated self evacuation time per neighbourhood

J

Evacuation time by bus

Table J.1: Demographics and assisted evacuation demand per neighbourhood

Neighbourhood	Population	Population 65+	% Assisted Evac.	$N_{\textbf{assisted65+}}$
Wijk 00 Centrum	*20235*	*3820*	*46%*	*1764*
Binnenstad	2155	215	59%	127
Jekerkwartier	1615	380	38%	145
Kommelkwartier	2575	660	48%	314
Statenkwartier	4660	650	56%	361
Boschstraatkwartier	1870	285	44%	126
Sint Maartenspoort	2025	235	58%	136
Wyck	5345	1395	31%	429
Wijk 03 Noordwest	*2130*	*515*	*11%*	*56*
Boschpoort	1565	385	12%	48
Bosscherveld	40	15	0%	0
Frontenkwartier	435	95	24%	23
Belvédère	25	5	0%	0
Lanakerveld	70	15	14%	2
Wijk 04 Oost	*30235*	*5990*	*25%*	*1507*
Wyckerpoort	3860	870	31%	266
Heugemerveld	2805	480	34%	162
Wittevrouwenveld	5530	810	38%	305
Nazareth	3105	570	31%	179
Limmel	1930	305	35%	107
Scharn	6550	1350	18%	246
Amby	6450	1610	8%	135
Wijk 06 Zuidoost	*20815*	*4525*	*13%*	*595*
Randwyck	2145	410	4%	18
Heugem	4380	975	19%	189
Heer	7310	1725	15%	255
De Heeg	5905	1120	15%	113
Vroendaal	1070	300	10%	31

Table J.2: Evacuation time estimation by bus per neighbourhood

Neighbourhood	B (buses)	C (pp/bus)	$T_{\text{roundtrip}}$ (min)	Roundtrips	T_{bus} (h)
Wijk 00 Centrum	-	-	*To Riemst*	-	-
Binnenstad	1	40	30	4	2.0
Jekerkwartier	1	40	30	4	2.0
Kommelkwartier	2	40	30	4	2.0
Statenkwartier	3	40	30	4	2.0
Boschstraatkw.	1	40	40	4	2.67
Sint Maartenspoort	1	40	50	4	3.33
Wyck	3	40	40	4	2.67
Wijk 03 Noordwest	*1*	*40*	*To Mopertingen*	*2*	*1.33*
Boschpoort	0	40	30	0	-
Bosscherveld	0	40	30	0	-
Frontenkwartier	0	40	40	0	-
Belvédère	0	40	40	0	-
Lanakerveld	0	40	30	0	-
Wijk 04 Oost	-	-	*To Maastricht Airport*	-	-
Wyckerpoort	2	40	30	4	2.0
Heugemerveld	1	40	30	5	2.5
Wittevrouwenv.	2	40	30	4	2.0
Nazareth	1	40	20	5	1.67
Limmel	1	40	20	3	1
Scharn	2	40	30	4	2.0
Amby	1	40	30	4	2.0
Wijk 06 Zuidoost	*1*	*40*	*To Margraten*	*2*	*1.0*
Randwyck	0	40	30	0	0
Heugem	1	40	30	5	2.5
Heer	2	40	20	4	1.33
De Heeg	1	40	20	3	1.0
Vroendaal	0	40	20	0	0

K

VCratio on OpenStreetMap

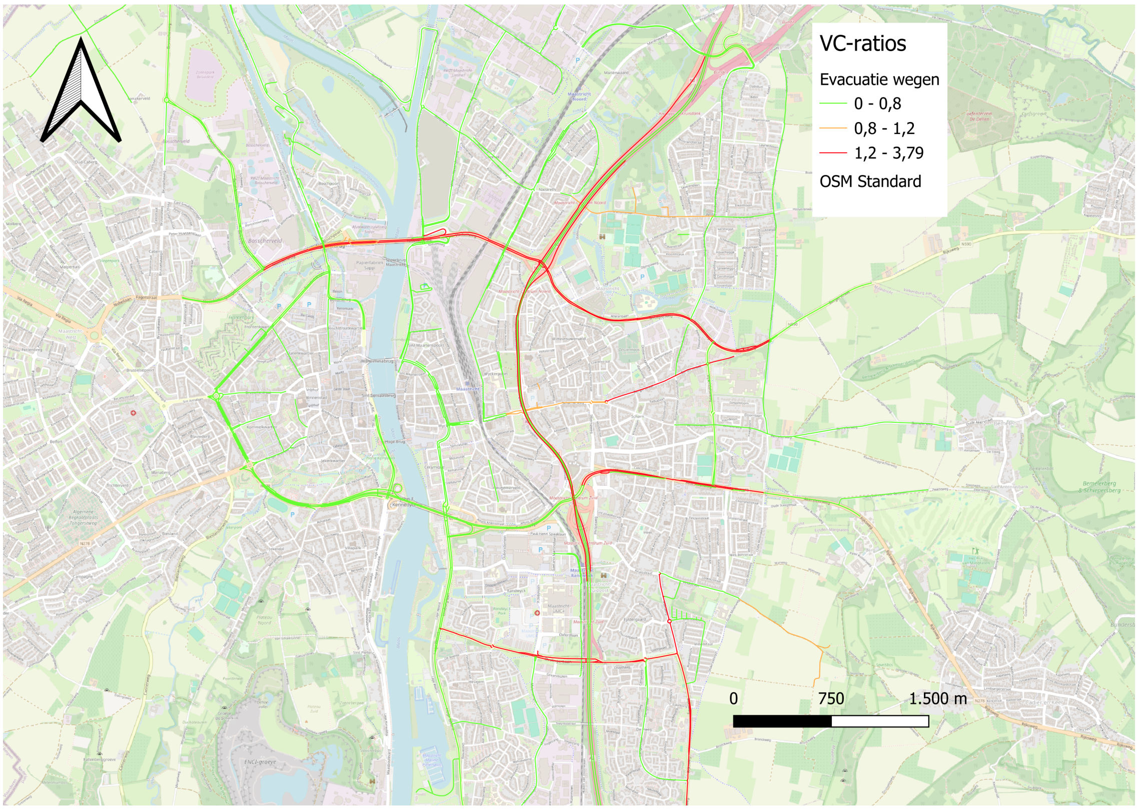

Figure K.1: VCratio map

L

Use of AI (ChatGPT)

In the process of writing this thesis, I used OpenAI's ChatGPT as a research and writing support tool. Specifically, AI was used to:

- Structure and refine the research subquestions to ensure logical progression toward the main research question.
- Translate and rephrase certain paragraphs between Dutch and English.
- Improve the academic tone and clarity of specific paragraphs.
- Assist with the use of tools such as QGIS and Excel.

All AI-assisted content was critically reviewed, adapted, and supplemented with academic sources and original analysis. All content was based on my own research and ideas. The AI was not used to generate conclusions or replace independent reasoning.