MASTER

Development of a GIS-based multi-criteria flood risk assessment tool

den Boer, A.B.T. (Mathilde)

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A.B.T. (Mathilde) den Boer

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Graduation Committee:

Dr. Ing. P.J.H.J. (Peter) van der Waerden

Dr. Ir. E.W. (Pauline) van den Berg

Prof. Dr. Ir. B. (Bauke) de Vries

21-06-2023

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Colofon

Author	A.B.T. (Mathilde) den Boer
Student number	1634100
University	Eindhoven University of Technology
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	Dr. Ir. E.W. (Pauline) van den Berg (2nd supervisor)
	Prof. Dr. B. (Bauke) de Vries (chairman)

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Preface

Almost seven years ago, I started my educational career in the built environment. After four years of studying Civil Engineering at the Avans University of Applied Sciences in Tilburg, I obtained my bachelor’s degree. The end of this bachelor's did not mean that I was done studying. Therefore, I applied for the Master ‘Construction Management and Engineering’ at the Eindhoven University of Technology. After a challenging premaster, I was able to successfully start my master’s. During my master, my enthusiasm for the built environment kept growing, and my interests became even wider.

From earlier on, my interest in infrastructure has mostly been in hydraulic engineering and water management. Therefore, I was very keen on combining this with the built environment in my master’s thesis. This research is the last step in the Master ‘Construction Management and Engineering’. In front of you lies the master thesis ‘’Development of a GIS-based multi-criteria flood risk assessment tool’’. In this thesis, I was able to obtain a lot of knowledge in flood risk management, analysis methodologies, and GIS-based assessments.

Without the guidance of several people, I would not have been able to finalize my thesis successfully. First of all, I would like to thank my first supervisor Peter van der Waerden, and my second supervisor Pauline van den Berg. They provided me with a lot of guidance and support throughout the process. I also want to thank my family, boyfriend, and friends who supported me during the period of writing my thesis, helped reading the chapters, and also provided me with the necessary distractions.

Dear reader, I hope you will be inspired, enjoy!

Mathilde den Boer

Dongen, June 2023

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Summary | English

Climate change has become a global threat and is putting stress on various sectors, such as the economy and biodiversity (Abbass et al., 2022). Because of climate change more events of extreme rainfall are occurring, as global warming raises the volume of moisture in the air. With increased amounts of precipitation, the chances of flooding are increasing (Rijksoverheid, 2021a). In the Netherlands, rainfall events cause water nuisance on local and regional levels, which possibly result in damages and disturbances for residents and authorities in the affected areas. Therefore, cities are preparing themselves to keep up with the climate change by implementing adaptation efforts, such as Green Infrastructure (GI) alternatives.

When focusing on pluvial flooding studies mostly concern the environmental benefits or citizen participation. However, Flood Risk Management (FRM) including the effects of GI has not particularly been researched for Dutch urban areas, as most FRM studies in the Netherlands are focused on fluvial and coastal flooding. However, pluvial flooding is the most commonly recognized risk for urban flooding events (O'Donnell & Thorne, 2020). This thesis will elaborate on both the determination of the flood risk in urban areas, as well as the effect of GI alternatives on the flood risk. Through the review of international literature, this research can adapt and combine the aspects considered to assess the flood risk probability and the effect of GI alternatives. This study aims to develop a tool that gains insight into the contribution of green infrastructure in relation to flood risk determination in Dutch urban areas. The development of such a tool could be used to support local Dutch authorities in decision-making for urban planning and to formulate targeted GI alternatives to reduce the risk of pluvial flooding in urban areas.

Before the tool could be developed, the framework for flood risk determination (FFRD) has been established based on the analysis of various indicators that have been used throughout different studies. The FFRD, shown in Figure S.1, represents the functioning of an area in relation to the flood risk. The overall index of the framework is the Flood Risk Level (FRL), which is represented by the categories runoff and capacity, which are further divided into sub-categories and indicators.

Starting on the left-hand side of the FFRD (Figure S.1), the sub-category land cover is represented by the indicators building, vegetation, pavement, and water. These land cover types represent the pervious and impervious surfaces within urban areas that generate a certain amount of runoff. The more infiltration is enabled by the land cover type, the less stormwater runoff will be generated during a heavy rainfall event. The runoff is also affected by the geographical indicators of

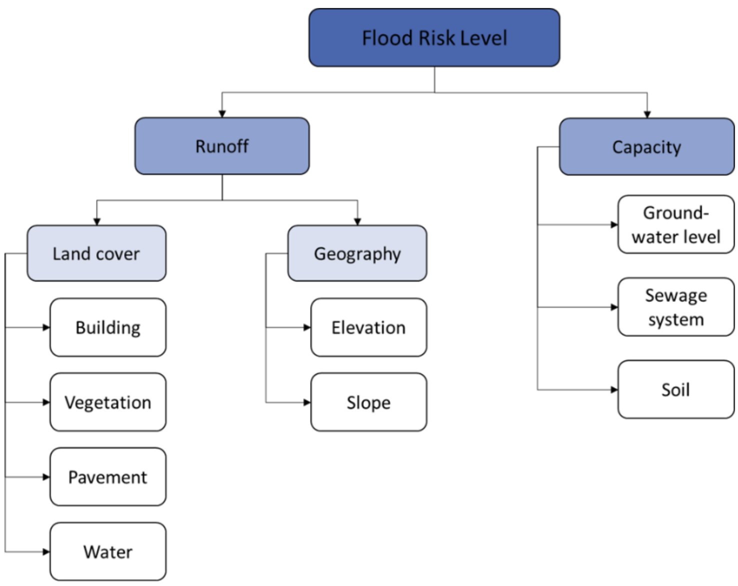

Figure S.1 Framework for flood risk determination (FFRD) elevation and slope. The slope affects the flow velocity and the elevation affects the flow direction. On the right-hand side of the FFRD (Figure S.1), the category capacity is represented by the indicators groundwater level, sewage system, and soil. The storage capacity of the ground is affected by the groundwater level. The sewage system capacity affects the capacity to diminish the flood risk, and the infiltration capacity is affected by the soil type. Within the FFRD GI alternatives are recognized in the indicators vegetation, pavement, elevation, slope, sewage system, and soil.

Based on the FFRD the flood risk assessment tool (FRAT) has been developed. The tool maps the FRL based on the contribution of urban aspects to the risk of flooding. The FRAT is established following a Multi-Criteria Analysis (MCA), in the form of an Analytical Hierarchy Process (AHP), while using a Geographical Information System (GIS). To indicate the performance of the indicators within the FFRD both quantitative and qualitative data have been used. Therefore, the scoring has been performed using the direct rating and proportional scoring approach. Relative importance has been assigned to the indicators and categories using weights based on experiences and findings from the literature. The scores and weights have been combined to calculate the weighted FRL score. Additionally, the FRL was also calculated based on equal weights to show the effect of applying weights to the indicators and categories.

The working of the developed FRAT was illustrated with a case study, which assessed the FRL of the city of Tilburg. The city center of Tilburg was expected to have a higher flood risk due to the higher building density than the surrounding neighborhoods, and the center areas are older and contain fewer redeveloped areas. When applying the tool in the case study, the difference between the scores with equal weights and the scores with weights became evident. The overall functioning of the FRAT provided the expected results and was able to correctly assess the FRL of the city of Tilburg. However, there is still room for improvement in the FRAT. Future research could further investigate the inclusion of neighboring cells, the assigned weights, and the sub-base of GI alternatives. Although future research is required, this thesis has contributed to the support in the decision-making for urban planning with a focus on flood risk probability.

Summary | Dutch

Klimaatveranderingen vormen wereldwijd dreigingen en zetten daarmee druk op verschillende sectoren, zoals de economie en biodiversiteit (Abbass et al., 2022). Door de klimaatveranderingen komt er steeds vaker extreme neerslag voor, doordat de opwarming van de aarde de hoeveelheid vocht in de lucht vergroot. Door de toenemende hoeveelheid regenval neemt de kans op overstromingen toe (Rijksoverheid, 2021a). Door de hevige regenval komt in Nederland steeds vaker wateroverlast voor op lokaal en regionaal niveau. Wateroverlast kan mogelijk leiden tot schade en verstoringen voor bewoners en autoriteiten. Hierdoor zijn steden bezig zichzelf te beschermen tegen de effecten van klimaatverandering, door het toepassen van klimaatadaptieve maatregelen zoals groene infrastructuur (GI).

Studies omtrent wateroverlast door hevige regenval hebben meestal betrekking op de voordelen voor de omgeving en burgerparticipaite. Echter is het beheersen van het overstromingsrisico met het effect van GI niet speciaal onderzocht voor stedelijke gebieden in Nederland. De meeste studies over overstromingsrisico's in Nederland zijn gefocust op overstromingen door rivieren en de zee. Overstroming als gevolg van neerslag is echter het meeste erkende risico voor overstromingen in steden (O'Donnell & Thorne, 2020). Deze scriptie gaat in op zowel de bepaling van het overstromingsrisico in stedelijke gebieden, als het effect van verschillende GI alternatieven op het overstromingsrisico. Door het bestuderen van internationale literatuur kan dit onderzoek de overwogen aspecten combineren en aanpassen om de kans op overstromingen en de effecten van GI alternatieven te bepalen. Het doel van dit onderzoek is om een tool te ontwikkelen die inzicht geeft in het effect van GI alternatieven in relatie tot de bepaling van het overstromingsrisico in stedelijke gebieden. De ontwikkeling van een dergelijke tool kan Nederlandse gemeenten ondersteuning bieden bij de besluitvorming voor ruimtelijke ontwikkeling en om gericht GI alternatieven te ontwerpen om het risico op overstromingen en wateroverlast in stedelijke gebieden te verminderen.

Voordat de tool ontwikkeld kon worden is het kader voor de bepaling van het overstromingsrisico (FFRD) opgesteld. Het FFRD is opgesteld op basis van een analyse van indicatoren die zijn gebruikt in verschillende studies. Het FFRD, weergegeven in Figuur S.2, geeft het functioneren van een gebied in relatie tot het overstromingsrisico weer. De algemene index van het FFRD is het overstromingsrisico (FRL), dat wordt vertegenwoordigd door de categorieën afvoer en capaciteit welke veder zijn onderverdeeld in subcategorieën en indicatoren.

Beginnend bij de linker kant van het FFRD (Figure S.2), is de subcategorie bodemgebruik vertegenwoordigd door de indicatoren gebouwen, vegetatie, verharding en water. De bodemgebruik types zijn vertegenwoordigd door doorlatende en ondoorlatende oppervlakken die een bepaalde hoeveelheid afvoer veroorzaken tijdens zware regenval. Des te meer doorlatend de oppervlakken in de stad, des te minder de oppervlakkige afvoer van regenwater. Naast

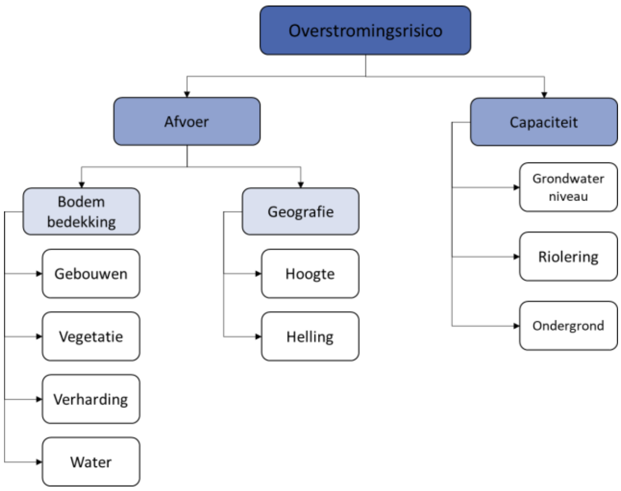

Figure S.2 Kader voor de bepaling van het overstromingsrisico (FFRD) het bodemgebruik wordt de afvoer ook beïnvloed door de geografische indicatoren hoogte en helling. De helling heeft betrekking op de stroomsnelheid van de oppervlakkige afvoer en de helling heeft betrekking op de richting van de oppervlakkige afvoer. Aan de rechter kant van het FFRD (Figure S.2) wordt de categorie capaciteit vertegenwoordigd door de indicatoren grondwater niveau, riolering en ondergrond. De opslag capaciteit van de bodem wordt beïnvloed door het grondwater niveau. De capaciteit van de riolering heeft invloed op de capaciteit om het overstromingsrisico te verminderen en de mogelijkheid tot infiltratie wordt beïnvloed door de ondergrond. Binnen het FFRD zijn de aspecten van GI alternatieven vertegenwoordigd door de indicatoren vegetatie, verharding, hoogte, helling, riolering, en ondergrond.

Op basis van het FFRD is de tool voor beoordeling van het overstromingsrisico (FRAT) ontwikkeld. De tool brengt het FRL in kaart op basis van de bijdrage van ruimtelijke aspecten aan het overstromingsrisico. De FRAT is opgesteld volgens een Multi-Criteria Analyse (MCA) in de vorm van een Analytisch Hiërarchisch Proces (AHP), waarbij gebruik wordt gemaakt van een Geografisch Informatie Systeem (GIS). Om de prestaties van de indicatoren binnen het FFRD aan te geven is zowel gebruik gemaakt van kwantitatieve als kwalitatieve data. Daardoor is bij het bepalen van de scores gebruik gemaakt van directe en proportionele scorebenadering. Aan de indicatoren en categorieën zijn gewichten toegewezen op basis van ervaringen en bevindingen uit de literatuur. De scores en gewichten zijn gecombineerd om het gewogen FRL te bepalen. Daarnaast is het FRL ook bepaald op basis van gelijke gewichten, om zo het effect van de toepassing van de gewichten op de indicatoren en categorieën in kaart te brengen.

De werking van de FRAT werd geïllustreerd aan de hand van een casus van de stad Tilburg. Er werd verwacht dat het stadscentrum van Tilburg een hoger overstromingsrisico zou hebben door de hogere bebouwingsdichtheid dan de omliggende wijken en doordat de centrumgebieden minder gerenoveerde gebieden omvat. Bij toepassing van de nieuw ontwikkelde FRAT werd het verschil duidelijk tussen de scores met gelijke en gewogen gewichten. De algemene werking van de FRAT leverde de verwachte resultaten op en was in staat om het FRL van de stad Tilburg correct te beoordelen. Echter is er nog wel ruimte voor verbetering van de nieuw ontwikkelde FRAT. In de toekomst kan er verder onderzoek verricht worden naar de betrekking van naastgelegen cellen, de gewichten van de indicatoren en categorieën en de ondergrond van GI alternatieven. Hoewel verder onderzoek nodig is heeft dit onderzoek bijgedragen aan de ondersteuning in besluitvorming voor ruimtelijke ontwikkeling met een focus op het overstromingsrisico.

Abstract

Climate change has become a global threat and is putting stress on various sectors, such as the economy and biodiversity. Because of climate change more events of extreme rainfall are occurring, which increases the chances of flooding. In the Netherlands, rainfall events cause water nuisance on local and regional levels. Therefore, cities are preparing themselves to keep up with climate change by implementing adaptation efforts, such as Green Infrastructure (GI) alternatives. This thesis will elaborate on both the determination of the flood risk in urban areas, as well as the effect of GI alternatives on the flood risk. This is achieved through the development of a flood risk assessment tool (FRAT), that incorporates the indicators of the urban flood risk and elements included in GI alternatives. The indicators are included in the framework for flood risk determination (FFRD), which represents the functioning of an area in relation to the flood risk. The overall index of the framework is the Flood Risk Level (FRL), which is represented by the categories of runoff and capacity. The category runoff is further divided into the sub-categories of land cover and geography. The sub-category land cover consists of the indicators building, vegetation, pavement, and water. The sub-category geography consists of the indicators elevation and slope. The other category, capacity, is divided into the indicators groundwater level, sewage system, and soil. Based on the FFRD the FRAT is developed following a multi-criteria analysis (MCA), in the form of an Analytical Hierarchy Process (AHP), while using a Geographical Information System (GIS). The working of the newly developed FRAT was shown in a case study of the city of Tilburg. The newly developed FRAT provides a methodology for the support of decision-making in urban planning, in which different aspects can be evaluated based on their contribution to the FRL. Because the aspects of GI alternatives are also taken into consideration, the FRAT can also clarify the influence of the adaptations that will be made for the implementation of GI alternatives. Thereby, the tool contributes to the understanding of the effect of flood risk when changing urban aspects.

Keywords: flood risk, green infrastructure, assessment

Glossary and Abbreviations

Additional benefits	See 'Co-benefits'.
Alternative	Different options for implementation of grey, green of blue infrastructures.
Analytical Hierarchy Process (AHP)	A well-known full aggregation method, which is widely used for structuring decision problems (Saaty, 1981). The AHP method as originally developed by Saaty (1981) and aims at assessing options through the calculation of a comprehensive score. The AHP seeks to reduce a multi-criteria decision problem to a series of smaller analyses based on the incapability of the human mind for considering too many factors simultaneously.
Blue infrastructure	Urban water bodies, such as ponds, lakes, streams, channels, and stormwater provision. Blue infrastructures have a positive effect on the urban environment, by reducing local temperatures, creating micro-climates, and the reduction of heat island formation in cities (Bellezoni et al., 2021).
Clay	Clay is a soil type that consists of mineral particles and fine flat rock fragments with a grain size of less than 0.002 millimeters (de Vree, n.d.-a).
Climate change adaptation	Adjustments that are made in the urban environment to create a better response to climate change. Thereby, It is anticipated to buffer, infiltrate and delay the drainage of stormwater for the ability to harvest water in periods of drought (Groenblauwe Netwerken, n.d.).
Climate stress test	In Dutch 'Klimaatstresstest'. A practical test that gains insight into the effect of climate change on the urban environment. Through mapping the vulnerability based on climate change aspects, the stress test also visualizes the vulnerable areas within the municipal boundaries based on flooding, water nuisance, heat stress, and drought.
Coastal flooding	Floods caused by sea level rising are referred to as coastal flooding.
Co-benefits	The additional benefits of green infrastructure besides flood risk management, have a positive side-effect on the people and environment of an urban area. With a focus on the environmental, economic, and social benefits.
Criteria-x-criteria matrix	A means to order the criteria in a matrix to perform a pairwise comparison.
Decision-making	Finding an outcome upon a different set of possibilities.
Environmental Act	In Dutch 'Omgevingswet'. Provides the Municipalities and Provinces with the necessary instruments for a comprehensive approach, customization, and better and faster decision-making
Environmental vision	In Dutch 'Omgevingsvisie'. The structural concept of municipalities. Dutch municipalities capture spatial aspects in the form of a structural concept, similar to provinces.
External validation	Validation by comparison to an independent dataset.

Flood hazard	The occurrence of potentially damaging flood events (Schanze, 2006).
Flood risk	The probability and consequences of flooding
Flood risk assessment tool (FRAT)	The developed tool that maps the Flood Risk Level (FRL) based on the contribution of urban aspects to the risk of flooding.
Flood risk determination	Determining the extent to which flood risk occurs.
Flood risk level (FRL)	The overall index indicates the risk of flooding within a specified area. The higher the index, the higher the risk.
Flood risk management (FRM)	The decisions and actions that need to be undertaken to analyze, assess and mitigate the flood risk (Schanze, 2006).
Flood risk mitigation	Diminishing the probability of flooding.
Flood risk probability	The chances of occurrence of pluvial flooding.
Flood risk reduction	See 'Flood risk mitigation'.
Flood vulnerability	The potential to be harmed because of flooding(Schanze, 2006).
Fluvial flooding	Floods caused by river overflow are referred to as fluvial flooding.
Framework for flood risk determination (FFRD)	The established framework that represents the functioning of an area in relation to the flood risk.
Geographical Information System (GIS)	A tool that can be used to examine spatial variation in the dimensions of vulnerability, as well as how these dimensions interact with one another. Thereby, GIS offers a number of advantages for spatial analysis, including data layering, querying, geo-referencing, and visualization (Woodruff et al., 2017).
Green Based Solutions (GBS)	Measures that simulate services provided by the ecosystem (Costa et al., 2021).
Green Infrastructure (GI)	A measure for FRM by its ability to climate change adaptation and mitigation by reducing heatwaves, improving stormwater infiltration, and reducing water nuisance (Choi et al., 2021). Thereby, GI offers a progressive planning approach facilitating environmental conservation, economic growth, and social development (Lennon, 2014).
Grey infrastructure	Traditional stormwater infrastructure that consist of hard engineering structures, such as gutters, drains, sewage pipes, and retention basins (US EPA, 2023).
Heavy rainfall	An enlarged amount of precipitation that affects health, livability, and the economy (Rijksoverheid, 2021a). Heavy rainfall during a short period primarily enlarges the chances of water nuisance in urban areas, while heavy rainfall during a long period primarily enlarges the chances of water nuisance in rural areas (Kennisportaal Klimaatadaptatie, n.d.-c).
Imperviousness	The extent to which a surface is not permeable.
Indicator	Factors affecting the flood risk probability.
Land-use plan	In Dutch 'Bestemmingsplan'. Considers the eventual spatial developments of the local water systems and points out

	destinations as water storage. These developments are illustrated on a map or included as policy statements
Loess	Loess is a soil type that is redundant from deposition and concerns a very fine-grained soil type from which the larger part of the grains is smaller than 0.063 millimeters. It is a sort of very fine sand with a high degree of chalk particles (de Vree, n.d.-b).
Minister of Economics and Climate	In Dutch 'Minister van Economische zaken en klimaat'. Part of the Dutch Ministry.
Minister of Infrastructure and Waterworks	In Dutch 'Minister van Infrastructuur en Waterstaat'. Part of the Dutch Ministry.
Multi-criteria Analysis (MCA)	An overarching term for different methodologies and techniques by which multiple objectives and decision criteria can be formally incorporated into the analysis of a problem (Dean, 2022).
National water management plan	In Dutch 'Nationaal waterplan'. See 'Operational management plan'.
Natural elements	Essential components of urban green infrastructure, such as plants, water, and soil, can be structured in a wide variety of forms (Hanna et al., 2021)
Natural flood response	The natural processes to defend, recover, and simulate the initial functioning of floodplains.
Natural processes	The natural system is recreated by the natural elements in green infrastructure alternatives (Green et al., 2021).
Nature Based Solutions (NBS)	Similar to Green Based Solutions, however, NBS can also contain other natural elements (such as water elements) instead of only green elements.
Non-structural measures	Cover warning and evacuation preparedness, land-use plan, and recovery (non-tangible measures)
Operational management plan	In Dutch 'Beheerplan'. Specifies the strategic targets for the practice of the state. For the state, this is done in the national water management plans, and for the provinces, this is done in the regional water management plans, these plans represent the national and regional strategic water policy.
Pairwise comparison	An indicator weight vector is made to present the relative importance of different indicators to the evaluation objective.
Pareto model	Also known as the 80/20-model, which illustrates the decrease of the effect with the increase in quantity.
Peat	Peat is a soil type that mainly consists of faded and carbonized residues of plants and trees, also considered organic matter, with a moisture content of at least 75% (de Vree, n.d.-c).
Pluvial flooding	Floods caused by rainfall are referred to as pluvial flooding.
Policy framework	In Dutch 'Beleidskader'.
Precipitation	Rainfall.
Rainwater policy	In Dutch 'Hemelwaterbeleid'.
Regional water management plan	In Dutch 'Regionaal waterplan'. Is established per province and captures the main lines of the water policy per province and the additional aspects of the provincial spatial policy

Resilience	The ability of an urban area to absorb, mitigate, and adapt to changes (in this context climate change), and to withstand an extreme event without undergoing considerable change, or quickly recovering from the disturbance state (Fu et al., 2021).
Risk analysis	Analysis task in the flood risk management process for the provision of knowledge about current, previous, and future flood risks (Schanze, 2006).
Risk assessment	Assessment task in the flood risk management process deals with the perception and evaluation of flood risk (Schanze, 2006).
Risk reduction	A task in the flood risk management process is seeking for the potential to reduce the risks of flooding (Schanze, 2006).
Sand	Sand is a soil type, that is considered to be a loose and grainy matter that is distinct from the erosion of rock formations. Different types of sand can be considered based on the size and distribution of the grain (de Vree, n.d.-d).
Structural concept	In Dutch 'Structuurvisie'. Gives meaning to an improved coherence between water and spatial planning.
Structural measures	Structural measures range from hard-engineering structures to natural measures (tangible measures).
Urban Water Buffer (UWB)	A new initiative to provide a solution to both water abundance as well as water shortage in urban areas, which enables the retention of stormwater runoff in urban areas in water-bearing layers of sand deep in the ground (Dooren & Boer, 2020).
Urban water management	In Dutch 'Stedelijke wateropgave'. The duty of care for Dutch municipalities for stormwater runoff and groundwater is determined in the 'Gemeentelijk rioleringsplan (GRP)'.
Water abundance	Excess amount of water.
Water Act	In Dutch 'Waterwet'. Gives the legal basis for the planning system in terms of water management.
Water Guide	In Dutch 'Handboek Water', also referred to as the 'Handboek wet- en regelgeving waterbeheer'. A manual that is established to make the contents of legislation and regulation of water management insightful for practice.
Water maintenance program	In Dutch 'Waterbeheerprogramma'. Outlines the vision and ambitions of every water board in the long term.
Water management plan	In Dutch 'Waterbeheerplan'. See 'Operational management plan'
Water nuisance	Disturbance by an excess amount of water.
Water regulations	In Dutch 'Waterverordeningen'. The standards, obligations, and enforcement of water management are included per province.
Water shortage	Limited amount of water available compared to the necessary amount.
Water test	In Dutch 'Watertoets'. Test for the consideration of spatial aspects that are included in the land-use plan, for which one of the water managers is included in the preparations.

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1. Introduction

The climate is changing which puts stress on urban areas in the form of more events of extreme rainfall, heatwaves, and longer periods of drought resulting in increased chances of flooding, health effects for vulnerable citizens, and declining soil levels. This research focusses on one of these phenomena of climate change through assessing the flood risk in urban areas. Additionally, this research takes into account the effect of green infrastructure alternatives on flood risk reduction.

This chapter starts by explaining the research context of this thesis (Section 1.1), followed by the associated problem definition (Section 1.2). From the problem definition, the main research question and sub-questions arise (Section 1.3). This is followed by the research relevance (Section 1.4) and research design (Section 1.5). Finally, a reading guide is presented for the layout of the thesis (Section 1.6).

1.1 Research context

Climate change has become a global threat and is putting stress on various sectors, such as the biodiversity (Abbass et al., 2022). Heat, drought, and heavy rainfall are affecting the health, livability, and economy of many countries (Rijksoverheid, 2021a). Making cities and human settlements safe, inclusive, resilient, and sustainable has attracted increased attention from both researchers and practitioners in urban planning (Fu et al., 2021). Because of climate change more events of extreme rainfall are occurring. With increased amounts of precipitation the chances of flooding are increasing (Rijksoverheid, 2021a).

In the Netherlands, the annual amount of rainfall has increased by 21% from 1906 until 2020. This increase is mostly due to more intense rainfall events. Global warming raises the volume of moisture in the air, increasing the amount of precipitation. Heavy rainfall during a short period primarily enlarges the chances of water nuisance in urban areas, while heavy rainfall during a long period primarily enlarges the chances of water nuisance in rural areas (Kennisportaal Klimaatadaptatie, n.d.-c).

The Netherlands has to deal with annual flooding throughout multiple places in the country, that are occurring repeatedly. Rainfall events can cause water nuisance on local and regional levels, with the possibility to result in damages and disturbances for residents and authorities in the affected areas. At the beginning of the summer of 2020, the Southern and Western parts of the country had to deal with heavy rainfall, which led to considerable nuisance. The water in cities, such as Helmond, could not be discharged through the sewage systems, which led to water disturbance on the streets and water running into buildings (RTL Nieuws, 2020). In August 2021 the province of Friesland was affected by heavy rainfall, causing floodings in Woudsend and Heerenveen amongst others. The water intruded on multiple houses and business properties, and similarly to the water nuisance in Helmond, the sewer system in Heerenveen could not discharge the water from the streets anymore (Omrop Fryslân, 2021). From annual events of flooding that are occurring throughout the country, it is noticed that the sewage system alone cannot process the increasing amount of precipitation. Thereby, the sewage system entirely consists of grey infrastructure elements and does not provide additional benefits to the effects of climate change.

The news items of floods annually occurring in the Netherlands have triggered to start this research. This research is set up with the intention of guiding local Dutch authorities to reduce the risk of flooding when heavy rainfall events occur in urban areas. The implementation of Green Infrastructure (GI) could help urban areas to increase the number of pervious surfaces, improve the drainage of stormwater during intense rainfall events, and keep stormwater in the catchment for reclamation in periods of drought (Groenblauwe Netwerken, n.d.). For a better response to climate change, it is anticipated to buffer, infiltrate and delay the drainage of stormwater for the ability to harvest water in periods of drought (Groenblauwe Netwerken, n.d.). This anticipation will decrease the flood risk probability.

1.1.1 Flood risk in urban areas

Cities are preparing themselves to keep up with climate change by implementing adaptation efforts. However, no city can completely protect itself from unforeseen risks or disasters. Through applying adaptation measures cities become more resilient and less vulnerable. The concept of urban resilience enables cities to prepare for disasters and unexpected events caused by climate change conditions (Büyüközkan et al., 2022). Urban resilience refers to the capability of the social-ecological system of a city to absorb, mitigate, and adapt to these changes, and to overcome extreme events on its own (Fu et al., 2021).

Examining the resilience of cities against disasters and unexpected events has become important for researchers, policymakers, and urban planners dealing with the management and planning of actions before and after extreme weather events occur. For these experts, it is important to get a better understanding of approaches in Flood Risk Management (FRM) (Sajjad et al., 2021). When looking at extreme weather situations, a common measure to deal with FRM is the use of GI alternatives. GI can be defined in various ways. In general it concerns the use of natural processes to defend, recover, and simulate the initial functioning of floodplains, and aims to enlarge, restore, and recreate a more natural flood response (Green, et al., 2021). Thereby, GI alternatives are appreciated for reducing the risk of flooding, improving water quality, harvesting stormwater for potential future use, and the reduction of the damages caused by flooding. To enhance sustainable development and urban resilience GI can be an important part of urban planning strategies (Fu et al., 2021).

1.1.2 Adaptation in the Netherlands

Municipalities and Provinces in the Netherlands are implementing adaptation efforts to restrain the negative impacts of climate change (RIVM, n.d.). To simplify the implementation of climate adaptation and to make it a more ordinary subject in environmental plans, the matter of climate adaptation has been included in the Environmental Act. This Dutch Environmental Act provides the Municipalities and Provinces with the necessary instruments for a comprehensive approach, customization, and better and faster decision-making (Kennisportaal Klimaatadaptatie, n.d.-a).

A solution to reduce heatwaves, stormwater infiltration, and water nuisance is the implementation of GI in urban areas. The use of GI in cities is a means for urban planners in the Netherlands to help reach their aim to buffer, infiltrate, and delay stormwater runoff on-site. However, this has only been applied to newly developed neighborhoods and in a couple of revived neighborhoods. In the center parts of cities, the stormwater runoff is still mainly discharged via the sewage system. This takes place via combined sewage systems (essentially in old urban areas), dual systems, or improved dual systems (Groenblauwe Netwerken, n.d.). Various Dutch municipalities and regions are already implementing GI alternatives to deal with FRM, however, one does this more explicitly than the other. A variety of municipalities are concerned with projects and initiatives implementing GI alternatives on behalf of climate adaptation (Kennisportaal Klimaatadaptatie, n.d.-b). According to Bos (2022), the implementation of green is a lot of times the first measure that is excluded from development projects because of budget issues. The implementation of GI asks for space and therefore the implementation costs money. In addition, there is no norm for GI implementation which allows for it to get tucked away. To enlarge the actual implementation of green in urban areas, the focus should be on the benefits of green to increase awareness of the implementation of green in urban areas (Bos, 2022). The extent to which GI is applied in the context of FRM in urban areas is unclear. For the implementation of GI alternatives and to raise awareness of their effect on mitigating the pluvial flood risk, it is necessary to generate an overview of urban areas with enhanced flood risk. Considering the aspects in urban areas that could be adapted to decrease the flood risk in such an overview would indicate, in a simple manner, why certain locations have an enhanced flood risk.

1.2 Problem definition

The growth of cities leads to changes in the hydrological cycle of cities, particularly with the expansion of impervious areas which reduces the interception, storage, and infiltration capacity of rainwater (Costa et al., 2021). With the challenge of urban flooding which is expected to aggravate due to more intense rainfall, many cities are rethinking their approach to Flood Risk Management (FRM) (Green et al., 2021). Green Infrastructure (GI) is recognized as a promising measure for FRM of its ability for climate change adaptation and mitigation by reducing heatwaves, improving stormwater infiltration, and reducing water nuisance (Choi et al., 2021). Thereby, GI offers a progressive planning approach facilitating environmental conservation, economic growth, and social development (Lennon, 2014).

Looking into the literature about flood risk probability including the effects of GI alternatives, it was found that studies primarily focus on climate/environmental, economic, and social benefits. Studies assessing the effectiveness of GI based on environmental benefits mainly focus on the reduction in peak flow, runoff, flood volume, inundation area, and hazard level (Costa et al., 2021). Assessments of economic benefits are using indicators such as the costs of construction, maintenance costs, and creation of green employment (Fu et al., 2021). The social benefits focus on the future social conditions concerning social capital and public issues (Thorne et al., 2018).

When focusing on pluvial flooding studies mostly concern the environmental benefits or citizen participation. However, FRM including the effects of GI has not particularly been researched for Dutch urban areas, as most FRM studies in the Netherlands are focusing on fluvial and coastal flooding. However, at the moment pluvial flooding is the most commonly recognized risk for urban flooding events (O’Donnell & Thorne, 2020). One of the few examples of Dutch research that focused on pluvial flooding is the research of Costa et al. (2021), which evaluated the effects of different nature-based solutions on urban flood mitigation for the city of Eindhoven in the Netherlands. However, their study only focused on the effects of nature-based solutions on flood extent, water depth, and flow velocity, without focusing on the determination of the flood risk probability of the whole urban area. This thesis will elaborate on both the determination of the flood risk in urban areas, as well as the effect GI alternatives have on the flood risk. Through the review of international literature, this research can adapt and combine the aspects considered to assess the flood risk probability and the effects of GI alternatives.

Currently, there is no Dutch methodology available that expresses the flood risk probability including the effects of GI on flood risk reduction. Such a methodology could help urban planners and policy makers in the decision-making process. Dutch municipalities are often not considering the overall flood risk in the city and the effect of adjustments that are made to the urban area. In other words, there is a need for a tool or methodology which allows for the determination of the level of flood risk and also that could express the contribution of GI concerning flood risk reduction. In order to design this tool, a better understanding indicators contributing to the flood risk level and the effect of GI on flood risk reduction is needed. The development of such a tool would provide local Dutch authorities with the support of decision-making in urban planning, in which GI implementation can be evaluated in terms of FRM.

1.3 Research question(s)

The defined problem in the previous section leads to the following research questions.

Main research question:

How can a tool be developed that gains insight into the contribution of green infrastructure in relation to flood risk determination in Dutch urban areas?

Sub-questions:

- *I. What is green infrastructure and how does it affect the flood risk probability in urban areas?*
- *II. What indicators affect the flood risk level and how can these be quantified in terms of scores and weights?*
- *III. How can the effect of green infrastructure on the reduction of flood risk probability be implemented in a tool?*

1.4 Research relevance

There is a need for insight into flood risk probability because more extreme rainfall events are putting stress on Dutch urban environments. Insight into the flood risk within an urban area could help municipalities in the decision-making process of urban planning. Additionally, the effect of Green infrastructure (GI) is taken into account for the food risk determination. GI in the Netherlands has mostly been implemented in newly developed neighborhoods and revived neighborhoods. However, research about the effect of GI on flood risk reduction in the Dutch context is relatively limited. This research contributes to scientific research by adding a literature review that considers various aspects affecting flood risk probability in urban areas and the effect of GI alternatives on flood risk reduction. The approach that translates the findings from the literature review to a flood risk assessment tool (FRAT) also contributes to scientific publication and can act as a basis for future research. Thereby, the tool presented in this research can be used to support local Dutch authorities in decision-making for urban (green) planning and to formulate targeted GI alternatives to reduce the risk of pluvial flooding in urban areas. Through the development of a FRAT, this thesis contributes to filling the gap in knowledge, were urban planners and policy makers can be supported in decision-making when certain locations have an enhanced risk of flooding.

1.5 Research design

The research will be carried out in nine steps. After defining the problem statement and research questions, the findings of a literature review will be presented. This literature study involves the subjects of flood risk management (1), and green infrastructure (2). The literature review is extended by a study assessing available methods and their application (3), performance indicators (4), and composing a framework based on the concerned indicators (5). The steps of the literature review will operate as a basis to define the methodology included in the tool (6), which is followed by the development of the tool (7). After the seventh step, the tool is applied in a case study (8). Finally, the conclusion of the study and recommendations for future research will be drawn (9).

This results in the following five phases of the study, consisting of nine steps and the research model shown in Figure 1.1.

Phase I: Literature review

1. Literature review on green infrastructure
2. Literature review on urban flood risk management

Phase II: Literature review (extension)

3. Literature study on the available methods for Green Infrastructure performance
4. Literature study on GI performance indicators
5. Composing a theoretical framework based on the concerned indicators

Phase III: Methodology

6. Defining the methodology of the tool
7. Development of the tool based on the theoretical framework

Phase IV: Application

8. The working of the tool is illustrated using a case study

Phase V: Conclusion and recommendations

9. Conclusion and recommendations

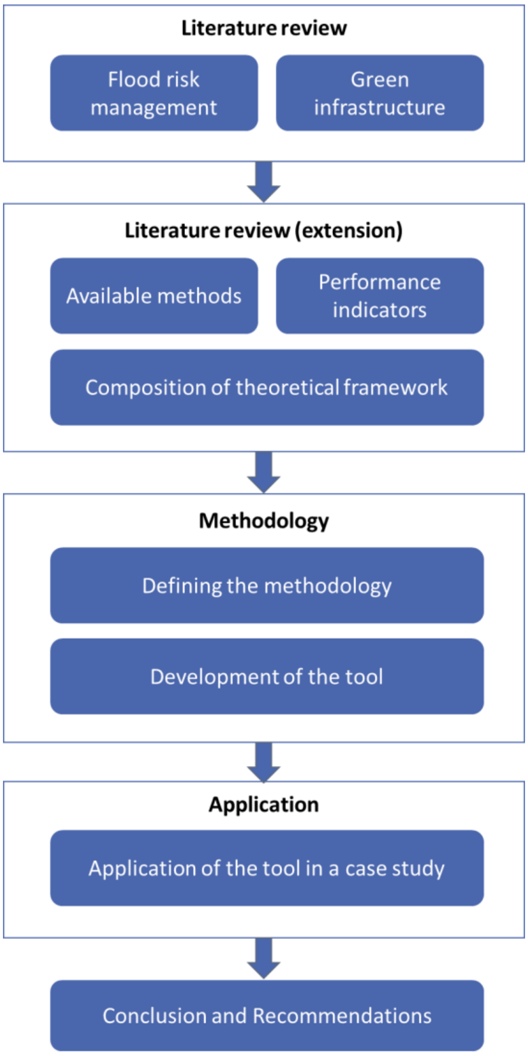


Figure 1.1 Research model

1.6 Reading guide

This research is structured as follows. In Chapter 2 the findings of the literature review and the extended literature review are presented, examining subjects relevant to this research. Then, Chapter 3 describes the methodology and the development of the tool. Hereafter, the tool will be applied in a case study and the tool will be validated in Chapter 4. Finally, the conclusion and recommendations will be drawn in Chapter 5.

2. Literature review

This chapter seeks to establish a foundation on which this work intends to build on and represents a review of the existing literature on green infrastructure in relation to flood risk management.

The chapter starts with explaining the concept of urban flood risk management (Section 2.1) and green infrastructure alternatives (Section 2.2). These sections are followed by a description of the effects of green infrastructure on flood risk determination (Section 2.3). Finally, the policy in the Netherlands and the municipal responsibilities regarding flood risk management are explained (Section 2.4). Finally, conclusions will be drawn (Section 2.5).

2.1 Flood risk management

To human societies, floods are one of the most threatening natural hazards. Floods temporarily cover parts of land with water that are normally not covered by water (Fratini et al., 2012; Schanze, 2006). Urban areas can be threatened by different sources of flooding: the rising sea level, rivers that drain vast hinterlands, and intense rainfall which cannot be drained from the catchment due to the high level of impervious areas (de Almeida et al., 2018; Klijn et al., 2015).

Flooding events in urban areas are one of the key global challenges of this century, also with the enhanced future flood risk through more intense rainfall, urbanization, and aging (water-based) infrastructure. Flood risks are further intensified by increased urbanization, as 68% of the world's population is expected to reside in cities by 2050, which probably reduces permeable green spaces and builds on floodplains. This makes urban environments particularly vulnerable to flooding events driven by intense rainfall (O'Donnell & Thorne, 2020).

More frequent and extensive floods are inevitable. Therefore, the appearance of flooding in designated areas has been increasingly accepted by urban planners and policy makers (da Silva et al., 2020). Floods involve risks, if floods cover parts of land with water that are normally not covered by water it can harm the urban system including the residents. Risks emerge from the complexity of flood hazards and flood vulnerability (Schanze, 2006). The term flood risk is determined based on the probability of flooding and the consequences of flooding (Klijn et al., 2015). Flood hazard is defined as the occurrence of potentially damaging flood events (Schanze, 2006). Flood events can cause damage to exposed elements, such as infrastructural elements or buildings. The actual damage by flood hazards depends on the vulnerability of exposed elements. The term vulnerability refers to the potential of elements to be harmed. Social and cultural, economic, and ecological vulnerability are three basic areas of flood vulnerability that are distinguished based on the principle of sustainability (Schanze, 2006).

Complete protection against flooding is considered unachievable, due to the nature of high costs and inherent uncertainties. Instead, managing the risks of flooding has been recommended to be more sustainable (Schanze, 2006). Flood Risk Management (FRM) can be defined as the decisions and actions that need to be undertaken to analyze, assess and mitigate the flood risk (Schanze, 2006). In general, FRM covers the procedures for preparing quantitative and qualitative estimates, so that the results include both the probability of the occurrence of the hazardous event as well as an assessment of their consequences (da Silva et al., 2020). FRM deals with a wide variety of tasks and issues, and due to this variety of aspects management of flood risks needs systematization and integration (Schanze, 2006).

Integrated FRM approaches help in decreasing flood damage in urban areas, through combining structural and non-structural measures. Where structural measures range from hard-engineering structures, such as sewage systems, to natural structures like trees that are tangible, non-structural measures cover non-tangible measures, such as warning and evacuation, preparedness, and land-use plans (Ishiwatari, 2016). Considering the complexity of urban flood risk management and the adaptation of urban areas to climate change a combination of underground and above-ground measures is required. Apart from this, engineers need to look further than the sole technical relation among system components and should also take into account uncertainties generated by the influence of nature and society. Nature and society are considered 'ever-changing surroundings' and therefore create uncertainties and complexity to which water management strategies should be adapted (Fratini et al., 2012). Traditionally, FRM has only been focusing on reducing the occurrence of potentially damaging flood events. However, policymakers, practitioners, and scientists have been challenged to develop adaptive flood mitigation measures such as retention basins, as a result of climate change and rapid urbanization. These days the likelihood of adopting and implementing measures that reduce flood hazard, vulnerability, and exposure opens up a wide range of new opportunities for flood risk mitigation that have the potential to considerably reduce the impacts of intense rainfall events and have not been explored yet (de Almeida et al., 2018). Therefore, FRM depends on the rules, regulations, policies, and implementations that aim to reduce the risk of flooding, but it also relies on how individuals react to those aspects and adapt their behavior (Abebe et al., 2018).

Rethinking current FRM policies and practices at different spatiotemporal scales is required to reverse the trend of increasing flood risks in urban areas. By taking advantage of interventions at different spatial scales, urban flood risks can be proactively managed through resilience (Zevenbergen et al., 2008). Schanze (2006) has specified a basic FRM framework in which three main tasks with specific components can be used for structuring the management activities of flood risk management. This proposed framework is based on FRM with the definition of a holistic and continuous societal analysis, assessment, and reduction of flood risk. The main tasks of the basic framework include risk analysis, risk assessment, and risk reduction as can be seen in Figure 2.1. The risk analysis provides knowledge about current, previous, and future flood risks, the risk assessment deals with the perception and evaluation of flood risk, and the risk reduction is seeking potentials to reduce the risks at different moments in time. Each of these tasks is supported by multiple components to achieve the aim of each task (Schanze, 2006).

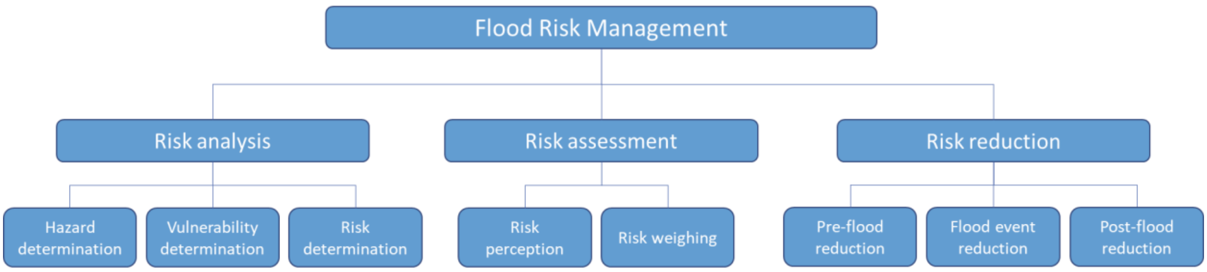


Figure 2.1 Tasks and components of flood risk management adapted from Schanze (2006)

Considering the FRM framework of Schanze (2006), the current study contributes to the flood risk assessment task. The purpose of this research is to identify the occurrence of flooding events. Therefore, the risk perception is based on the potential of flood hazards, without including the flood vulnerability. This contribution is mainly through the identification of the flood risk perception, based on the flood risk probability in Dutch urban areas. Additionally, this study takes into account the pre-flood risk reduction, based on the consideration of different urban planning aspects and their contribution to the flood risk level. The consideration of these aspects helps to identify which aspects could be altered in a certain location to reduce the risk of flooding.

2.1.1 Measures affecting flood risk probability

A possibility when performing the flood risk assessment is that risks are assessed as not tolerable, meaning that the flood risk probability is too high. In this case, measures are applied to reduce the risk of flooding (Schanze, 2006). New approaches in flood risk reduction are shifting from traditional strategies using built infrastructure (grey infrastructure) to multi-functional and distributed efforts that contribute to an increased ecosystem resilience and help restore the hydrological cycle (Alves, Gersonius, et al., 2018). Different strategies affect the flood risk probability in urban areas. The strategies consider grey, green, and blue infrastructure alternatives. Each of these alternatives will be further elaborated on below.

Flood management was traditionally focused on the grey solution, such as sewage pipes. Grey infrastructure alternatives have the strength of reliability to cope with moderate rainfall events and are thoroughly tested. Likewise, these measures offer opportunities for methods of design and high acceptability. However, grey infrastructure alternatives have the weakness of being single-oriented towards FRM, without providing adaptability for future changes (Alves, Gersonius, et al., 2018). Nowadays, it is understood that this approach offers low sustainability to urban areas, while green and blue infrastructure alternatives provide numerous complementary benefits. Compared to green and blue infrastructure alternatives, grey infrastructure alternatives only appear to be feasible when co-benefits are not taken into account. Meaning the performance of grey infrastructure is solely focused on reducing the risk of flooding and does not bring any additional benefits, that can be offered by green or blue infrastructure alternatives (Alves et al., 2019).

Green infrastructure alternatives make use of natural processes to deal with excess runoff, and at the same time offer multiple benefits and improve the adaptability of the urban area. Above-ground green infrastructure alternatives are effective to cope with extreme events, other options such as infiltration-based alternatives, are less reliable in rainfall events with a medium to high return period. Additionally, green infrastructure applicability depends strongly on local characteristics such as soil conditions and slope (Alves, Gersonius, et al., 2018). Thereby, it is important to take into account the additional benefits of green infrastructure alternatives when identifying strategies to improve urban FRM, or else green infrastructure is likely to become less efficient than conventional grey infrastructure (Alves et al., 2019). As this study focusses on green infrastructure as a flood risk measure Section 2.2 further elaborates on green infrastructure.

Blue infrastructures are urban water bodies, such as ponds, lakes, streams, channels, and stormwater provision. Blue infrastructures have a positive effect on the urban environment, by reducing local temperatures, creating micro-climates, and the reduction of heat island formation in cities (Bellezoni et al., 2021). Additionally, this type of infrastructure enables the purification of wastewater and serves for flood protection and rainwater management. In recent years, urban planners have started to associate blue with green infrastructures to enhance their attractiveness and deal with environmental challenges more efficiently (Iojă et al., 2021).

2.1.2 Initiatives in urban areas

Most parts of urban areas consist of roads, car parks, squares, buildings, and other types of impervious surfaces. The amount of impervious areas reduces the interception, storage, and infiltration capacity of rainwater (Costa et al., 2021). The rain that falls onto these surfaces can only partially be absorbed into the ground, and the rest of the rainwater runoff will be led into the sewage systems. However, when the rainfall becomes more intense the sewage system alone is not always able to handle all this runoff, leading to water nuisance in the city. With the challenge of water nuisance in urban areas, which is expected to aggravate due to more intense rainfall, many cities are rethinking their approach to Flood Risk Management (FRM) (Green et al., 2021). It is not beneficial to keep enlarging the capacity of sewage systems, and thereby the sewage system is considered a grey infrastructure that does not add any additional benefits to the urban area. For this reason, initiatives are appearing throughout the country, a couple of initiatives regarding the storage and infiltration of stormwater will be further elaborated on below.

A broad consortium of knowledge institutes, engineering consultancies, suppliers, governmental bodies, and end-users have been working on a new initiative to provide a solution to both water abundance as well as water shortage in urban areas. Dooren & Boer (2020) came up with the Urban Waterbuffer (UWB), which enables the retention of stormwater runoff in urban areas in water-bearing layers of sand deep in the ground. Eventually, when there is a water demand the water can be reclaimed from the deep layers so it can be reused. The UWB consists of multiple components. When it rains the runoff water will be captured, leading the stormwater to underground tubes to retain and filter the water so it can be purified by using plants. After this, the tubes discharge the water to the deeper layers of sand in which the water is stored, from which the water can be reclaimed via installed wells for reuse of water. This project is still in development and experiments are set up to test the applicability of the UWB in urban areas (Dooren & Boer, 2020).

Another example can be found in the city of The Hague, where infiltration crates have been realized as a basement of newly developed buildings, for example in the Cannenburglaan as shown in Figure 2.2. The infiltration basement that was realized serves as a buffer for an extensive amount of water. The total amount of water can be stored during heavy rainfall events, which buffers the water before it infiltrates into the ground. So, after the heavy rainfall event, the stormwater that was buffered in the crates can slowly infiltrate into the ground (Tukker, 2017). Aside from the positive effect of infiltration crates, this initiative also has its limitations. Examples of these limitations are the need for regular maintenance, investment costs, and the need for additional measures to prevent the crates from clogging (Waterbewust Bouwen, n.d.).


Figure 2.2 Infiltration crates as a basement at the Cannenburglaan (Kennisportaal Klimaatadaptatie, n.d.-b)

Residents in some municipalities are activated to participate in the initiative to incorporate more green on their private property. Less paving in the garden and urban areas especially has the advantage that there is the possibility for rainwater to be absorbed into the ground. The use of vegetation as surface coverage improves the surface's infiltration capacity, by increasing the porosity of the ground and keeping the soil from becoming dry. Dry soil does not infiltrate water as easily as hydrated soil, so more water would run off. Additionally, small areas of green affect the urban microclimate (Gemeente Zwijndrecht, 2021). The municipality of Breda also stimulates the incorporation of green on private property through the provision of rewards. Therefore, a special regulation is set up to stimulate measures on private properties that are of effect for the infiltration or retention of rainwater, stimulation of the biodiversity, recovery of the hydrological cycle, or the temperature or air quality due to the character of the green that is added. This regulation applies to green roofs, green facades, the greening of gardens, and attaching pavement or roof runoff to the rainwater sewage system (Gemeente Breda, 2022). In the next section, the contribution and benefits of GI will be further elaborated on.

2.1.3 Existing flood risk management approaches

When looking into the existing approaches for the understanding of flood risk and the effect of GI on flood risk, it is noticed that a diverse range of approaches and maps are available. It has come to the attention that maps indicating the flood risk are mostly based on computer-simulated models that emphasize the flood risk as the water depth that occurs when a certain rainfall event takes place.

One of these maps is the flood risk map indicating the water depth that can be found at the ’Klimaateffectatlas’ and is facilitated by Deltares & ROR (2018). This map indicates the water depth throughout the Netherlands, based on a computer simulation of a heavy rainfall event with an intensity of 70 or 140 millimeters and a duration of two hours. A couple of principles were used for the simulation, including sewage system capacity, superficial runoff, infiltration, and elevation (Deltares & ROR, 2018).

Sometimes municipalities take the matter of determining the flood risk into their own hands. Such as the municipality of Eindhoven, which developed a climate atlas combining the climate stress test, sewage system plan, and the water vision map (Gemeente Eindhoven, n.d.). Looking into the climate effect of heavy rainfall the municipality of Eindhoven has simulated the consequences of multiple rainfall events, which maps vulnerable locations for water nuisance (see Figure 2.3). Additionally, the municipality has also anticipated heatwaves and drought (Gemeente Eindhoven, n.d.).

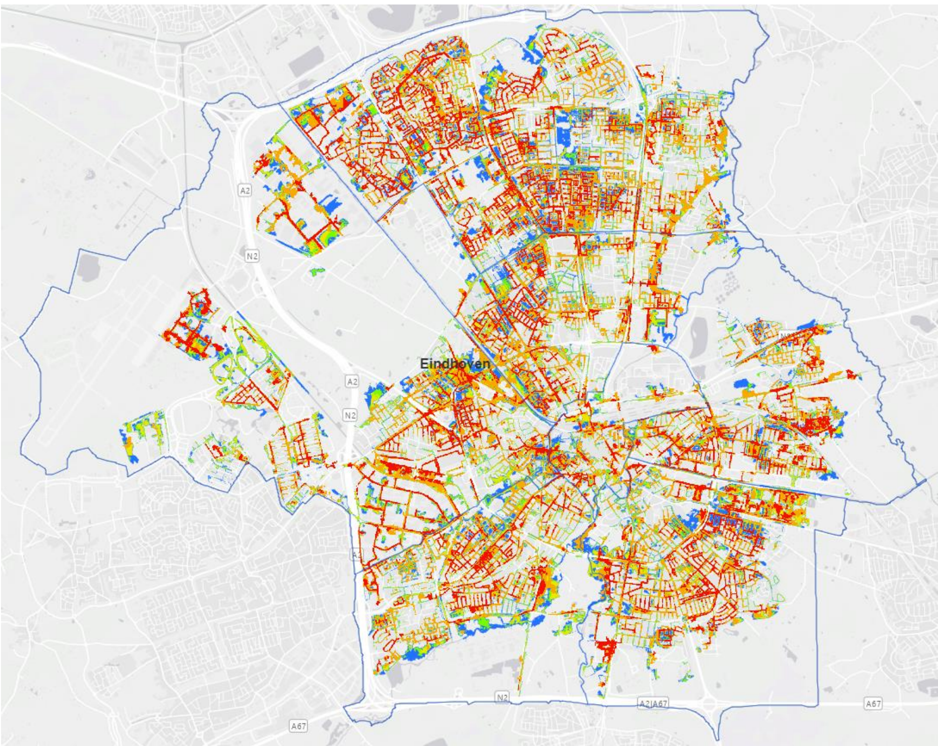


Figure 2.3 Vulnerable locations for water nuisance in Eindhoven (Gemeente Eindhoven, n.d.)

A different tool is the Climate Resilient City Tool, developed by Deltares. This is an interactive tool that shows the effectiveness of different climate adaptation measures in a certain location. The tool of Deltares allows for informing urban designers and water managers on different adaptation measures and where these measures can be implemented. The tool thereby focusses on support in the exploratory and conceptual phases. After it has been tested where problems are to be expected in a risk analysis, this tool helps to decide on the type of adaptation measure and the location (Deltares, n.d.).

2.2 Green Infrastructure

Green Infrastructure (GI) can be considered as a strategically designed and managed network of natural and semi-natural areas, which delivers ecosystem services of a broad spectrum and strengthens human well-being (Chatzimentor et al., 2020). However, the interpretation of the concept of GI varies among different studies. According to Lennon (2014), the different interpretations of GI have a common belief in the ability and necessity of planning, designing, constructing, and managing nature to address desired benefits from particular environmental assets. GI is commonly understood as a network consisting of the combination of natural and engineered elements intended to obtain climate change adaptation and/or urban growth management (Lennon, 2014; Staddon et al., 2018).

Instead of GI, some studies make use of different terms, such as Sustainable Drainage Systems, Green Based Solutions, or Low Impact Development, among many others. Sustainable Drainage Systems are installations for stormwater management based on natural hydrological processes, which are often utilized by vegetated land surfaces (Hoang & Fenner, 2015). Green Based Solutions (GBS), or similar Nature Based Solutions (NBS) are alternatives that simulate services provided by the ecosystem (Costa et al., 2021). A difference in terminology is made between GBS and NBS, as NBS can also contain other natural elements (such as water elements) instead of only green elements. Low Impact Developments are environmentally sustainable techniques that are designed to reduce runoff quantity and improve runoff quality from a natural and aesthetic perspective (Raei et al., 2019). All of these terms are more specified within the broad perspective of GI, as GI concerns a hybrid network of natural, semi-natural, and engineered features in urban areas planned to provide multiple ecosystem services and benefits (Choi et al., 2021). In this research, the term GI is used based on its comprehensive interpretation and a clear focus on the use of green.

Natural elements are essential components of urban GI, which can be structured in a wide variety of forms (Hanna et al., 2021). Alternatives of GI can range from trees to forests, swales, rain gardens, green roofs, wetlands, retention ponds, detention basins, rainwater storage, permeable paving, or other pervious surfaces (Staddon et al., 2018). GI can provide opportunities for urban sustainable development by, among others, providing shade to hard surfaces, reducing heat, slowing down rainfall and water surges through vegetation installation, and increasing pervious surfaces which can absorb or infiltrate rainwater (Parker & de Baro, 2019). A representation of the continuum from grey to green infrastructure is shown in Figure 2.4.

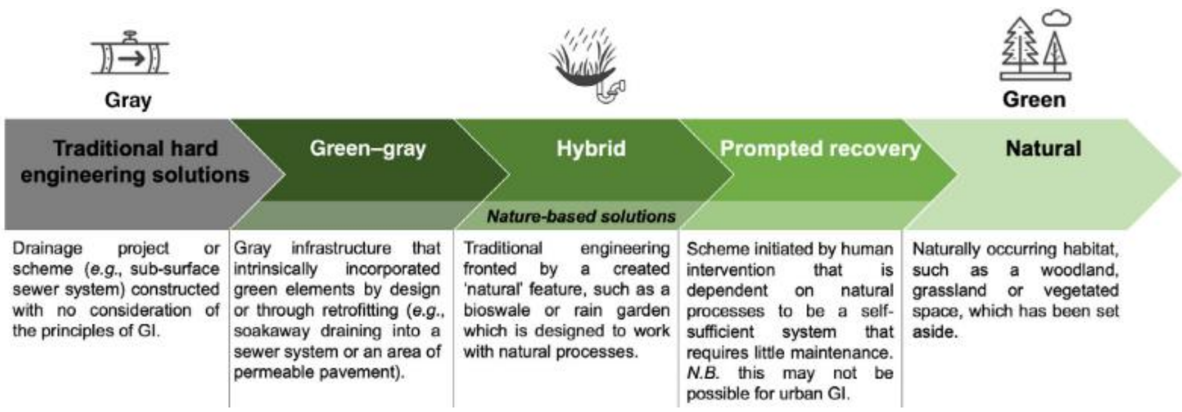


Figure 2.4 Green-grey framework for adaptive measure implementation (Green et al., 2021)

As an adaptation measure, GI contributes to ecological, social, and economic benefits, leading to the achievement of sustainable, resilient, inclusive, and competitive urban areas (Monteiro et al., 2020). Many studies have identified GI as an important urban planning measure to satisfy the needs of people living in urban areas, throughout the benefits of GI to climate change adaptation in urban areas (Sturiale & Scuderi, 2019). Thereby, it provides a natural life support system for the regional environment by securing an ecological foundation for sustainable development in urban areas (Ying et al., 2021), in which GI is considered a key strategy (Hanna et al., 2021; J. Wang & Banzhaf, 2018; Ying et al., 2021). The implementation of GI alternatives creates opportunities for a connection between urban development, nature conservation, and public health and wellbeing (Tzoulas et al., 2007). Urban GI design, provision, maintenance, conservation, and restoration are recognized as critical components for urban sustainability. Therefore, the network of GI and its distribution in urban areas are important aspects of urban planning (Hanna et al., 2021).

2.2.1 GI and aspects of sustainable development

As mentioned the implementation of green in urban areas contributes to several aspects of sustainable development in cities. These aspects consider the effect of GI on stormwater management, heat islands, ecological, and social aspects. Below each of these aspects will be elaborated on.

GI uses natural processes to defend, recover, and simulate the initial functioning of floodplains. Thereby, GI aims to enlarge, restore, and recreate a more natural flood response (Green et al., 2021). This natural flood response is recognized for reducing the risk of flooding, improving water quality, harvesting stormwater for potential future use, and the reduction of the damages caused by flooding. To enhance sustainable development and urban resilience GI can be an important urban planning measure (Fu et al., 2021). However, the primary flood mitigation purpose of GI is to slow the stormwater runoff through urban areas and store excess amounts of water, reducing the peak runoff rates during storm events through a natural response (Green et al., 2021). The effectiveness of GI on stormwater management can differ substantially based on the type of GI, scales, and site conditions (Costa et al., 2021; Green et al., 2021; Raei et al., 2019).

Urban GI has been identified as one of the most effective countermeasures against the urban heat island effect (Liu et al., 2021; Wang et al., 2022). Due to the vegetation cover and tree shade area of urban green, a cooling effect emerges (Aram et al., 2019). This cooling effect is caused by shading, guiding airflows, intercepting precipitation, and evapotranspiration (Liu et al., 2021; Wang et al., 2022; Yao et al., 2020). Urban green can influence the temperatures of the area, as well as the surrounding area. This influence of GI in reducing heat island effects is already proven through measurements and computer simulation (Aram et al., 2019). Increasing the amount of GI is considered to be an effective and manageable way to improve the urban thermal environment (Xu et al., 2022), it has thus been shown that GI is successful in alleviating human thermal stress (Yao et al., 2020).

Urban GI is a critical habitat for the support of biodiversity in the urban environment (Lepczyk et al., 2017). The elements of GI can be seen as preserving and enhancing diversity within ecosystems in terms of habitats, species, and genes. Ecosystem health is prominently indicated by diversity, as GI could influence the urban ecosystem health through its contribution to ecosystem resilience, organization, and vitality (Tzoulas et al., 2007). The ability of GI to conserve biodiversity varies with landscape configuration, biotic interactions, land-use history, human population density, economic input, and management activities. To ensure the future of urban biodiversity effective management of GI is required (Aronson et al., 2017). In addition, GI contributes to the sustainability of urban areas by reducing the emission of greenhouse gasses (Hanna et al., 2021). For instance, the ability of trees to buffer air pollutants which can ensure better air quality in urban areas (Enssle & Kabisch, 2020).

GI in urban areas positively influences the livability of cities. The livability of a city refers to the quality of life and well-being of urban citizens (Parker & Simpson, 2018). Urban GI provides a healthy living environment, and physical and psychological health benefits to the people residing in them (Tzoulas et al., 2007). Public green areas provide urban citizens with social cohesion, through the opportunities to recreate, play sports, socialize, relax, learn, and experience nature (Enssle & Kabisch, 2020; Parker & Simpson, 2018). These activities may lead to people spending a greater amount of time outdoors, and increase people's physical activity. Furthermore, green in residential areas affects residents' feelings of attachment towards the community, and their interactions with other residents (Tzoulas et al., 2007). To conclude, GI offers benefits for both the healthy and social environment.

2.2.2 Green infrastructure and flood risk management

Traditionally, governments implemented grey engineering methodologies, such as sewage systems, to mitigate flood risks in urban areas. However, with climate change, population growth, accelerated urbanization, and expansion of impervious surfaces a more integrated approach towards urban FRM is needed. A key component for this shift towards an integrated approach covers GI alternatives, which focus on using natural processes for managing the consequences of intense rainfall events whilst delivering additional benefits for the environmental, social, and economic aspects of a city (Soz et al., 2016). The popularity of GI as a sustainable development strategy for FRM is growing (Venkataramanan et al., 2019), as it attenuates, restores, and recreates a more natural flood response than grey infrastructure (Green et al., 2021).

The use of GI as a part of a FRM approach is especially attractive as it provides a wide range of other benefits to an urban area, as discussed previously in Chapter 1. Multiple studies also take into account the co-benefits of GI in decision-making processes for FRM, such as the research of Alves et al. (2019) that presents an approach to include a monetary analysis of co-benefits into a cost-benefit analysis. Due to these co-benefits, the implementation of GI needs an interdisciplinary approach and the involvement of multiple stakeholders. For the development of effective strategies, GI alternatives should be evaluated considering their potential to achieve multiple benefits (Alves, Gómez, et al., 2018). The paper of Hoang & Fenner (2015) highlighted GI as a holistic FRM approach that has the potential to enhance benefits in urban ecology, energy, landscape, and socio-economic systems. Thereby, it was shown that the inclusion of GI in urban areas is of effect under both flood and non-flood conditions (Hoang & Fenner, 2015). When conducting the literature review it was noticed that the three main groups of additional benefits are environmental, economic, and social benefits. The research of Fu et al. (2021) included both the benefits of GI related to flood risk, as well as co-benefits that are related to the environmental, economic, and social system. Multiple studies have identified these three groups of co-benefits provided by GI (Costa et al., 2021; Fu et al., 2021; Huang et al., 2020; Lennon, 2014; Newman et al., 2022; Pakzad & Osmond, 2016; Reu Junqueira et al., 2022; Wang et al., 2020).

However, the actual effect of GI is often difficult to determine and depends on the magnitude of the storm event as well as the spatial scale of the GI alternative (Green et al., 2021). Reu Junqueira et al. (2022) found that GI alternatives are effective in reducing flood risks even when a very small area within the whole catchment consists of GI. GI has the potential to reduce regular flood events of low to medium magnitude, and larger-scale GI may help in mitigating more severe flood events (Green et al., 2021). Although the effectiveness of flood risk reduction during intense rainfall has been questioned, GI can also be combined with grey infrastructure alternatives to ensure resilience during higher-intensity precipitation and still maintain the co-benefits of GI (Huang et al., 2020). For example, GI can have hidden grey engineering elements, such as a pipe or outlet (Green et al., 2021), ensuring reliability in front of extreme events (Alves, Gersonius, et al., 2018).

There has been an increased awareness of the effect of GI in FRM. However, GI panning has been based on experience, lacking strategy and resulting in sub-optimal outcomes. This has resulted in some quantitative urban planning approaches that seek careful placement of GI. In addition, a growing amount of studies become available which perform suitability analysis to determine the suitability of a location for GI implementation (Li et al., 2020). Opportunities for the adaptive properties of GI will be limited in many scenarios due to given space and logistical constraints. Thereby, monitoring and regular maintenance are necessary to maintain the key functions of flood protection (Green et al., 2021)

2.3 Flood risk determination

In this section, a literature review was carried out to identify and evaluate existing methodologies that can be used for assessing flood risk probability. The methodologies were assessed and compared based on the developed tool or methodology, software, analysis method, the indicators that were used to perform the assessment, and GI alternatives.

The focus of the current study is to develop a tool for the determination of flood risk probability including the effect of GI in Dutch urban areas. In order to understand the determinants of the flood risk and the effect of GI alternatives different methodologies have been assessed, to gain knowledge for the development of a tool specifically for Dutch urban areas. The flood risk depends on a variety of conditions within an urban area, such as the infiltration capacity and sewage system density.

Research in the Netherlands about the contribution of GI in relation to the reduction of flood risk probability is limited. In contrast, there is a growing number of studies addressing flood risk mitigation based on the performance of GI in urban areas around the world. However, the flood risk depends on the local context and varies between urban areas, so the findings of these studies cannot just be applied to the Dutch situation.

2.3.1 Methodologies for flood risk determination

When performing the literature study it was noticed that three types of methodologies for assessing the effect of GI on flood risk probability were repeatedly and prevalently applied, namely:

- Computational models
- Flood risk assessments (multi-criteria)
- Bayesian network approach

Computational models for hydrological performance can help to assess potential challenges for the implementation of GI and strategic decision-making, as unforeseen outcomes can be mitigated and recognized (Reu Junqueira et al., 2022). Many researchers have used computational models to investigate GI performance and placement in urban areas using Storm Water Management Model (SWMM), a rainwater runoff simulation model (Mei et al., 2018; Raei et al., 2019; Reu Junqueira et al., 2022; Shojaeizadeh et al., 2021; Steis Thorsby et al., 2020). SWMM allows for the integration between hydrological and spatial analysis (Reu Junqueira et al., 2022). For example, Raei et al. (2019) couple urban surface runoff based on historical rainfall data with other catchment features, in order to find the optimal area size of GI alternatives using a SWMM. To reach their outcomes, computational models involve calculations that are often complicated and not understandable to all urban planners and policy makers.

Flood risk assessments determine areas with high and low risks of flooding based on objective and scientific methods (Park & Lee, 2019). A means to perform a flood risk assessment is the multi-criteria approach. The research of Pacetti et al. (2022) performed a multi-criteria analysis, in which they identify areas prone to pluvial flooding by a spatial multi-criteria analysis to build a combined index. After the flood-prone areas are identified, they merge the information with the analysis of urban planning and GI design constraints to identify suitable locations for GI implementation.

Lastly, the Bayesian network (BN) approach is reviewed. The BN is a probabilistic model that represents indicators, dependencies of indicators, and quantitative relationships between indicators (Li et al., 2023). In doing so, the BN can capture the potential relationships between different indicators influencing flood risk and has the capability of quantifying uncertainty (Wu et al., 2020). The research of Wu et al. (2020) proposed a model coupling ontology and Bayesian Network to capture the potential relationships between factors that influence flood risk disasters and has the capability of quantifying uncertainty. The research of Li et al. (2023) proposed an integrated model for flood risk assessment based on a risk assessment model in the framework of a Bayesian Network by incorporating an Interpretative Structural Modeling method. This method was employed to identify the relations among multiple risk factors and then helped to configure the Bayesian Network structure to conduct the risk inference.

Where computational models mainly focus on the hydrological performance of the GI alternative and BN assesses the relationship between factors influencing the flood risk, the flood risk assessment allows for the identification of areas prone to flood risk incorporating the indicator relations and suitability mapping. Thereby, flood risk assessments do not involve complicated calculations, such as in computational models, and are often easily interpretable.

Multiple flood risk assessment methodologies have been included in the literature review. In this paragraph, the studies that involve a flood risk assessment will be further explained. The research of Fu et al. (2021) approached the common problem of gaining insight into GI performance for flood risk management (FRM). Their evaluative approach forms an effective means to address the problem and facilitates multiple criteria for thorough decision-making. This is achieved through both establishing an extensive set of indicators and weighting the indicators. In addition, the research of Mubeen et al. (2021) generated a suitability map for GI implementation based on spatial criteria. To generate the suitability map, each spatial criterion was mapped separately. Therefore, base maps had to be derived for each criterion, so these could be transformed to match the conditions for each criterion. Although the focus of Mubeen et al. (2021) is on suitability mapping for the implementation of GI alternatives, the approach of their methodology can be used to map the indicators and generate a general Flood Risk Level (FRL) map. A comparable research was conducted by Pacetti et al. (2022) that could be used as a reference for generating the FRL map. Their study integrated GIS-based and multi-criteria analysis to identify the most suitable areas for the implementation of GI. Therefore, multiple indicators were compared including the importance of one indicator over another. For the suitability analysis of the GI implementation, the study of Pacetti et al. (2022) made use of constraints that represent the aspects of GI alternatives. In the next section, all methodologies from the literature review are further analyzed based on the indicators that were used. A different approach was used by Do et al. (2022) that determined the flood risk based on urban expansion using the Gauss process regression model combined with the firefly algorithm, based on this model the flood risk has been mapped.

2.3.2 Indicators for flood risk determination

This section analyses the potential indicators of urban pluvial flooding. Therefore, the indicators will be screened first, after which they will be selected and the typology between the indicators and the flood risk will be established.

The flood risk probability can be impacted by different conditions of the natural system. Meaning that the ability to manage flood risk is affected by several characteristics (Huang et al., 2020). Thereby, the planning of GI to help mitigate the flood risk requires careful consideration of various indicators and local contexts (Mubeen et al., 2021). Kalantari et al. (2022) indicated that the placement and size of GI are two important parameters in achieving the full potential of GI in terms of flood risk determination. Even though the size of GI is considered a relevant factor, research has shown that small-scale GI alternatives can also have a positive impact (Pereira Almeida & Moura, 2022). Throughout different studies, various indicators are considered that affect the flood risk, such as hydrology, soil, slope, and land use. Some of these indicators also illustrate the aspects of GI, such as imperviousness and surface area. To analyze the indicators used throughout different studies, an overview was created which shows the indicators used per study (Table 2.1).

The overview shows all the indicators included in the reviewed methodologies. A score has been assigned to each of the indicators (see last column in the table) that implies the number of methodologies that used the particular indicator. Based on this score, a distinction can be made between the most commonly assessed indicators and the less commonly assessed indicators. The indicators that are assessed in three or more studies are considered to be the commonly assessed indicators and are highlighted in blue in the table, indicators that were

Table 2.1 Indicators of flood risk determination

Indicators	Research																		Score
	Costa et al. (2021)	Do et al. (2022)	Fu et al. (2021)	Huang et al. (2022)	Li et al. (2020)	Li et al. (2023)	Liu et al. (2014)	Mei et al. (2018)	Mubeen et al. (2021)	Newman et al. (2022)	Pacetti et al. (2022)	Raei et al. (2019)	Reu Junqueira et al. (2022)	Shojaeizadeh et al. (2021)	Steis et al. (2020)	Wang et al. (2020)	Webber et al. (2020)	Wu et al. (2020)	
Air quality			●							●									2
Amenity																●			1
Cost																●			1
Depth			●											●	●				3
Distance from stream		●		●		●			●									●	5
Drain					●								●						2
Elevation		●				●												●	3
Energy																●			1
Flood depth	●																		1
Flood-prone buildings					●														1
Flood-prone road infrastructure				●	●														2
Habitat creation																●			1
Human health and wellbeing increase			●																1
Imperviousness	●						●	●	●		●		●		●			●	8
Land use/Land cover		●	●	●	●	●			●								●		7
Microclimate			●																1
Noise reduction			●																1
Pavement	●				●			●					●						4
Peak flow																●			1
Pollutant removal										●									1
Population density				●		●												●	3
Rainwater harvesting																●			1
Recreational area increase			●		●														2
Road density						●												●	2
Runoff quality																●			1
Runoff volume (quantity)	●	●	●	●	●	●	●			●		●				●		●	11
Sewage system (density)	●										●							●	3
Slope		●	●	●		●		●	●		●		●		●			●	10
Social interaction increase			●																1
Soil			●	●			●	●	●		●		●				●		8
Storage	●						●	●					●						4
Surface	●		●					●					●	●					5
Temperature		●		●			●												3
Vegetation volume								●		●			●						3
Vulnerability residents (social)					●						●								2
Water quality			●																1
Water storage capacity of the soil	●	●	●				●		●										5

used in less than three studies are considered to be the uncommonly assessed indicators and are left blank in the table. In this analysis, it is noticed that the most commonly used indicators are almost all applicable to a location aspect.

In order to obtain a comprehensive perspective of the flood risk probability, both the location characteristics and the GI aspects should be included in the framework for flood risk determination. Preferably, the considered indicators must be urban planning elements, that can be influenced by the human hand. This is important as the results of the analysis will be able to indicate the impact of making changes to certain elements, so it can help urban planners and policy makers in the decision process of making changes to the urban environment.

2.3.2.1 Analysis of the indicators

Considering the analysis of the indicators used throughout studies assessing flood risk probability, the indicators imperviousness, land use/land cover, surface, runoff, elevation, slope, soil, storage, the water storage capacity of the soil, depth, pavement, river density, sewage system, vegetation, population density, and temperature are commonly used indicators in flood risk assessments.

In the research of Costa et al. (2021), imperviousness is considered as the impervious surfaces within the urban area, therefore they considered buildings and paved areas. Similarly to this research, most other researches that also include imperviousness make use of buildings and paved areas (Mei et al., 2018; Mubeen et al., 2021; Reu Junqueira et al., 2022; Steis Thorsby et al., 2020; Wu et al., 2020). Liu et al. (2014) made a distinction between pervious and impervious areas considering the amount of runoff that would be generated from these surfaces. Buildings and paved areas were considered impervious areas and green spaces and bare soils were considered pervious areas. Another type of surface that is distinct is water bodies, which are devices where stormwater may be temporarily or permanently stored (Liu et al., 2014). According to Mubeen et al. (2021), imperviousness is directly related to changes in land use.

Studies that included land use/land cover generally classify the land use/land cover types as agricultural lands, forest land, grassland, urban or developed land, and water surface (Do et al., 2022; J. Huang et al., 2022; G. Li et al., 2023; L. Li et al., 2020). Within these land use/land cover types, urban land is mostly characterized by residential areas, buildings, vegetation, roads, and paved areas. Therefore, land use/land cover has a reasonable overlap with the surface types that are considered throughout multiple studies from the analysis.

In the research of Costa et al. (2021), the surface was divided into four classes, namely, unpaved areas, open and closed paved areas, and roofs. Therefrom, it can be noticed that in this study the surface area is linked to the pavement and imperviousness of the surface. However, the study of Fu et al. (2021) and Shojaeizadeh et al. (2021) interpret the surface as the size of the GI alternative.

The runoff volume is the amount of stormwater that is collected on the surface and then becomes part of either the surface runoff or the sewage water. Both the infiltration rate of the surface and soil, as well as the steepness of the terrain affect the runoff generation (Costa et al., 2021).

The elevation has been introduced in multiple studies based on the geographical fact that the location of floods is mainly located at the lower elevated lands. Thereby, the elevation also relates to the slope. The slope is a topographical indicator that influences the flood risk. The slope is a measure of the average rate of change of elevation (Wu et al., 2020). Steeper slopes contribute to generating major floods, while areas with a lower slope have a higher probability of flooding (Pacetti et al., 2022).

The indicator soil expresses the soil type that is present within the specified area. The soil type affects the infiltration capacity of the ground within the urban area (Webber et al., 2020). The infiltration capacity of the soil is based on both the porosity and the conductivity (Reu

Junqueira et al., 2022), thereby the soil also is of effect on the imperviousness of the surface (Pacetti et al., 2022).

The water storage capacity of the soil is included in some of the research, it examines the capacity of the soil for storage and infiltration of stormwater. One of the factors that is of influence on the infiltration capacity is the saturation of the soil, below the groundwater level the soil is completely saturated (Liu et al., 2014). When groundwater levels are near the soil surface, there is almost no place in the ground for infiltration of stormwater, which could lead to pluvial flood events (Costa et al., 2021).

The indicator depth expresses the extent to which the considered GI alternative reaches below ground level (Fu et al., 2021; Shojaeizadeh et al., 2021; Steis Thorsby et al., 2020). This indicator is linked to each GI alternative that can be implemented in an urban area.

The indicator pavement is linked to the imperviousness and permeability of the surface in the research of Reu Junqueira et al. (2022) and Mei et al. (2018), as the imperviousness and permeability of the surface layer are dependent on the type of pavement.

Some studies also included the river density, or the distance from the stream as an indicator. In the study of Do et al. (2022) this indicator is included based on the likelihood of a river flood occurring. Similarly, the research of (Li et al., 2023) included the river density based on the close relation between flooding and the river system.

The sewage system is also included in some of the research. In case the runoff in the sewage system exceeds its capacity, the pipes of the sewage system will be filled completely and the water might flow out to the surface (Costa et al., 2021). So, based on the sewage system capacity a certain amount of stormwater can be redirected from the urbanized area.

Despite the indicator vegetation has not been included in most studies as a separate indicator, some studies also included vegetated areas and trees as pervious surfaces (Do et al., 2022; Fu et al., 2021; Mei et al., 2018; Reu Junqueira et al., 2022; Webber et al., 2020), and in other studies, the vegetation is included as a part of the GI alternatives (Costa et al., 2021; Li et al., 2020; Liu et al., 2014; Mubeen et al., 2021; Pacetti et al., 2022; Shojaeizadeh et al., 2021; Steis Thorsby et al., 2020; Wang et al., 2020)Thus, vegetation can be considered a key aspect of GI alternatives.

Population density is considered to be a social indicator, which influences the impact of the flood disaster (Wu et al., 2020). The temperature is a meteorological condition that cannot be influenced directly by urban planners and policy makers. Therefore, the population density and temperature will not be further examined during this research.

2.3.3 Green infrastructure alternatives

To deal with the implementation of GI alternatives in the flood risk assessment, it is necessary to decompose GI alternatives based on their aspects. These aspects of the GI alternatives could then be implemented in the framework for the planning support system. The following citation defines GI including some aspects that are included in GI alternatives:

''Green infrastructure is defined by the U.S. Environmental Protection Agency (U.S. EPA) as the following: Green infrastructure uses vegetation, soils, and other elements and practices to restore some of the natural processes required to manage water and create healthier environments.'' (Steis Thorsby et al., 2020, p.2)

Aspects of GI that can be considered are thus vegetation, soils, and other elements. The elements depend on the type of GI alternative, for example tree pits contain the elements vegetation and storage capacity. Throughout different studies, various types of GI alternatives are considered. To analyze these GI alternatives, an overview was created which shows the GI alternatives used per study (Table 2.2). Together, the aspects of GI provide for the functions of GI, which reflects its effectiveness. The functions of GI include infiltration, retention, storage, and discharge of stormwater, purification, and insulation of the vegetation and soil layer (J. Wang et al., 2020). At the same time, thanks to the presence of vegetation, GI contributes to increasing water and air quality, biodiversity, and amenity of the area, and to reducing noise levels, urban heat islands, and respiratory disease (Pacetti et al., 2022).

Table 2.2 Green infrastructure alternatives

Green infrastructure alternatives	**Research**												**Score**
	Costa et al. (2021)	Fu et al. (2021)	Li et al. (2020)	Mei et al. (2018)	Mubeen et al. (2021)	Newman et al. (2022)	Pacetti et al. (2022)	Raei et al. (2019)	Reu Junqueira et al. (2022)	Shojaeizadeh et al. (2021)	Steis et al. (2020)	Webber et al. (2020)	
Bio-retention basin					●		●				●		3
Bio-retention cells				●				●	●	●			4
Floodplain restoration					●								1
Green roofs	●			●		●					●	●	5
Infiltration trench	●	●				●	●			●		●	6
Permeable/porous pavement		●		●		●	●		●	●		●	7
Rain barrel		●									●	●	3
Rain garden		●				●	●		●	●	●	●	7
Retention pond					●		●			●			3
Retention pond (dry)										●			1
River widening					●								1
Sand filter										●			1
Shared detention basin		●								●			2
Tree pit							●			●		●	3
Vegetated swale (bioswale)				●			●	●		●	●		5

The overview shows all the GI alternatives included in the reviewed studies. A score has been assigned to each of the GI alternatives (see the last column in the table) which implies the number of studies that used the particular GI alternative. Based on this score, a distinction can be made between the most commonly assessed GI alternatives and the less commonly assessed GI alternatives. The GI alternatives that are assessed in five or more studies are considered to be the commonly assessed GI alternatives and are highlighted in blue in the table, GI alternatives that were used in less than five studies are considered to be uncommonly assessed GI alternatives and are left blank in the table.

For this research, the GI alternatives rain gardens, bioswales, infiltration trenches, and permeable pavements will be examined based on their functioning and the included aspects (see Sections 2.3.3.1 to 2.3.3.4). The GI alternative green roofs will not be further examined as green roofs cannot be implemented in the publicly accessible space, often the implementation of green roofs involves collaboration with third parties. The GI alternatives considered in this research are known as suitable urban revitalization alternatives and already known examples of implementation in Dutch urban areas.

2.3.3.1 Rain gardens

Rain gardens are vegetated land depressions that detain and treat stormwater runoff from impermeable surfaces, such as rooftops, sidewalks, and streets (Brears, 2018). Rain gardens have only been implemented in the Netherlands over the last few years (Boogaard, 2022). Runoff that enters the rain garden is first filtered by the vegetation implemented in the rain garden and then soil layers further filter the runoff (Brears, 2018). In this process, part of the runoff is absorbed through the roots of the vegetation. The remainder part of the infiltration either becomes part of the groundwater or is directed to a downstream detention system via a drain (perforated pipe). The excess amount of runoff that enters the rain garden is directed to the drain via an overflow (Boogaard, 2022). The three main components of the rain garden are as followed:

1. Drainage area that collects the stormwater runoff;
2. Distribution system that connects the drainage area to the receiving area;
3. Receiving area that retains and infiltrates the rainwater (Brears, 2018).

To ensure the effectiveness of rain gardens they should be sited to treat as much runoff from an impervious area as possible and sized to match the volume of soil storage with the extent of the drainage area (Brears, 2018). Rain gardens are often relatively small systems, which can be implemented without using a lot a space in the urban area, for example, compared to a bioswale. A rain garden often consists of straight concrete walls, which allows for limited use of space in comparison to a bioswale, as a bioswale has embankments that slowly slope into the system. Thereby, a rain garden often contains a diverse spectrum of vegetation which increases the biodiversity and aesthetics of the urban area, resulting in beneficial effects for both ecological and social aspects (Boogaard, 2022).

2.3.3.2 Bioswales

Bioswales are open channels that collect stormwater runoff via overland flow while providing open green space for developments. As stormwater runoff slowly flows into the swale because of its sloped embankment, it enables sediments and other pollutants to settle. In doing so, bioswales remove coarse materials from stormwater and serve as a pre-treatment before infiltration of the stormwater (Brears, 2018). The bioswale allows for temporary storage of stormwater runoff and infiltration of the stormwater. The stormwater infiltrates directly into the ground without any additional soil layers. Besides the stormwater infiltrating into the ground and becoming part of the groundwater, part of the infiltrated stormwater is drained via the drainage system that is implemented in the bioswale. This drainage system is also connected to an overflow, which allows for the excess amount of stormwater that enters the bioswale to be drained (RIONED & Stowa, 2003).

In the Netherlands bioswales often consist of shortly mown grass, without any additional vegetation. However, it is possible to include more vegetation in a bioswale. In nature-friendly or vegetated swales a diversity of vegetation is used to increase the attractiveness for bees and butterflies, which contributes to the biodiversity (Boogaard, 2022).

2.3.3.3 Infiltration trenches
Infiltration trenches, also known as vegetative buffer strips, increase water evaporation and infiltration through the accumulation of stormwater (Brears, 2018). Infiltration trenches can temporarily store the stormwater runoff before infiltrating into the ground. For infiltration of stormwater, the permeability of the soil is important (Amersfoort Rainproof, 2023). The stormwater is partially filtered when infiltrating through the vegetation and possibly a gravel layer. Contrary to bioswales and rain gardens, the infiltration trench is designed for infiltration only as no drainage system is implemented (Brears, 2018).

For the dimensioning of the infiltration trench, similar to the rain garden and the bioswale, it is not meaningful to make the infiltration trench deeper than the groundwater level (Blauw Groen Vlaanderen, n.d.).

2.3.3.4 Permeable pavements
In essence, permeable pavements are a modification of surfaces that would normally be impermeable. They are mostly incorporated in areas where space concerns would mean that additional structures, such as bioswales, could not be used (Dover, 2015). Two main types of pavements can be distinguished, namely permeable pavements and pervious pavements. Permeable pavements are pavements were stormwater passes around the paver, as space is left between the joints of the pavement. The space that is left between the joints is generally filled with dirt, sand, or gravel. Contrary to permeable pavements, pervious pavements allow for stormwater to percolate through the surface, instead of around the pavers (Dover, 2015). Based on the type of pavement that is used and the soil underneath the pavement, a certain amount of water can infiltrate into the ground.

2.3.4 Framework for flood risk determination
The framework for flood risk determination (FFRD) represents the aspects within an area that affect the flood risk. The Flood Risk Level (FRL) is the overall index that indicates the available risk of flooding in an area. The higher the index, the higher the risk.

The index is subdivided into categories and indicators, where a category can also be divided into sub-categories that include the accompanying indicators. The indicators are the characteristics of an area, and the categories and sub-categories help to divide the indicators into groups of similar attributes. The FFRD structure is shown in Figure 2.5.

Starting on the left-hand side of the FFRD, the sub-category land cover is represented by the indicators building, vegetation, pavement, and water. The research of Liu et al. (2014) made a distinction between impervious and pervious surfaces, where green spaces and bare soils were considered pervious surfaces. Additionally, they included an extra surface type, namely water bodies. The surface types included in these impervious and pervious surfaces generally represent the land covers of urban areas and are represented in the sub-category land cover. The imperviousness, which has been considered throughout a significant number of studies,

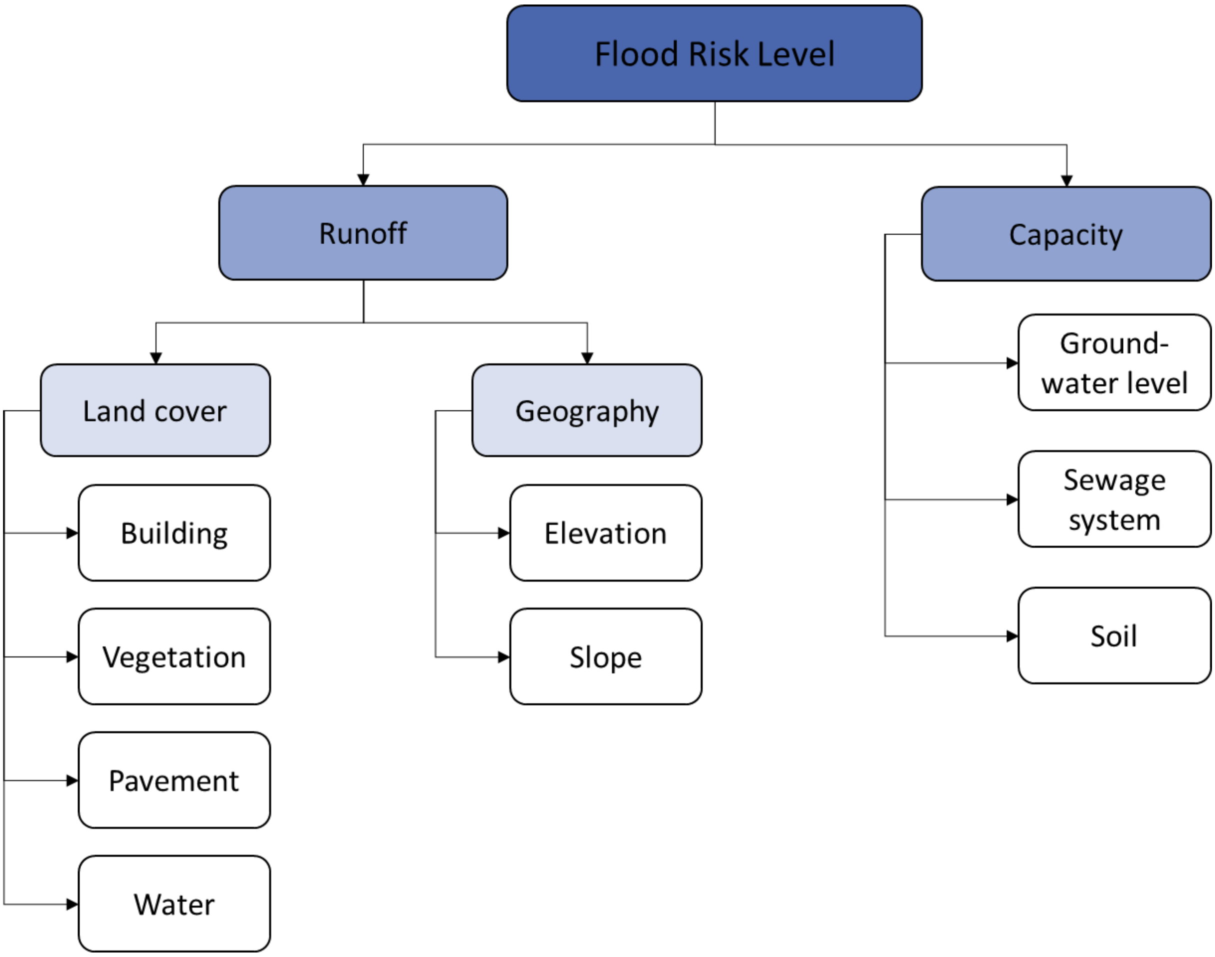


Figure 2.5 Framework for flood risk determination (FFRD)

represents the impervious surfaces within an urban area. Often, buildings and paved areas are considered impervious surfaces.

Dependent on the land cover, a certain amount of runoff is generated, which is represented by the category runoff. The runoff volume represents the superficial discharge of stormwater, which decreases with the perviousness of the land cover. The more infiltration is enabled by the land cover type, the less stormwater runoff will be generated during a heavy rainfall event. Other than the land cover, the runoff is also affected by the sub-category geography. The sub-category geography is represented by the geographical conditions elevation and slope. The slope affects the flow velocity of the runoff, meaning the steeper the slope, the higher the runoff velocity (Pacetti et al., 2022). The runoff flows that are generated based on the slope, are generally flowing towards the lower elevated locations increasing the flood risk in lower elevated locations (Li et al., 2023).

On the right-hand side of Figure 2.5, the category capacity is represented by the indicators groundwater level, sewage system, and soil. The storage capacity of the ground will be determined based on the groundwater level, as the ground below the groundwater level is completely saturated (Liu et al., 2014). The sewage system capacity affects the capacity to diminish the flood risk, as the sewage system discharges the stormwater out of the urban area (Costa et al., 2021). Lastly, the infiltration capacity of the soil is affected by the soil type that is present within the urban area (Webber et al., 2020). Together with the category runoff, the category capacity represents the FRL.

In this research, the effect of GI on the FRL will also be considered. This is fulfilled through the implementation of GI aspects in the FFRD. The next part will explain how the indicators included in the framework also cover the aspects of GI.

2.3.4.1 Green infrastructure aspects

One of the concerns of GI alternatives is to help restore and recreate a more natural flood response. A large part of this matter is fulfilled by vegetation. The natural flood response includes four processes, namely interception, evaporation, infiltration, and depression. The precipitation is firstly intercepted by the vegetation canopy, after which the net rainfall reaches the ground to infiltrate and is stored in the soil, and water is stored in depression. Only when stormwater excesses the depression storages, the water is becoming part of the runoff. It can thus be considered that the runoff in a natural flood response is equal to the precipitation minus the loss amounts of interception, evaporation, infiltration, and stored stormwater (Liu et al., 2014). However, this natural flood response has been disturbed by urbanization.

> ‘’Thanks to the presence of grass, bushes and trees, NBS contribute to increase water and air quality, biodiversity, amenity of the area, and to reduce noise level, urban heat island and respiratory diseases. NBS can be used alone or in combination with grey infrastructures, favoring cities adaptation to climate change and strengthening the management and utilization of rainwater runoff.’’ (Pacetti et al., 2022, p.3)

In most studies, such as in the study of Pacetti et al. (2022) it is seen that within vegetation the distinction is made between trees, bushes, and grasses, turfs, or ornamental plants. According to Berland et al. (2017), urban trees deserve additional consideration as a stormwater control measure. Therefore, they draw on existing research to describe how trees can provide alternative pathways for urban stormwater via a broader range of losses from the urban hydrologic cycle, and note opportunities to pair trees with other green infrastructure alternatives. Then they discuss the outlook for using trees as elements of green infrastructure to achieve reliable stormwater control. Grasses, turfs, and ornamental plants protect the landscape from erosion and possibly reduce runoff through infiltration and transpiration. However, their impacts on the urban hydrological cycle are highly variable and understudied (Selbig et al., 2022).

The first process of the natural flood response is the interception. There are numerous different interception types, as every surface that can store water can principally be considered an interception type. The major type that occurs in urban environments is canopy interception, which is the interception that is stored on the leaves and branches of a tree and subsequently is evaporated (Gerrits & Savenije, 2011). Canopy can intercept and store rainfall, and delay or lessen the volume available for throughfall. The infiltration capacity is strongly influenced by canopy structure and architecture which varies among species (Selbig et al., 2022). Although urban trees have a strong effect on the reduction of stormwater runoff, the reduction of runoff is not solely due to canopy interception, as the rainfall interception is dependent on the canopy crown area. Smaller trees only have a small effect on the total runoff volume compared to larger trees. The implementation of a tree often involves a change in surface coverage at the concerned location, which increases the infiltration capacity (Armson et al., 2013). Grasses and bushes have a much lower roughness and thus do not have as high potential interception and evaporation rates (Gerrits & Savenije, 2011).

Secondly, the process of evaporation is a part of the natural flood response. Urban areas vary in magnitude and seasonality of evapotranspiration due to differences in climate, soil moisture status, irrigation, and vegetation cover. Acquiring accurate evapotranspiration estimates is generally complex and time-consuming. Evaporation of intercepted precipitation is affected by meteorological factors such as temperature, cloud cover, relative humidity, and wind speed. Thereby, evaporation is dependent on vegetation-specific information, which will vary among different species (Berland et al., 2017). Due to their extensive root systems and high leaf area, trees can transpire substantial amounts of soil moisture, reducing antecedent moisture content during the inter-storm period, and leading to higher infiltration rates during subsequent storms (Selbig et al., 2022). Evergreen needle-leaf trees tend to have lower leaf transpiration rates than deciduous broadleaf trees, yet both types tend to be deeply rooted and will be able to access deeper water sources (Berland et al., 2017). Based on evapotranspiration Berland et al. (2017) suggest that green infrastructure design that incorporates a mixture of vegetation types may be preferred when considering year-round stormwater retention in urban areas.

Additionally, the process of infiltration is a part of the natural flood response. Trees improve the infiltration of the soil by modulating the soil ecosystem via root growth and senescence, higher organic matter inputs, higher microbial activity, and stabilization or formation of soil structure. The expansion of roots is especially important for generating channels in the soil to facilitate infiltration (Berland et al., 2017).

Finally, the process of depression is a part of the natural flood response. For the collection of stormwater, GI alternatives are often constructed as a depression, with a lower elevation and a sloped border. Changing the slope and elevation within the designated area. Therefore, slope and elevation are also considered aspects of GI alternatives in the framework for flood risk determination (FFRD). The indicator groundwater level is not directly related to GI alternatives, as realizing a GI alternative does not change the groundwater level. However, it changes the distance of the groundwater level relative to the surface as GI alternatives are often constructed as a depression. Relative to the original surface, depressions increase the storage capacity, as the soil is excavated and the whole volume can be used as temporary storage for stormwater. Other than constructing a depression, the soil underneath a GI alternative is often improved to reach higher levels of infiltration and purification. To even further increase infiltration sometimes drainage systems are included in some GI alternatives. These drainage systems are part of the sewage system and drain part of the infiltrated stormwater and possibly drain the excess amount of stormwater via an overflow.

2.4 Policy

This section considers the policy in the Netherlands, regarding the involved parties in spatial planning when implementing GI alternatives. Thereby, some general rules and regulations are taken into consideration. A conclusion can be drawn on how this study relates to the governmental system in the Netherlands. The municipal responsibilities and the need for an assessment will be elaborated on.

In the Netherlands, the government is composed of different levels, separating national, regional, and local governments. The authority at the national level is the state, at the regional level a distinction can be made between provinces and water boards, and at the local level municipalities are the primary authorities. Over these different governmental levels, each level has its authorizations. On the national level laws are established, that have to be honored at the regional and local levels. Similarly, national goals are set by the state, which the regional and local authorities have to include in their plans to contribute to and help achieve the national goals. This stratification is also applicable to water management in urban areas (Ministerie van Binnenlandse zaken en Koninkrijksrelaties, n.d.).

2.4.1 National policy

The state has established the 'Handboek Water', also known as the 'Handboek wet- en regelgeving waterbeheer', hereafter referred to as the Water Guide. The Water Guide is a manual that is established to make the contents of legislation and regulation of water management insightful for practice. An important law that is included in the manual is the 'Waterwet' (English: Water Act), this act is focused on the prevention and restriction of flooding, water nuisance, and water shortage, as the protection and improvement of the quality of water systems and the fulfillment of social purposes by water systems. The Water Act gives the legal basis for the planning system in terms of water management. In the strategic plans of the state and the provinces, the targets of the Water Act will be considered and elaborated (Rijksoverheid, 2009).

The Water Act will remain in force until the new 'Omgevingswet', also known as the Environmental Act, will take effect. The Environmental Act will combine multiple laws, which reduces the number of rules and simplifies the permit system which will diminish the administrative burden for regional and local authorities. Subsequently, the strategic targets are specified for practice in the operational management plans of the state. For the state, this is done in the national water management plans, and for the provinces, this is done in the regional water management plans, these plans represent the national and regional strategic water policy. In the national water management plan, the main lines of the national water policy and the additional aspects of the national spatial policy are set by the Minister of Infrastructure and Waterworks and the Minister of Economics and Climate. The national water management plan forms a framework for regional water management plans and operational management plans, based on the spatial aspects the regional plan is designed as a structural concept (Rijksoverheid, 2009).

2.4.2 Regional policy

The regional water management plan that is established per province captures the main topics of the water policy per province and the additional aspects of the provincial spatial policy. The regional water management plans have a planning cycle of six years, which implies that every six years the regional water management plans are revised (Provincie Zuid-Holland, 2021). The main structure of the regional water management plan is outlined in the 2nd paragraph of Article 4.4 of the law of water (Rijksoverheid, 2021b). In the regional water management plan the provinces capture their strategic targets, also the policy framework. The spatial components are captured in the structural concept, which gives meaning to an improved coherence between water and spatial planning (Provincie Zuid-Holland, 2021). Together with the national water management plan and operational management plans of the state and the water boards, the regional water management plans form the planning system (Rijksoverheid, 2021b).

Besides the regional water management plans, the provinces also define water regulations at the regional level. In the regional water regulations, the standards, obligations, and enforcement of water management are included per province. Most provinces include the obligation for permits and registration for extracting groundwater and the exceptions in their water regulations (Provincie Fryslân, 2016; Provincie Zeeland, 2016; Provincie Zuid-Holland, 2016). Furthermore, the outline and preparation for the regional water management plan and maintenance plan are discussed (Provincie Zeeland, 2016; Provincie Zuid-Holland, 2016), in which some provinces include advice for the preparation of the 'Waterakkoord' (Provincie Fryslân, 2016).

Besides the provinces, there are also water boards that operate on a regional level. Some water boards cross the borders of multiple provinces, and these water boards have to establish their water regulations that are separate from the water regulations of the provinces. Moreover, all water boards have to establish a water maintenance program once every six years. The water maintenance program outlines the vision and ambitions of every water board in the long term (Waterschap Rivierenland, 2021). Besides the water maintenance program, the water boards compile additional documentation for the water policy at their initiative. An example of this is the rainwater policy of the water board Brabantse Delta. Comparing the frameworks and plans of the water boards and provinces it is noticed that the provinces regulate the general policy at the regional level and the water boards have a more specified authority to navigate and coordinate the water quality, quantity, and safety at a regional level.

2.4.3 Local policy

Lastly, there is the authority of the municipalities at the local level. Municipalities are not considered water managers in the law of water. However, municipalities are considered responsible for the care of rainwater and groundwater in urbanized areas according to Articles 3.5 and 3.6 of the law of water (Rijksoverheid, 2021b). Municipalities give meaning to their duty of care in the 'Gemeentelijk rioleringsplan (GRP)', this plan is determinant for urban water management based on stormwater runoff and groundwater (Gemeente Eindhoven, 2019). Additionally, municipalities capture spatial aspects in the form of a structural concept, similar to provinces. The structural concept of municipalities is also known as the environmental vision. Considerations for spatial aspects are included in the land-use plan, for which one of the water managers (the state or one of the water boards) is included in the preparations that are tested via a water test. The land-use plan considers the eventual spatial developments of the local water systems and points out destinations as water storage. These developments are illustrated on a map or included as policy statements (Gemeente Lelystad, 2021).

The Delta Program of spatial adaptation is of force for all governmental bodies in the Netherlands. The Delta Program is intended to establish that the state, provinces, water boards, and municipalities together ensure that the Netherlands is as climate-proof and robust as possible by 2050. A total of seven ambitions are included in the program, which among others include mapping vulnerable areas and setting up a time planning (Deltaprogramma, 2020).

Most municipalities have set up a vision for their goals based on climate adaptation. In these visions, municipalities develop a long-term strategy for the realization of measures for climate adaptation. An example of such a vision is the vision of the municipality of Nieuwegein:

> ''An attractive and healthy city, in which climate adaptation obtains a position in such a manner that the consequences of climate change can be minimalized in the short term (2025), and the long term (2050).'' (Gemeente Nieuwegein, 2018, p.7)

Before defining such a vision, a lot of municipalities obtain a climate stress test, which gains insight into the effect of climate change on the urban environment. Through mapping the vulnerability based on climate change aspects, the stress test also visualizes the vulnerable areas within the municipal boundaries based on flooding, water nuisance, heat stress, and drought (Gemeente Nieuwegein, 2018). An example of such a climate stress test is from the municipality of Dongen (Figure 2.6). The climate stress test helped the municipality of Dongen to map their vulnerable areas within the municipality, based on the four main climate change aspects and the comparison of different sectors. From their vulnerability analysis, it can be concluded, when focusing on water nuisance, that water nuisance will appear mostly on the streets at the core of the municipality as a result of climate change (Arcadis, 2020).

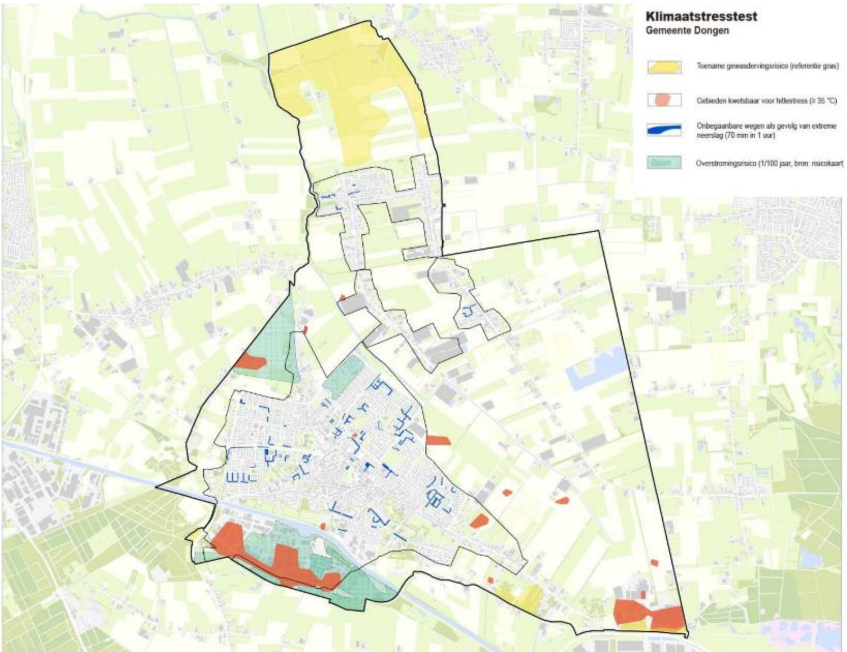


Figure 2.6 Results of climate stress test in the municipality of Dongen (Arcadis, 2020)

When it comes to the implementation of climate adaptation measures there are noticeable differences in the actions undertaken by municipalities. From the analysis of municipal approaches for climate adaptation, in the research of van Bijsterveldt et al. (2021), these differences appear to be based on obstacles that municipalities are facing. One of these obstacles is the limited amount of available space, as GI alternatives compete with other interests, such as housing construction and energy transition, that also ask for a considerable amount of space. Thereby, climate adaptation is often not seen as a priority in the spatial domain for municipalities, and budgets are limited. Therefore, the main stakeholder to be considered during this research will be the municipalities.

2.5 Conclusion

Climate change, rapid urbanization, and aging infrastructures are ensuring cities are exposed to risks of flooding due to intense rainfall. Floods involve risks, if floods cover parts of land with water that are normally not covered by water. With the increasing rainfall intensities, the flood risk and the associated damages also increase. Not all urban areas are equally affected by the risk of flooding, but the impacts depend on factors such as land use and the geographical position of the urban area.

When assessing the risks of an area, it can be found that the flood risk probability is not tolerable. In the case of flood risk reduction, different measures can be taken that affect the flood risk probability. One of these measures is the use of Green Infrastructure (GI) alternatives. GI are strategically designed and managed networks of natural structures. GI alternatives can range to a wide variety of types and open up opportunities for sustainable development. Thereby, the inclusion of GI in urban areas is of effect under both flood and non-flood conditions. Additionally, GI alternatives contribute to ecological, social, and economic benefits. These benefits are seen in multiple studies when assessing the implementation of GI.

In this literature review, multiple studies have been assessed based on their methodology. It was found that the research in the Netherlands about pluvial flood risk assessments combined with GI implementation is limited. Thereby, a lot of studies about the determination of flood risk are hydrology related and focused on the hydrologic performance of GI alternatives. Where computational models mainly focus on the hydrological performance of the GI alternative and BN assesses the relationship between factors influencing the flood risk, the flood risk assessment allows for the identification of areas prone to flood risk incorporating the indicator relations and suitability mapping. Thereby, flood risk assessments do not involve complicated calculations, such as in computational models, and are often easily interpretable. This research will continue to develop a flood risk assessment tool (FRAT) for flood risk determination in Dutch urban areas.

The indicators for the determination of flood risk probability used in the assessed studies were compared, and different GI alternatives were examined based on their functioning and included aspects to include GI alternatives in the flood risk assessment. Based on the indicators and GI aspects applied throughout the assessed studies a framework for flood risk determination (FFRD) has been developed. The FFRD concerns one overall index, the Flood Risk Level (FRL), that indicates the risk of flooding in an area. The FRL is divided into categories, sub-categories, and indicators.

When it comes to spatial planning, there are multiple parties involved in the Netherlands. There is the state at the national level, the provinces and water boards at the regional level, and the municipalities at the local level. In general, the state establishes national laws and goals for spatial planning that have to be honored by the regional and local level. In addition, the province captures the main topics of the water policy and the additional aspects of the provincial spatial policy. At the local level, also the city level, municipalities are the authority. Municipalities are considered responsible for the care of rainwater and groundwater in urbanized areas.

Based on the literature review a connection is made between Flood Risk Management (FRM) and GI alternatives. Thereby, the available methodologies for the determination of flood risk probability and the effect of GI are assessed to determine how an assessment tool for determining the flood risk probability in Dutch urban areas can be developed. To develop a tool based on the assessed literature the perspective and development of the tool will be illustrated in the next chapter.

3. Development of the tool

In this chapter, the methodology used to develop the flood risk assessment tool will be explained. The methodology presented in this chapter is a representation of the codebook, which is included in Appendix 1 and elaborates on each of the indicators included in the framework for flood risk determination. First, in Section 3.1 the goal of the tool will be explained. After this, in Section 3.2 the steps involved multi-criteria analysis will be explained. Then, in Sections 3.3 to 3.6 the scoring and calculations of the different (sub-)categories and indicators are discussed. In Sections 3.7 and 3.8 the calculation method of the flood risk level based on the category and indicator scores will be explained. Finally, the chapter will be concluded in Section 3.9.

3.1 The goal of the tool

The main goal of the tool will be to give municipalities a simple and straightforward method to gain insight into the areas within a municipality with an enhanced risk of flooding. When zooming in on a location, an understanding of the conditions that cause the enhanced flood risk can be obtained. Understanding the conditions within certain locations can help municipalities to guide and to assess the possible adjustments for reduction of the flood risk. The adjustments for flood risk reduction can be tested by implementing the changes of category and indicator scores in the tool and reloading the results to present the new flood risk probability. Because the aspects of Green Infrastructure (GI) alternatives are also taken into consideration, it can also clarify the influence of the adaptations that will be made for the implementation of a GI alternative.

The development of such a tool would provide a methodology for the support of decision-making in urban planning, in which different aspects can be evaluated based on their contribution to the reduction of the flood risk probability. Thereby, the tool contributes to the understanding of the effect of flood risk when changing urban aspects. The tool that will be developed results in an index that is calculated based on the indicators' and categories contribution to the reduction of the flood risk probability. This index allows for the comparison of potential adjustments and contributes to the decision-making process based on the municipalities' satisfaction with the results. In this research, a GIS-based multi-criteria approach will be used. This type of methodology has been previously used for other research, such as the national transportation poverty research of CBS & PBL (2019).

The objective of the tool is to map the Flood Risk Level (FRL) and understand the contribution of indicators, such as land cover and soil type, in relation to flood risk determination in Dutch urban areas. Additionally, the FRL score will capture the contribution of GI alternatives through the use of indicators that cover the aspects of GI. GI contributes to the reduction of the flood risk probability in urban areas through the recreation of more natural flood responses. Thereby, GI also provides a wide range of co-benefits for urban areas and is of effect under both flood and non-flood conditions. An important consideration in the development of the current index is the inclusion of indicators that affect the amount of stormwater that becomes part of the runoff, as well as the indicators that affect the storage and infiltration capacity. The index allows for potential adjustments to be compared and evaluated as assistance in decision-making.

In addition, from the differentiation in the implementation of GI across Dutch municipalities, the need for a tool in the form of a decision support system arises. Municipalities often develop their own methods for the implementation of GI, or do not follow any methodology. For this reason, the adopted methodology is kept transparent and uncomplicated to increase the chances of municipalities using the tool in practice. Transparency of the tool will be ensured through the use of open data and the data is combined and analyzed using the software QGIS, which is a publicly available GIS software. The method is kept uncomplicated through an easily interpretable pathway and set of indicators, meaning that both the results and intermediate steps should be understandable for both urban planners and decision-makers.

3.2 Multi-criteria analysis

Multi-criteria analysis methods appraise and evaluate a problem by taking into account various dimensions of interest, the interaction between multiple objectives, and different decision criteria metrics. Multi-criteria analysis (MCA) is an overarching term for different methodologies and techniques by which multiple objectives and decision criteria can be formally incorporated into the analysis of a problem (Dean, 2022).

MCA methods can be separated into formal and simplified methods, where formal methods can be further sub-divided into continuous and discrete methods, and discrete methods are divided into full and partial aggregation methods. By comparison, discrete methods are generally a better representation of planning and policy problems in the real-world, as the alternatives that will be assessed are limited and relatively well-defined at the beginning of the analysis. In particular, the discrete full aggregation method aims at synthesizing the performance of an option against all the different criteria into a comprehensive score (Dean, 2022). Therefore, the discrete full aggregation method is a methodology that can help to incorporate the performance of one indicator against all other indicators and categories into a single score, the Flood Risk Level (FRL).

Different spatial scales can be used when performing a multi-criteria analysis (MCA). The spatial scale classifies and defines the size of the studied area (J. Wang et al., 2020). A distinction between the scales of the city, watershed, catchment, block, and site can be made. All the different spatial scales are related to one another, which is shown in Figure 3.1. It is easiest to apply GI over a small-scale area to express the hydrological performance. When focusing on a closed catchment system it might also not be needed to focus on a larger scale. However, at smaller scales, the effect of GI on streams can be dispersed (J. Wang et al., 2020).

In the current study, the spatial scale is defining the size of the studied area is the city region. The research focusses on urban areas and the tool should apply to the spatial scale of municipalities. The scale at which the FRL is determined is site level, one site is represented by a raster grid cell.

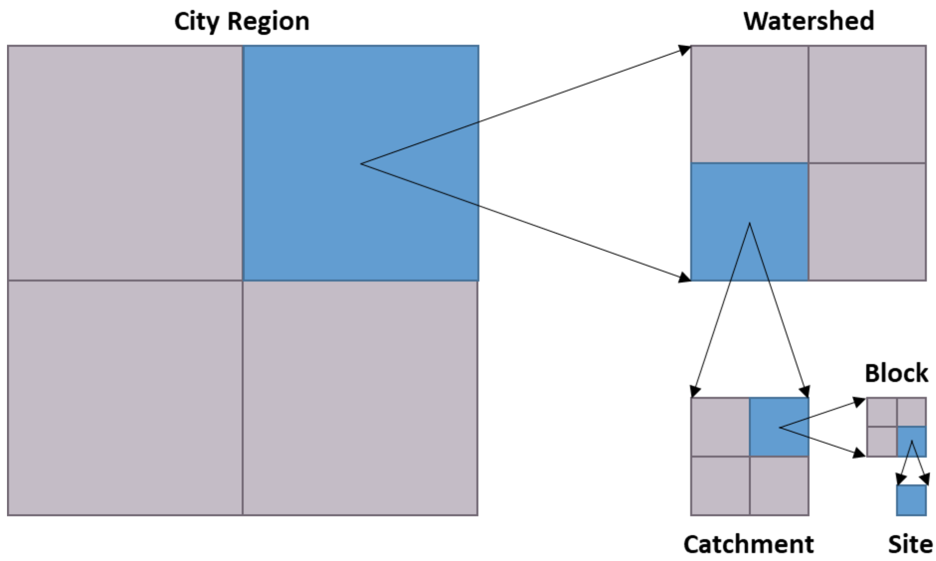


Figure 3.1 Relationship between different spatial scales (Wang et al., 2020)

The MCA will be implemented to map the flood risk level using a Geographical Information System (GIS). The maps that will be used will be converted to raster data, so all data input is the same sort and size. Different sources were compared based on the raster grid sizes that were used, as it needed to be considered what the size of the raster data should be. Throughout this comparison it was noticed that different raster grid sizes were used, ranging from 0.5-by-0.5 meters to 500-by-500 meters. However, a common thought of the sources Park & Lee (2019) and Provincie Zuid-Holland (2023) as to use the grid size of one of the reference layers. For this research, the input layer of the elevation, the AHN (Algemeen Hoogtebestand Nederland) is used as the reference to use the raster grid size of 5-by-5 meters for further analysis in GIS. Within the multi-criteria analysis the following steps, based on Dean (2022) and Saaty (1981), must be followed to transform a set of criteria into a decision:

1. Problem definition
2. Development of the categories and indicators
3. Structuring the decision model
4. Scoring of impacts of each indicator
5. Weighting of indicators
6. Combining the scores and weights
7. Validation of the tool
8. Presentation of the results to support the final decision.

In the following paragraphs, each step will be further elaborated on.

Step 1. Problem definition

The first step of the MCA is the problem definition. The problem definition involves the identification of the problem, which entails finding out what problems or opportunities exist (Saaty, 1981). However, this step also allows for the analysis to be structured based on the scope, type of MCA, the steps of the process, and the problem (Dean, 2022).

The scope of the analysis in this research is focused on urban areas of municipalities in the Netherlands. So, the analysis should be universally adoptable to all municipalities within the region of the Netherlands.

The type of MCA that will be employed during this research is the Analytical Hierarchical Process (AHP), which is a well-known full aggregation method, and which is widely used for structuring decision problems (Saaty, 1981). The AHP method as originally developed by Saaty (1981) and aims at assessing options through the calculation of a comprehensive score. The AHP seeks to reduce a multi-criteria decision problem to a series of smaller analyses based on the incapability of the human mind for considering too many factors simultaneously. By arranging the elements of the analysis into smaller contained analyses, each set of options is considered separately per decision criteria (Dean, 2022). Thereby, it offers a way to integrate complexity, set the right objectives, establish priorities, and determine the overall value of each option (Saaty, 1981).

The steps for computing the AHP were previously defined in this section. The defined steps were based on the practical guides of Dean (2022) & Saaty (1981) for computing the AHP analysis.

The MCA should define the Flood Risk Level (FRL) for each defined location. For the execution of the analysis, it is necessary to involve the indicators that influence the flood risk within the urban area, thereby, aspects of Green Infrastructure (GI) alternatives need to be taken into consideration to also include the impact of GI implementation in the results. The problem at hand is identified by the typology of a 'sorting problem'. A sorting problem is characterized as a problem where the options are distinguished into classes of 'acceptable' and 'unacceptable' (Dean, 2022).In the current study, the sorting problem is indicated by the risk perception, the analysis could result in the classes of 'very high risk', 'high risk', 'moderate risk', 'low risk', or 'very low risk'.

Step 2. Development of the categories and indicators

In the second step of the AHP, the indicators are considered. The indicators are the factors that influence the problem and will be located at the bottom level of the hierarchy structure (Saaty, 1981). For the identification of the indicators a bottom-up approach has been used, as the indicators have been identified first, and later on, the categories involved in the hierarchy will be determined.

The research on the indicators can be found in Section 2.3.2, were all considered indicators in relevant literature were compared and a selection has been made. For this research, the following indicators are considered:

- Buildings;
- Vegetation (sub-divided into high vegetation, medium vegetation, and lower vegetation);
- Pavement;
- Water;
- Elevation;
- Slope;
- Groundwater level;
- Sewage system;
- Soil type.

All indicators were then grouped into categories for clustering of the analysis, the concerned categories are ‘runoff’ and ‘capacity’. These categories are the options considered to evaluate the problem and come to a comprehensive score, the flood risk level. All categories and indicators that are included in the analysis will be further explained in Sections 3.3 to 3.6. In these sections, the importance of the elements will be discussed and it will be clarified how it is included in the calculation of the comprehensive score of FRL.

Step 3. Structuring the decision model

In the third step of the AHP the decision model, also known as the framework for flood risk determination (FFRD), is structured. The indicators are linked to the categories and sub-divided into sub-categories when necessary. The categories ‘runoff’ and ‘capacity’ divide the indicators into two main groups. This division is made based on the indicators influencing either the runoff volume of the stormwater or the capacity for infiltration or storage of the stormwater. Within the category ‘runoff’ a separate distinction is made between the concerned indicators, by creating the sub-categories ‘land cover’ and ‘geography’. The sub-category ‘land cover’ represents the land use type that covers the surface and is represented by the indicators building, vegetation, pavement, and water. The sub-category ‘geography’ represents the geographical characteristics of the area and is represented by the indicators elevation and slope. Within the category ‘capacity’ no additional sub-division is made, the category is represented by the indicators groundwater level, sewage system, and soil. This forms the FFRD, which was previously presented in Section 2.3.4 (Figure 2.5).

Step 4. Scoring of impacts of each indicator

The performance score identifies the performance of an alternative against a specific indicator. This score is in the shape of a pure number, without physical meaning, belonging to a given scale (Dean, 2022). To indicate the performance of the indicators both quantitative and qualitative formats have been used. Therefore, the scoring of the indicators had to be performed using different approaches. The scoring of indicators has been performed using both the direct rating approach, as well as the proportional scoring approach.

The direct rating approach is mainly used when the time and resources to undertake the analysis are limited. With this approach, the scores are based on the judgments of analysts and decision-makers. For this scoring technique, a score scale is set, where the high-performing options are scoring high on the scale, and the low-performing options are ascribed low scores (Dean, 2022). In the current study the multi-criteria decision analysis, with the direct rating approach is used for the scoring of qualitative indicators. However, it must be noticed that the distance between the values of the scale is not ensured to be equal when using this scoring technique (Dean, 2022). Therefore, the Likert-type scales are only used for determining the ordinal ranking of options.

The other scoring technique, the proportional scoring approach, is a straightforward and quick way to assign scores to quantitative-based indicators. Using this approach all quantitative performance data is translated to the defined interval scale. For all indicators, the lowest score on the scale is assigned to the option with the worst performance, and the highest score is assigned to the option with the best performance. For the options with an intermediate performance, the score is examined relative to the two outer points (Dean, 2022). The general formula (1), retrieved from Dean (2022), for calculating the score using the proportional scoring approach is composed as followed:

$$x(a) = [Highest\ score\ on\ the\ scale] * \frac{Performace\ of\ option\ a - Worst\ performance}{Best\ performance - Wost\ performance} \quad (1)$$

Step 5. Weighting of indicators

In the fifth step of the AHP weights can be assigned to the indicators to understand their relative importance. In order to assign relative importance to the indicators it is necessary to discretize them into several intervals to gain consistency between the indicators (Li et al., 2023). The indicator weight is a coefficient that is commonly intended to represent the level of importance of a goal and corresponding categories and indicators relatively to the other categories and indicators under consideration (Dean, 2022).

Through assessing the different methodologies of GI planning, it became clear that studies that applied weights to the indicators considerably made use of pairwise comparison (Fu et al., 2021; Mei et al., 2018). The study of Mei et al. (2018) was the only assessed study that made use of equal weights for all indicators, which may not fit the real situation. Based on the AHP combined with the method of pairwise comparison an indicator weight vector is made to present the relative importance of different indicators to the evaluation objective (Fu et al., 2021). With the use of the AHP technique, the Multi-Criteria Decision problem for assigning relative importance to the indicators is supported. In this process, pairwise comparison assesses the weights of indicators in a criteria-x-criteria matrix to present the evaluation objective (Saaty, 1981).

A pairwise comparison will require quite an exhaustive process to obtain weights for all indicators, based on understanding and expertise of the process. Therefore, this research will not make use of a pairwise comparison to assign relative importance to the indicators. Nevertheless, there will be assigned weights to the indicators. Weights will be added to the indicator and category level based on experiences and findings from the literature. These findings and weights will be further elaborated on in Section 3.8. However, the tool will first be developed without assigning any weights to the indicators or categories. By adding the weights later on, the effects of relative importance can be observed.

Step 6. Combining the scores and weights

Once the scores have been assigned to the indicators and categories, the FRL score can be determined. First, the FRL will be determined without relative importance. The scores of the indicators will be combined per sub-category and category, to later combine the category scores to form the index (FRL). Combining the indicators of the sub-categories land cover and geography are presented in Sections 3.3.5 and 3.4.3. These sub-categories are then combined with the score of the category runoff in Section 3.5. The remaining indicators are then combined in Section 3.6.4 to form the capacity category score. Finally, both the runoff and capacity scores are then combined to calculate the FRL (section 3.7).

After the FRL without relative importance is determined, the FRL with relative importance will be determined. In Section 3.8, the calculations on how to combine the indicators scores and weights are given. The weights will be assigned to the indicators per (sub-)category. So, the calculation of the FRL based on relative importance will involve the same steps as the calculation of the FRL without relative importance.

Step 7. Validation of the tool

Every evaluative study is affected by several uncertainties and is based on extensive value judgments (Dean, 2022). To validate the tool, the results of the case study will be compared with the map of Deltares & ROR (2018) which indicates the water depth of intense rainfall for two hours. The map indicates the result of a computer simulation for the maximum water depth that can occur in a certain area as a result of intense rainfall (Deltares & ROR, 2018).

Step 8. Presentation of the results to support the final decision

To test the tool a case study will be performed in the Municipality of Tilburg. The case study will be performed using the Geographical Information System (GIS) QGIS and the calculations as described in the following sections. The activities involved in the case study and the results will be presented in Chapter 4.

3.3 Runoff – Land cover

The first category of the framework for flood risk determination (FFRD) is the runoff. One of the sub-categories from the category runoff is land cover (Figure 2.5). The land cover can be seen as a key indicator of flood risk, as land cover concerns the land use type that covers the surface which affects the amount of stormwater runoff. It is often included in urban flood risk tools and is considered to be a core aspect of flood risk probability. Some tools include land use or land cover as an indicator to characterize the type of land, while others include imperviousness to consider surfaces that cannot infiltrate any stormwater.

Land cover types can consist of pervious or impervious surfaces. Comparing both surface types, impervious surfaces contribute the most to stormwater runoff in urban areas (Liu et al., 2014). Impervious surfaces can alter the hydrological cycle of an urban area by obstructing the infiltration of stormwater into the ground, increasing the stormwater runoff, and consequently increasing the risk of flooding (Pacetti et al., 2022). Therefore, the evaluation of land cover types allows identifying areas prone to flooding, due to their ability or inability to effectively drain the stormwater.

For the calculation of the land cover sub-category score, the land cover present within a raster cell will be assessed based on four indicators (Figure 2.5). These indicators are used to calculate the land cover score for each individual raster cell in the considered area. The indicator cell scores can in the end be combined into one overall score which represents the cell's land cover score.

For the current study, the sub-category 'land cover' will consist of the following four indicators:

- Building
- Vegetation
- Pavement
- Water

These indicators will be elaborated on in further detail in Section 3.3.1. to 3.3.4.

3.3.1 Building

The first indicator of the sub-category land cover is building. The presence of buildings will be determined for each raster cell. The presence of buildings will be captured by the amount of building surfaces that cover the area of a raster cell, also referred to as the building density. 'Building' is an important indicator as buildings are considered to be impervious surfaces (Wu et al., 2020). As buildings are considered to be impervious areas, they increase the stormwater runoff volume. So, the higher the building density, the higher the runoff volume.

The score of each raster cell is based on the amount of the raster cell that is covered by buildings, which is represented as a percentage. In order to make the score comparable to the other scores, the score needs to be translated based on the proportional scoring approach. The building score will be calculated using equation 2, which allows for the building score to be evaluated on a scale of 0 to 10.

$$Building_{score} = 10 * \frac{Building_{performance} - lowest\ building\ density}{highest\ building\ density - lowest\ building\ density} \quad (2)$$

3.3.2 Vegetation

The second indicator of the sub-category land cover is vegetation. The vegetation coverage will be determined for each raster cell, therefore, different vegetation types will be categorized based on their characteristics. The distinction that will be made is considered through the sub-indicators of higher vegetation (trees), medium vegetation (bushes), and lower vegetation (grasses). The distinction of types of vegetation between trees, bushes, and grasses is often seen in studies, such as in the studies of Pacetti et al. (2022) and Gunnarsson et al. (2017).

'Vegetation' is an important indicator as vegetated surfaces are considered to be pervious surfaces, they decrease the stormwater runoff volume and allow for stormwater infiltration. So, the higher the vegetation density, the lower the runoff volume. The total vegetation score is a combination of the three sub-indicators scores that can be calculated based on equation 3. The three sub-indicators are represented by the summation of the vegetation score in the equation. How the scores of the sub-indicators will be calculated is elaborated on in Sections 3.3.2.1 to 3.3.2.3.

$$Vegetation_{score} = \frac{Higher\ vegetation_{score} + Medium\ vegetation_{score} + Lower\ vegetation_{score}}{3} \quad (3)$$

3.3.2.1 Higher vegetation (trees)

The first sub-indicator of the indicator vegetation is higher vegetation. The presence and effect of higher vegetation (trees) will be determined for each raster cell. The presence of trees will be captured by the number of trees that are present within the area of a raster cell, and the effect of the present trees will be taken into account by several characteristics are taken into account.

Trees are an important type of vegetation to consider when assessing the flood risk. Thereby, trees are already included in many designs for GI, such as rain gardens and bioswales. Since trees interact with the urban hydrological cycle via interception, removing water from the soil via transpiration and enhancing infiltration (Berland et al., 2017). Most surfaces of trees, such as the leaves, branches, and trunk can store a few millimeters of precipitation. Although interception storage is generally small, dependent on the time-scale, the number of times that the storage is filled and depleted can be so large that the interception rate is generally of the same size as the evaporation rate. Additionally, interception redistributes the precipitation, some parts of the surface will receive less stormwater due to interception, whilst other parts receive more due to the funneling of the vegetation (Gerrits & Savenije, 2011).

Different tree attributes are of effect on the interception and evaporation loss. To define the effect of trees on flood risk three characteristics are taken into account, namely: type, size (diameter), and the number of trees within a raster cell. For now, every tree is given a score based on the type and diameter, as trees can have a different effect on the flood risk level.

Table 3.1 Higher vegetation (trees) performance

Performance		Size (diameter)				
		<0.4	0.4-0.6	0.6-0.8	0.8-1	>1
Type	Pine	9	7	5	3	1
	Deciduous	8	6	4	2	0

The type of tree is represented by pine and deciduous trees. Pine trees tend to have lower leaf transpiration rates than deciduous trees (Berland et al., 2017), and therefore are considered to have a higher risk perception than deciduous trees, as can be seen in Table 3.1. The size of the trees is taken into account by the diameter of the tree trunk. The size of the tree trunk is mostly related to the crown of the tree. The size of the tree is often related to the effects of stormwater interception and evaporation and contributes to the mitigation of the flood risk (Hiemstra, n.d.). As the size of the tree is negatively correlated with the FRL, the score of a tree with a larger size is higher than the score of a tree with a smaller size. Other than the type and size, also the number of trees is considered. At first, the presence of a tree can have a large impact on the flood risk level of the area, the more trees within an area does not mean that all trees have the same influence on the flood risk level. This can be explained based on the 80/20-model, also known as the Pareto model, which illustrates the decrease of the effect with the increase in quantity (Dasgupta, 2013). The Pareto distribution is widely applied throughout natural sciences. This distribution implies that 20% of the effort needs to be performed in order to gain 80% of the results (Sengupta, 2012). This is similar to the performance of trees within an area. At a certain time, the amount of trees does not increase the effect of the trees on the reduction of the flood risk probability. Based on the principle of the Pareto model a maximum of two trees is taken into account per area. The two trees that are taken into account are based on the average score of all trees in the area. This average score of the trees that are in the same area is then divided by two, to take into account the effect of multiple trees within the same area. The range of the score has a minimum of 0 and a maximum of 10, where 10 also indicates the areas without trees. As the scale of the performance already is 0 to 10, no additional calculation is needed to generate the higher vegetation score.

3.3.2.2 Medium vegetation (bushes)

The second sub-indicator of the indicator vegetation is medium vegetation. The presence of medium vegetation (bushes) will be captured by the amount of bushes that cover the area of a raster cell, also referred to as the bush density. The bush density will be calculated by the percentage of bushes covering the area. Similar to the other types of vegetation, bush density is negatively correlated with the FRL. Therefore, the score contributing to the FRL is lower when a higher bush density is present, and the other way around.

The score of each raster cell is based on the amount of the raster cell that is covered by bushes, which is represented as a percentage. In order to make the score comparable to the other scores, the score needs to be translated based on the proportional scoring approach. The medium vegetation score will be calculated using equation 4, which allows for the medium vegetation score to be evaluated on a scale of 0 to 10.

$$Medium\ vegetation_{score} = 10 * \frac{Medium\ vegetation_{performance} - highest\ bush\ density}{lowest\ bushe\ density - highest\ bush\ density} \quad (4)$$

3.3.2.3 Lower vegetation (grasses)

The third sub-indicator of the indicator vegetation is lower vegetation. The presence of lower vegetation (grasses) will be captured by the amount of grassed surface that covers the area of a raster cell, also referred to as grass density. The grass density will be calculated by the percentage of grass covering the area.

Preferably, a distinction between different grassed areas can be made, based on the type of low vegetation. Ranging from ryegrass and meadow grasses to creeping bent (Plantum, 2023). Similar to the other types of vegetation, grass density is negatively correlated with the FRL. Therefore, the score contributing to the FRL is lower when a higher grass density is present, and the other way around.

The score of each raster cell is based on the amount of the raster cell that is covered by grassed surfaces, which is represented as a percentage. In order to make the score comparable to the other scores, the score needs to be translated based on the proportional scoring approach. The lower vegetation score will be calculated using equation 5, which allows for the lower vegetation score to be evaluated on a scale of 0 to 10.

$$Lower\ vegetation_{score} = 10 * \frac{Lower\ vegetation_{performance} - highest\ grass\ density}{lowest\ grass\ density - highest\ grass\ density} \quad (5)$$

3.3.3 Pavement

The third indicator of the sub-category land cover is pavement. Paved surfaces impact the flood risk as the increased amount of paving and loss of water storage space in urban areas is increasing the vulnerability to pluvial flooding (Wu et al., 2020). The presence of pavement will be determined for each raster cell. The pavement will be captured by the type of pavement and the amount of pavement that is covering the area of a raster cell. The type of pavement represents the permeability of the surface, as most paving does not allow for infiltration or only partial infiltration. The less permeable the pavement the more stormwater runoff will be generated.

Table 3.2 Type of pavement performance

Type of pavement	Performance
No pavement	1
Permeable pavement (space is left between the joints of pavement, so water can pass around the pavement)	2
Pervious pavement (allows for water to percolate through the surface)	3
Impermeable pavement (completely sealed surface, such as asphalt and concrete)	4

The score of each raster cell is based on the type and amount of pavement that is present within a raster cell. The types of pavements that are distinguished are categorized based on the permeability of the pavement (Table 3.2). Pavement types that consist of completely sealed surfaces, such as asphalt and concrete are perceived as impermeable pavements and generate a high runoff volume. Therefore, impermeable pavement is valued as a greater risk preceptor than pavement types that allow for water to percolate through the surface or around the pavement. Although asphalt is a surface with very high runoff, it does not discharge all captured rainfall. In the research of Armson et al. (2013), it was found that only 50-60% respectively (dependent on winter and summer) of the total rainfall was discharged. The rainfall capture being less than 100% could be attributed to stormwater evaporating from the asphalt surface and water being caught in small puddles on the asphalt surface. Thereby, the meteorological conditions throughout seasons could account for the difference in evaporation rate, as the surface temperature of the asphalt would be increased by warmer meteorological conditions in summer. However, this does not only apply to asphalt, other surface types also have an evaporation rate (Armson et al., 2013). Additionally, the amount of pavement present within a raster cell is of influence on the stormwater runoff. The larger the paved surface the larger the runoff volume that will be produced during a rainfall event. The amount of pavement will be captured by the coverage of paved surfaces per raster cell, also referred to as the pavement density.

The score of each raster cell is based on the area of the cell that is covered by pavement, which is represented as a percentage. Both the pavement type and pavement density are of effect on the pavement score. In order to combine both performances, the pavement type performance will be multiplied by the pavement density. As the highest possible pavement type performance is four and the highest possible pavement density is 100%, multiplying both scores results in an outcome range of 0 to 400. In order to make this score comparable to the other score, the score needs to be translated based on the proportional scoring approach. The pavement score will be calculated using equation 6, which allows for the pavement score to be evaluated on a scale of 0 to 10.

$$Pavement_{score} = 10 * \frac{(\sum Type\ of\ pavement * Pavement\ density) - lowest\ pavement\ performance}{highest\ pavement\ performance - lowest\ pavement\ performance} \quad (6)$$

3.3.4 Water

The fourth indicator of the sub-category land cover is water. The presence of open water will be determined for each raster cell. This presence of water will be captured by the amount of open water surface that covers the area of a raster cell, also referred to as the water density.

The land cover of water allows for the stormwater to maintain in the same area as were it reaches the surface (Huang et al., 2022). Open water, such as ponds or ditches, can help to slow down the peak in runoff during heavy rainfall events (Claessens et al., 2012). As the stormwater is kept in place, urban water bodies are considered to negatively correlate to the stormwater runoff volume. If the water density increases, the amount of runoff decreases, and the other way around.

The score of each raster cell is based on the amount of the raster cell that is covered by open water, which is represented as a percentage. In order to make the score comparable to the other scores, the score needs to be translated based on the proportional scoring approach. The water score will be calculated using equation 7, which allows for the water score to be evaluated on a scale of 0 to 10.

$$Water_{score} = 10 * \frac{Water_{performance} - highest\ water\ density}{lowest\ water\ density - highest\ water\ density} \quad (7)$$

3.3.5 Calculation of the land cover sub-category score

As mentioned at the start of this section, the land cover score is calculated based on the land cover types that are present within the area of a raster cell. The indicators discussed in Sections 3.3.1 to 3.3.4 are used to calculate the overall land cover score of each raster cell. Table 3.3 shows an overview of all these indicators and their measurements.

Table 3.3 Overview of indicators and their measurements in the land cover sub-category score

Indicators	**Performance**	**Score**	**Weight**
Building	0-100%	$10 * \frac{Building_{performance} - lowest\ building\ density}{highest\ building\ density - lowest\ building\ density}$	1
Vegetation	0-30	$\frac{Higher\ vegetation_{score} + Medium\ vegetation_{score} + Lower\ vegetation_{score}}{3}$	1
Higher vegetation (trees)	[0] = deciduous / >1.0m [1] = pine / >1.0m [2] = deciduous / 0.8-1.0m [3] = pine / 0.8-1.0m [4] = deciduous / 0.6-0.8m [5] = pine / 0.6-0.8m [6] = deciduous / 0.4-0.6m [7] = pine / 0.4-0.6m	[0] = 0 [1] = 1 [2] = 2 [3] = 3 [4] = 4 [5] = 5 [6] = 6 [7] = 7	1

	[8] = deciduous / <0.4m [9] = pine / <0.4m [10] = no tree	[8] = 8 [9] = 9 [10] = 10	
Medium vegetation (bushes)	0-100%	$10 * \frac{Medium\ vegetation_{performance} - highest\ bush\ density}{lowest\ bush\ density - highest\ bush\ density}$	1
Lower vegetation (grasses)	0-100%	$10 * \frac{Lower\ vegetation_{performance} - highest\ grass\ density}{lowest\ grass\ density - highest\ grass\ density}$	1
Pavement	0-400	$10 * \frac{(\sum Type\ of\ pavement\ * Pavement\ density) - lowest\ pavement\ performance}{highest\ pavement\ perfomance - lowest\ pavement\ performance}$	1
Water	0-100%	$10 * \frac{Water_{performance} - highest\ water\ density}{lowest\ water\ density - highest\ water\ density}$	1

As can be seen in Table 3.3, all indicators have an equal weight of 1, indicating that all indicators are considered to be of equal importance. Based on the performance of the indicators it appears that the maximum score a raster cell can have is equal to 10, and the minimum score is equal to 0. The overall 'land cover' sub-category score per raster cell is calculated by equation 8, which has a scale of 0 to 10.

$$Land\ cover_{score} = \frac{Building_{score} + Vegetation_{score} + Pavement_{score} + Water_{score}}{4} \quad (8)$$

3.4 Runoff – Geography

The first category of the framework for flood risk determination (FFRD) is the runoff. The second sub-category of the category runoff is geography (Figure 2.5). The geographical position of a raster cell can be seen as a key aspect of flood risk probability, as geography concerns the placement which affects the amount of stormwater runoff. It is often included in urban flood risk tools and is considered to be a core indicator of flood risk probability. Some tools only include the slope, whilst others include both the elevation and slope.

For the calculation of the geography sub-category score, the geographical aspects present within a raster cell will be assessed based on two indicators (Figure 2.5). These indicators are used to calculate the geography score for each individual raster cell in the considered area. The indicator cell scores can in the end be combined into one overall score which represents the cell's geography score.

The sub-category 'geography' will consist of the following two indicators:

- Elevation
- Slope

These indicators will be elaborated on in further detail in Sections 3.4.1. and 3.4.2.

3.4.1 Elevation

The first indicator of the sub-category geography is elevation. The elevation will be determined based on the surface height in meters relative to N.A.P. (National Amsterdam Level). The elevation will be based on the average elevation within a raster cell.

The elevation is an important indicator as it impacts the flood risk as stormwater finds its way from higher elevated areas to lower elevated areas. Otherwise said, flooding starts from the lower elevated lands. So, the greater the elevation of a raster cell compared to its surrounding cells, the less risk of flooding (Li et al., 2023).

The performance of each raster cell is based on the actual elevation that is present within a raster cell. In order to make the score comparable to the other scores, the score needs to be translated based on the proportional scoring approach. The elevation score will be calculated using equation 9, which allows for the elevation to be evaluated on a scale of 0 to 10.

$$Elevation_{score} = 10 * \frac{Elevation_{performance} - highest\ elevation}{lowest\ elevation - highest\ elevation} \tag{9}$$

3.4.2 Slope

The second indicator of the sub-category geography is the slope. The slope will be determined based on the difference in elevation within a raster cell. The slope will be represented by the degrees of height difference.

The slope is an important indicator as high slopes generally produce faster motion and greater flow velocities compared to lower slopes. Therefore, runoff from steep slopes will cause increased water accumulation in areas with lower slopes (Do et al., 2022). Most literature considers flood risk to be negatively correlated with the slope. The steeper the slope, the easier the flow generation and the increase in flood risk (Li et al., 2023).

The performance of each raster cell is based on the actual slope that is present within a raster cell. The slope can be derived from a digital elevation model, in degrees or percentages (Mubeen et al., 2021). In the tool, the slope will be derived in degrees, which indicates the slope performance. In order to make the score comparable to the other scores, the score needs to be translated based on the proportional scoring approach. The slope score will be calculated using equation 10, which allows for the slope to be evaluated on a scale of 0 to 10.

$$Slope_{score} = 10 * \frac{Slope_{performance} - lowest\ slope}{highest\ slope - lowest\ slope} \tag{10}$$

3.4.3 Calculation of the geography sub-category score

As mentioned in at the beginning of this section, the geography score is calculated based on the geographical characteristics of the area within a raster cell. The indicators discussed in Sections 3.4.1 and 3.4.2 are used to calculate the overall geography score of each raster cell. Table 3.4 shows an overview of the indicators and their measurements.

Table 3.4 Overview of indicators and their measurements in the geography sub-category score

Indicators	Performance	Score	Weight
Elevation	Meters relative to N.A.P.	$10 * \frac{Elevation_{performance} - highest\ elevation}{lowest\ elevation - highest\ elevation}$	1
Slope	Degrees	$10 * \frac{Slope_{performance} - lowest\ slope}{highest\ slope - lowest\ slope}$	1

As can be seen in Table 3.4, both indicators have an equal weight of 1, indicating that both considered indicators are of equal importance. Based on the performance of the indicators it appears that the maximum score a raster cell can have is 10, and the minimum score is 0. The 'geography' sub-category score per raster cell is calculated by equation 11, which has a scale of 0 to 10.

$$Geography_{score} = \frac{Elevaion_{score} + Slope_{score}}{2} \qquad (11)$$

3.5 Calculation of the runoff category score

The runoff category represents the amount of stormwater that is superficially discharged. As mentioned before the indicators that influence the runoff were divided into the sub-categories of land cover and geography. Both the sub-category scores will be combined to form the runoff category score. As both sub-category scores have the same scale, they can be combined without any conditional formatting. The 'runoff' category score per raster cell is calculated by equation 12, which has a scale of 0 to 10.

$$Runoff_{score} = \frac{Land\ cover_{score} + Geography_{score}}{2} \qquad (12)$$

3.6 Capacity

The second category of the Flood Risk Level (FRL) is capacity. The capacity of a raster cell can be seen as a key aspect of flood risk probability, as the capacity concerns the amount of stormwater that can be processed within the area. The indicator scores included in the capacity category can in the end be combined into one overall score which represents the cell's capacity score.

For the current study, the category 'capacity' will consist of the following three indicators:

- Groundwater level
- Sewage system
- Soil

These indicators will be elaborated on in further detail in Section 3.6.1. to 3.6.3.

3.6.1 Groundwater level

The first indicator of the category capacity is groundwater level. The groundwater level is an important indicator as it indicates the storage capacity of the soil, based on the separation between the saturated and unsaturated zone. The saturated zone is the zone were the pores of the soil are filled with water, so there is no space left. The infiltrating stormwater can only be stored in the unsaturated zone, which is above the groundwater level. The lower the groundwater level the more available space for infiltrating stormwater, and the more storage capacity in the ground, the lower the risk of flooding (Grondwatersysteem - Waterhuishouding, 2020).

The groundwater level can be derived from the map of Deltares (2017), this map indicates the amount of water in the ground throughout the Netherlands. In this map, the amount of water in the ground is expressed in millimeters relative to the surface level. For the determination of the groundwater level, the performance of each raster cell is based on the actual groundwater level that is present within a raster cell. In order to make the score comparable to the other scores, the score needs to be translated based on the proportional scoring approach. The maximum groundwater level that is used in this calculation is 2500 millimeters, which is based on the highest rating that is given in the map of Deltares (2017). The groundwater level score will be calculated using equation 13, which allows for the groundwater level to be evaluated on a scale of 0 to 10.

$$Groundwater\ level_{score} = 10 * \frac{Groundwater\ level_{performance} - highest\ groundwater\ level}{lowest\ groundwater\ level - highest\ groundwater\ level} \quad (13)$$

3.6.2 Sewage system

The second indicator of the category capacity is the sewage system. Based on the capacity of the sewage system a certain amount of stormwater can be redirected from the urbanized area. Ones the pipes of the sewage system are completely filled, the water might flow out to the surface (Costa et al., 2021). The sewage system indicator expresses whether there is a sewage system available based on the sewage system density. The more dense the sewage system network, the higher the reduction of the flood risk.

The score of each raster cell is based on the sewage system density within the area of the raster cell, which is expressed by the unit meters of sewage pipes per square meter. In order to make the score comparable to the other scores, the score needs to be translated based on the proportional scoring approach. The sewage system score will be calculated using equation 14, which allows for the sewage system score to be evaluated on a scale of 0 to 10.

$$Sewage\ system_{score} = 10 * \frac{Sewage\ system_{performance} - lowest\ density}{highest\ density - lowest\ density} \quad (14)$$

3.6.3 Soil

The third indicator of the category capacity is soil. The soil is an important indicator as it indicates the permeability of the soil. The permeability of the soil refers to the infiltration capacity, which is the ability of the ground to infiltrate stormwater. The larger the infiltration capacity, the lower the flood risk probability during a heavy rainfall event.

Throughout multiple studies, the soil is expressed in the form of hydrological soil groups (Fu et al., 2021; J. Huang et al., 2022; Pacetti et al., 2022). Other studies incorporated multiple sub-indicators of the soil, such as the thickness, porosity, and conductivity (Mei et al., 2018; Reu Junqueira et al., 2022; Webber et al., 2020). In this research, the soil permeability is indicated based on a classification of different soil types that often occur in the Netherlands.

The soil permeability is based on the infiltration capacity of the soil. Each soil type has a different infiltration capacity. Common types of soils that occur in the Netherlands have been distinguished in this research, see Table 3.5. From RIONED (2019) it appears that sand has a 10^6 times larger permeability than clay. In between the permeability of clay and sand are more fine sands (RIONED, 2019), which is representative of loess as loess is a fine-grained soil type (de Vree, n.d.-b). Peat is an organic matter, in contrast to sand, clay, and loess which are all products of erosion. Additionally, peat does not have a high permeable performance, however, the permeability of peat is higher that the permeability of clay (de Vree, n.d.-c).

Table 3.5 Soil type and scores

Soil type	Permeability (performance)	Score (ordinal)
Sand	High	1
Loess	Moderate	2
Peat	Low	3
Clay	Very low	4

The score of each raster cell is based on the soil type classification, which represents a spectrum of different soil types based on their permeability. The classification score ranges from 1 to 4 which is made based on the direct rating approach. However, the classification concerns ordinal ranking and the distance between the values of the scale are not ensured to be equal.

In order to make the score comparable to the other scores, the score needs to be translated. The soil score will be calculated using equation 15, which allows for the soil score to be evaluated on a scale of 0 to 10.

$$Soil_{score} = 10 * \frac{Soil_{score\ ordinal} - lowest\ ordinal\ soil\ score}{highest\ ordinal\ soil\ score - lowest\ ordinal\ soil\ score} \quad (15)$$

3.6.4 Calculation of the capacity category score

The capacity category score represents the amount of stormwater that can be infiltrated in the ground, and discharged from the area. As mentioned at the beginning of this section, the indicators that influence the capacity were the groundwater level, sewage system, and soil. These indicators are used to calculate the overall capacity category score of each raster cell. Table 3.6 shows an overview of the indicators and their measurements.

Table 3.6 Overview of indicators and their measurements in the capacity category score

Indicators	Performance	Score	Weight
Groundwater level	0 – 2500 mm	$10 * \frac{Groundwater\ level_{performance} - highest\ groundwater\ level}{lowest\ groundwater\ level - highest\ groundwater\ level}$	1
Sewage system	m/m^2	$10 * \frac{Sewage\ system_{performance} - lowest\ density}{highest\ density - lowest\ density}$	1
Soil	1-4	$10 * \frac{Soil_{score\ ordinal} - lowest\ ordinal\ soil\ score}{highest\ ordinal\ soil\ score - lowest\ ordinal\ soil\ score}$	1

As can be seen in Table 3.6, not all indicators have equal weight, indicating that not all considered indicators are of equal importance. The indicator scores will be combined to form the capacity category score using the following equation.

$$Capacity_{score} = \frac{Groundwater_{score} + Sewage\ system_{score} + Soil_{score}}{3} \tag{16}$$

3.7 Flood risk level calculation

The final step of the tool consists of the calculation of the overall Flood Risk Level (FRL) score based on the previously determined category scores. Each of the categories has a score ranging from 0 to 10, where 0 indicates that the category has a low probability of flooding, and 10 indicates a high probability of flooding. A simple and straightforward way to calculate the FRL would be to look at the average scores of both categories. However, this would imply that both categories are of equal importance. Therefore, the ability to include weights representing the importance of the categories will be included. Higher weights would indicate more importance in the category. Table 3.7 shows the categories that are used to calculate the FRL and their corresponding weight.

Table 3.7 Categories and their weights for determining the FRL

Categories	Measurement	Scoring	Weight
Runoff	See Tables 3.3 & 3.4	Range: 0 – 10	1
Capacity	See Table 3.6	Range: 0 – 10	1

As can be seen in Table 3.7, both categories have an equal weight of 1, indicating that both considered categories are of equal importance. Based on the measurements of the categories it appears that the maximum FRL a raster cell can have is 10, and the minimum FRL is 0. To calculate the FRL the following equation will be used:

$$Flood\ Risk\ Level = \frac{Runoff_{score} + Capacity_{score}}{2} \tag{17}$$

Based on the above-described calculations, the FRL is expressed within a range of 0 to 10. Where a low FRL indicates a small risk of flooding, a high FRL indicates a greater risk of flooding. A classification of the risk perception can be made a shown in Table 3.8.

Table 3.8 Perception of the FRL (initial)

0.0-2.0	2.0-4.0	4.0-6.0	6.0-8.0	8.0-10.0
Very low risk	Low risk	Moderate risk	High risk	Very high risk

3.8 Flood risk level with relative importance of the categories and indicators

In the previously defined tool, all indicators and categories were considered to be of equal importance when calculating the overall Flood Risk Level (FRL). However, in a real-world situation, the contribution of each of these factors might not be of the same value. To understand the relative importance of each indicator, weights will be added to the indicators and categories based on experiences and findings from the literature.

3.8.1 Assessment relative importance of the categories and indicators

Based on the assessed literature the following similarities in importance are noticed. The runoff is considered to be the most important when assessing flood risk probability. This is also seen when looking into the indicators. The indicators considered under the category runoff are mostly considered to be of greater importance then the indicators considered in the category capacity. Within the runoff category, it is noticed that the elevation is of greater importance than the slope. Looking at the sub-category land cover, the impact of the vegetation is larger compared to the developed land (e.g. building and paved areas), and the water surfaces are of the lowest importance. Considering the capacity category, the soil is considered to be of slightly more importance than the sewage system. Based on these conclusions from the assessment, the weights as shown in Table 3.9 are indicating the relative importance of the categories and indicators.

Table 3.9 Relative importance

Category	**Sub-category**	**Indicator**	**Weight**
Runoff			2
	Land cover		1
		Building	2
		Vegetation	3
		Pavement	2
		Water	1
	Geography		1
		Elevation	2
		Slope	1
Capacity			1
		Groundwater level	1
		Sewage system	1
		Soil	2

The research of Reu Junqueira et al. (2022) considered the runoff to be the most important factor for evaluating flood risk mitigation, as a reduction in runoff indicates a lower risk of sewage overflow and less flooding and water quality problems. Looking into the indicators of the runoff and capacity categories, the importance of the runoff category over the capacity category is noticed. The study of Pacetti et al. (2022) allows for comparison between the imperviousness (in this research also the considered land cover types), slope, soil, and sewage system. Comparing these indicators the slope is considered to be of utmost importance in the research of Pacetti et al. (2022), followed by the imperviousness. The importance of the soil and sewage system, which are indicators of the capacity category, are considerably lower. Although, the slope is considered of utmost importance in the research of Pacetti et al. (2022), the study of Wu et al. (2020) performed an analysis using a Bayesian Network, in which the sensitivity analysis showed a considerably lower impact of the slope compared to the imperviousness, elevation, and sewage system. However, the sensitivity analysis of Wu et al. (2020) showed a significant impact of the elevation, which is somehow coherent to the slope. It was confirmed by the research of Li et al. (2023) that the value of the elevation is of greater impact than the slope. Additionally, the study of Wu et al. (2020) showed that imperviousness had the highest impact on flood perception, followed by elevation, and a lower impact on the sewage system.

In most studies, only the runoff or land use/land cover is considered without considering the difference between land use/land cover types. Based on the research of Huang et al. (2022) the different land cover types forest land, grass land, open water, and developed land can be compared. From this comparison, it arises that forest land stands out most, followed by grassland and developed land, and open water has a lower impact. Comparing these land cover types to the land cover types of this research, a combination of forest land and grassland represents the vegetation. The developed land covers both buildings as well as paved areas, and the open water covers the water surface areas.

Based on the weights included in Table 3.9, the FRL with relative importance can be determined. The following section will elaborate on the determination of the FRL with relative importance.

3.8.2 Calculation of the flood risk level with relative importance

Previously the tool with the related calculations was developed without including the relative importance. This section will show how the relative importance can be included in the tool. In Section 2 of Appendix 1, the codebook of the FRL with relative importance is included, which elaborates on each of the indicators included in the framework for flood risk determination (FFRD).

To include the weights in the calculation, only the equations for the category and sub-category determination have to be adapted. Table 3.10 shows the equations of the categories and sub-categories where the weights are included.

As can be seen in Table 3.10, the categories and sub-categories can be calculated using the weights of the indicators and (sub-)categories. Using weights does not change anything about the range of measurements of the (sub-)categories. The table does not yet elaborate on the calculation of the eventual FRL. Considering that the measurements of the (sub-)categories remain the same, it appears that the maximum FRL a raster cell can have is 10, and the minimum FRL is 0. To calculate the FRL the following equation will be used:

$$Flood\ Risk\ Level_{weighted} = \frac{\sum Category_{score} * Weight}{\sum Weights} \tag{18}$$

Table 3.10 Overview of the category, sub-category, and indicator calculations to determine the FRL with relative importance

Category	Sub-category	Indicator	Calculations
Runoff			$Runoff_{score} = \frac{\sum Sub-category_{score} * Weight}{\sum Weights}$
	Land cover		$Land\ cover_{score} = \frac{\sum Indicator_{score} * Weight}{\sum Weights}$
		Building	$Building_{score} = 10 * \frac{Building_{performance} - lowest\ building\ density}{highest\ building\ density - lowest\ building\ density}$
		Vegetation	$Vegetation_{score} = \frac{Higher\ vegetation_{score} + Medium\ vegetation_{score} + Lower\ vegetation_{score}}{3}$
		- Higher	Qualitative measurement with a range of 0 to 10
		- Medium	$Medium\ vegetation_{score} = 10 * \frac{Medium\ vegetation_{performance} - highest\ bush\ density}{lowest\ bushe\ density - highest\ bush\ density}$
		- Lower	$Lower\ vegetation_{score} = 10 * \frac{Lower\ vegetation_{performance} - highest\ grass\ density}{lowest\ grass\ density - highest\ grass\ density}$
		Pavement	$Pavement_{score} = 10 * \frac{(\sum Type\ of\ pavement * Pavement\ density) - lowest\ pavement\ performance}{highest\ pavement\ performance - lowest\ pavement\ performance}$
		Water	$Water_{score} = 10 * \frac{Water_{performance} - highest\ water\ density}{lowest\ water\ density - highest\ water\ density}$
	Geography		$Geography_{score} = \frac{\sum Indicator_{score} * Weight}{\sum Weights}$
		Elevation	$Elevation_{score} = 10 * \frac{Elevation_{performance} - highest\ elevation}{lowest\ elevation - highest\ elevation}$
		Slope	$Slope_{score} = 10 * \frac{Slope_{performance} - lowest\ slope}{highest\ slope - lowest\ slope}$
Capacity			$Capacity_{score} = \frac{\sum Indicator_{score} * Weight}{\sum Weights}$
		Groundwater level	$Groundwater\ level_{score} = 10 * \frac{Groundwater\ level_{performance} - highest\ groundwater\ level}{lowest\ groundwater\ level - highest\ groundwater\ level}$
		Sewage system	$Sewage\ system_{score} = 10 * \frac{Sewage\ system_{performance} - lowest\ density}{highest\ density - lowest\ density}$
		Soil	$Soil_{score} = 10 * \frac{Soil_{score\ ordinal} - lowest\ ordinal\ soil\ score}{highest\ ordinal\ soil\ score - lowest\ ordinal\ soil\ score}$

3.9 Conclusion

In this chapter, the methodology for the development of the flood risk assessment tool (FRAT) was presented. The goal of the tool is to map the Flood Risk Level (FRL) and understand the contribution of the indicators in relation to flood risk determination in Dutch urban areas. Thereby, the tool will provide municipalities with a simple and straightforward method to gain insight into areas with enhanced flood risk.

The methodology of the FRAT is based on a multi-criteria analysis (MCA). This is performed in the form of an analytical hierarchy process (AHP), which helps to incorporate the performance of one indicator against all other indicators and categories into a single score, the FRL. The framework for flood risk determination is the decision model for the AHP and divides the FRL into categories and indicators.

The indicators are scored based on the performance per specific indicator. The indicator scores are combined with the (sub-)category scores, which are then combined to determine the FRL score. To make all indicator scores comparative to one another the direct rating and proportional scoring approach have been applied. Additionally, weights have been assigned to the indicators and categories, to determine the FRL with relative importance. The methodology has shown all scores and calculations to perform the FRAT.

It is important that the newly developed FRAT provides new possibilities in terms of assessing the Flood Risk Level (FRL) on a raster level and providing insight into how to improve the flood risk probability. Looking at the newly developed tool, it can be concluded that the tool differentiates itself from existing tools and with those differentiations provides new possibilities for assessing the FRL and providing insight in how to improve the flood risk probability.

4. Case study Tilburg

In this chapter, a case study will be conducted to illustrate the functioning of the newly developed flood risk assessment tool. During this case study the working of the flood risk assessment tool will be illustrated. The case study will be performed in the city of Tilburg, the Netherlands. Section 4.1 introduces the Tilburg case study. In Sections 4.2 to 4.4 the application of the tool will be illustrated. Then, in Section 4.5 the tool will be validated. Finally, Section 4.6 will conclude with the overall functioning of the tool. Additionally, in Appendix 2, the complete process of applying the case study in QGIS has been explained.

4.1 Study area

To illustrate the working of the flood risk assessment tool (FRAT), a case study will be performed. The case study will be performed in the city of Tilburg, which is the sixth largest city in the Netherlands with an inhabiting population of 227,701 (CBS, 2023). The municipality of Tilburg has been focusing on the effects of climate change and developed a climate adaptation agenda in which is described how there will be collaborated within the municipality of Tilburg to maintain an endurable city (Gemeente Tilburg, 2020). Thereby, the municipality of Tilburg is already active in the implementation of green in newly developed and revived neighborhoods.

The municipality of Tilburg already knows some implementations of climate adaptive measures, also including Green Infrastructure (GI) alternatives. However, since these implementations have mostly been applied in newly developed and revived neighborhoods, it is expected that these neighborhoods will have a lower flood risk compared to neighborhoods that have had nor or limited attention, like the city center. The city center is expected to have a higher flood risk due to a higher building density compared to the surrounding neighborhoods, and the center areas are older and contain fewer redeveloped areas.

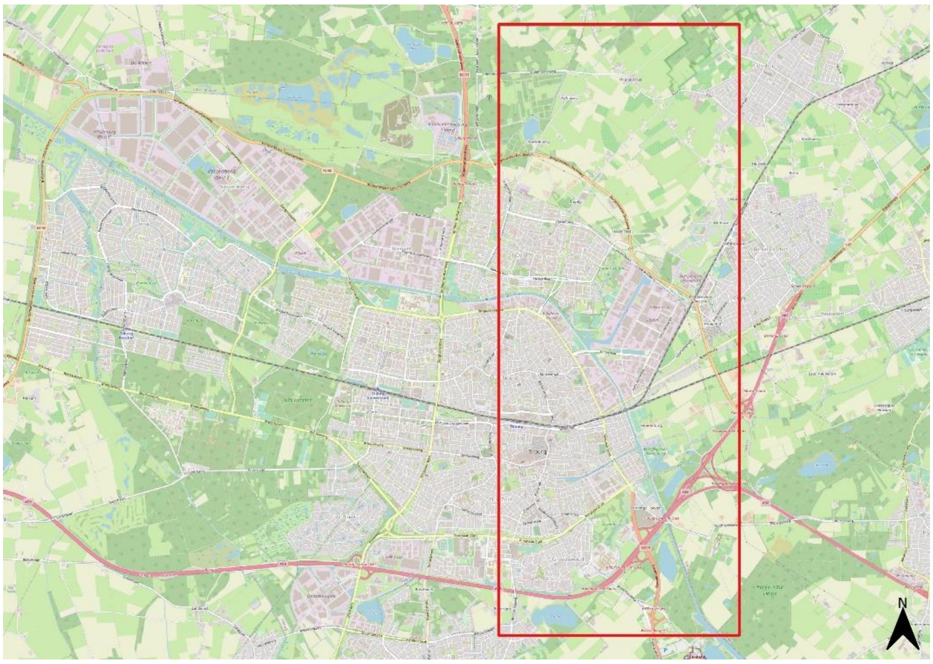


Figure 4.1 The case study area of analysis

In order to perform the assessment the municipal boundary of Tilburg was extracted from the OSM place search plugin in QGIS. This layer was converted to a raster layer with a size of 5-by-5 meters, that is used to align all indicator maps. Working with raster data in QGIS allowed to combine multiple layers and assign different weights to each of the layers, which contributed to the eventual ranking system. However, when performing the assessment it was noticed that the scale of the analysis had to be diminished to make it easier accessible. Therefore, the assessment was decreased to one-fourth of the original size of the municipality. The assessed area is shown in Figure 4.1. The part of the municipality for the analysis was chosen based on the types of urban areas within the quartile. The selected quartile covers parts of the city center as well as other neighborhoods. Additionally, the municipal boundary of Tilburg also covers some parts outside the city of Tilburg, which clarifies the coverage of outer city areas within the selected quartile.

4.2 Runoff score Tilburg

For the calculation of the runoff category score, information regarding the land cover and geography of the municipality needs to be obtained. Therefore, the data sets as stated in Table 4.1 were used to identify the indicator values for the municipality of Tilburg. The data for the indicators vegetation and pavement was retrieved from municipal specific sources. The data for the other indicators was retrieved from national data sources.

Table 4.1 Data sources of runoff category indicator maps

Indicator	**Data**	**Source**
Building	Bebouwing kadaster gegevens	PDOK (services plugin QGIS)
Vegetation - Trees	 Bomen Tilburg	 https://www.dataplatform.nl/#/data/96b46ab5-7638-46bb-b416-c480170b9a84
- Bushes	Kernregistratie Topografie (KRT)	https://data.overheid.nl/dataset/kernregistratie-topografie-tilburg
- Grasses	Kernregistratie Topografie (KRT)	https://data.overheid.nl/dataset/kernregistratie-topografie-tilburg
Pavement	Kernregistratie Topografie (KRT)	https://data.overheid.nl/dataset/kernregistratie-topografie-tilburg
Water	Natural water	QuickOSM query
Elevation	AHN3 DTM 5m	PDOK https://app.pdok.nl/rws/ahn3/download-page/
Slope	AHN3 DTM 5m	PDOK https://app.pdok.nl/rws/ahn3/download-page/

Although an open data source could be used for each of the indicators, not all indicators are represented by the most preferred data maps. For example, the medium vegetation (bushes) is derived from a topographical registration map of Tilburg. However, within this map, the bushes seem to be only present at places surrounding the national and provincial roads, and railways. From this, it appears that not all existing bushes within the municipality are included in this map. Therefrom it can be concluded that not all data is complete or according to the theoretical specified needs, and the results are less accurate.

Notable about the water map is that includes both larger water surfaces, such as the channel and Piushaven, as well as the smaller water surfaces, such as ponds and ditches. The visible water surfaces only include locations that are permanently filled with water, which is similar as described in the methodology (see Chapter 3). The inclusion of locations that are not permanently filled with water could improve the inclusion of green infrastructure (GI) in the flood risk assessment tool (FRAT).

The acquired pavement map presented the pavement types to a more detailed extent than described in the methodology. Therefore, the acquired pavement types had to be categorized to the pavement types given in the methodology.

From the height map (AHN – Algemeen Hoogtebestand Nederland) it is noticed that the city of Tilburg has a slightly higher elevation at the center than in the surrounding areas. The highways and railways within the municipality are elevated and contain a steeper slope. The slope is derived from the height map using the slope algorithm in QGIS. The algorithm calculated the angel of inclination of the terrain from the height map. Stormwater runoff is expected to be mainly influenced by the geographical conditions in higher elevated places with steeper slopes, the additional minimum height differences will limit the amount of stormwater runoff.

All indicator layers are converted to the defined indicator score, see Chapter 3, using the vector algorithm 'field calculator' in the attribute table. After this, the indicator vector layers were converted to raster layers using the algorithm 'rasterize'. After obtaining all the data and preparing the indicator scores, the (sub-)category scores can be calculated. These scores are calculated through performing a raster overlay analysis using the indicator raster layers, that contain the indicator scores. This results in two layers, containing the land cover and geography score of the municipality of Tilburg. These two layers were combined to indicate the runoff category score. This was done for both the equal weights and weighted method.

The runoff category score is based on the land cover and geography sub-category scores (see Chapter 3). The land cover sub-category consists of the indicators building, vegetation, pavement, and water. The geography sub-category consists of the elevation and slope. The runoff category score is determined for a quarter of the municipality of Tilburg with equal weights and the weighted approach. The resulting runoff score based on equal weights can be seen in Figure 4.2, and the weighted runoff score is shown in Figure 4.3. These maps have also been included in Appendix 3.

Most prominent in the runoff score with equal weights is that the areas that consist of open water have a very low runoff score, compared to the other parts of the city. Thereby, it is noticed that the more elevated areas, such as the main roads and railways, have a higher runoff score. This can be explained based on the high scores for slopes and paved areas, and also for the higher scores of vegetation, as less vegetation is present in these areas.

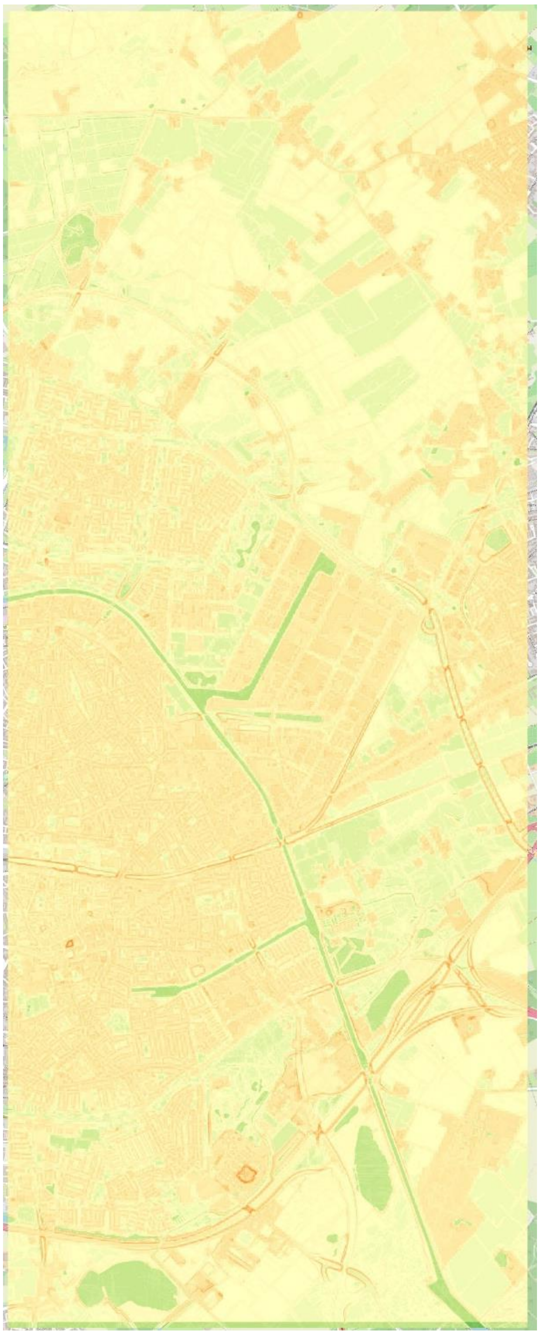


Figure 4.2 Runoff score with equal weights

Figure 4.3 Runoff score weighted

Additionally, the difference is seen between agricultural lands and built areas, which is caused by the amount of vegetation, buildings, and paved areas. For this difference, the land cover type is the largest driver. A higher vegetation cover mostly comes with low coverage of buildings and paved areas and the other way around.

The weighted runoff score is more evenly spread around the municipality of Tilburg, compared to the runoff score with equal weights. The areas of open water have a slightly higher runoff score compared to the runoff score with equal weights, as the indicator water has been considered to be of lower importance than the other land cover types. The impact of the slope is lessened due to the higher involvement of the elevation. On the contrary, the difference between agricultural lands and build areas has become stronger. Particularly, it is seen that the impact of the build and paved areas have increased.

4.3 Capacity score Tilburg

For the calculation of the capacity category score, information regarding the infiltration and storage capacity of the municipality needs to be obtained. Therefore, the data sets as stated in Table 4.2 were used to identify the indicator values for the municipality of Tilburg. The data for the indicator sewage system was retrieved from a municipal specific source. The data for the other indicators was retrieved from national data sources.

Table 4.2 Data sources of capacity category indicator maps

Indicator	Data	Source
Groundwater level	Berging in de grond	Atlas Leefomgeving https://www.atlasleefomgeving.nl/
Sewage system	Riolering Tilburg	https://www.dataplatform.nl/#/data/ff417681-302e-4466-aa90-7574171678be
Soil	Geologische kaart	Dinoloket https://www.dinoloket.nl/geologische-kaart

Although an open data source could be used for each of the indicators, not all indicators are represented by the most preferred data maps. For example, the soil types are retrieved from the geological map of the Netherlands. However, this map mostly contains information for deeper soil layers and does not provide detailed information about the top soil layers, and possible soil improvements that have been made within the municipality.

Notable about the groundwater level map is the large raster grid size. The raster grid size of the retrieved groundwater level map is 250-by-250 meters. Although the size of the raster pixels has been adjusted to 5-by-5 meters, the pixels withing each 250-by-250 meters have the same groundwater level score. The overall groundwater level within the city is moderate compared to the edges of the city, where the groundwater level is a little higher and the capacity for infiltration and water storage is lower.

The sewage system density is determined based on the sewage system map of the municipality of Tilburg. The sewage system lines within this map are compared based on a circular neighborhood within each raster cell by using the 'line density' algorithm in QGIS. The sewage system is most dense in the more urbanized areas and neighborhoods, and less dense in the industrial areas. However, around the provincial road on the North side of the city, the sewage system is most dense. This can be explained based on the amount of branching from this part of the sewage system and the neighboring sewage system underneath the adjacent agricultural lands.

All indicator layers are converted to the defined indicator score, see Chapter 3, using the vector algorithm 'field calculator' in the attribute table. After obtaining all the data and preparing the indicator scores, the category scores can be calculated. These scores are calculated through performing a raster overlay analysis using the indicator raster layers, that

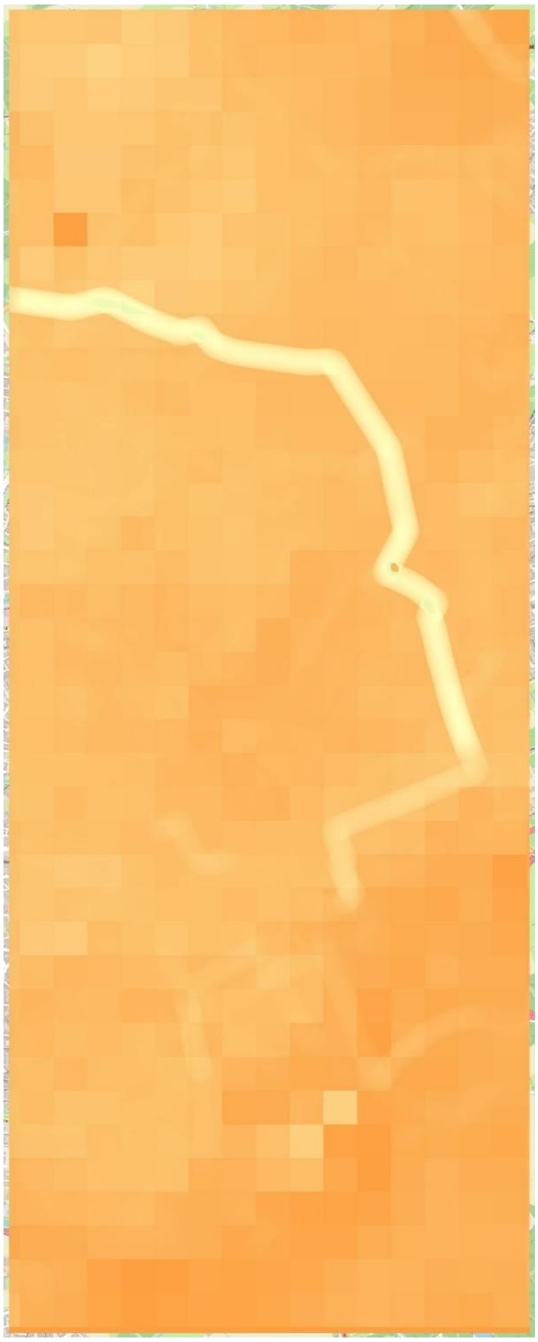


Figure 4.4 Capacity score with equal weights

Figure 4.5 Capacity score weighted

contain the indicator scores. This results in a layer that indicates the runoff category score. This was done for both the equal weights and weighted method.

The capacity category score is based on the indicators groundwater level, sewage system, and soil. The capacity category score is determined for a quarter of the municipality of Tilburg with equal weights and the weighted approach (see Figure 4.4 and 4.5).

Remarkable about the capacity score is the green area that crosses the study area. This area is formed by the increased sewage system density, which was discussed in the preceding section. The remaining parts have a quite high capacity score, which is caused by the groundwater level. The soil type, according to the geological map, is sand all over the municipality of Tilburg and therefore does not cause any fluctuations.

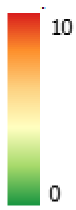
The weighted capacity score is lower when comparing it roughly to the capacity score with equal weights. The overall capacity score has decreased due to the increase in the importance of the soil indicator. As the soil throughout the whole study area has the same, and also the lowest score, for the soil type. Thereby, the other indicators have remained of similar importance and did not cause any other differentiations.

4.4 Flood risk level Tilburg

The Flood Risk Level (FRL) is the overall score that indicates the risk of flooding within a specified area. The FRL is indicated by a score ranging from 0 to 10, where a high score indicates a high risk of flooding. For the calculation of the FRL, the runoff and capacity category scores are combined.

Figure 4.6 Flood risk level equal weights

Figure 4.7 Flood risk level weighted



The FRL is determined for a selected quarter of the municipality of Tilburg. Similar to the runoff and capacity category score, the FRL has been determined based on equal weights and the weighted approach. The resulting FRL score based on equal weights can be seen in Figure 4.6, and the weighted score is shown in Figure 4.7. These maps have also been included in Appendix 3.

The FRL with equal weights is based on the runoff and capacity category score with equal weights. In the map of the FRL with equal weights, it is noticeable that the overall study area has a moderate to high FRL. The distribution that is seen mainly comes from the runoff score, however, the height of the score has been severely risen due to the high capacity score.

The FRL weighted is based on the runoff and capacity category score with relative weights. In the map of the FRL with weights, it is noticeable that the effect of the high capacity score has been suppressed by the applied weights. Additionally, when comparing the weighted FRL to the FRL with equal weights it is seen that the impact of the sewage system on the FRL has decreased. This was already somewhat noticed within the weighted capacity score, and now has been further suppressed by the higher importance of the runoff compared to the capacity.

4.4.1 Potential adjustments

When looking closer at the underlaying scores that form the FRL, it can be seen more specifically what indicator scores have impacted the FRL within a certain location. Looking further into the details of the scoring can support urban planners and policy makers to make decisions on potential adjustments in the urban environment to decrease the risk of flooding.

In order to give an example of the decision support to adjust the urban area, a random selection of raster cells has been made to give an overview of the scoring. This selection has been made as the total amount of cells (in total: 2,265,324) exceeds the practicability. The selection is shown in Appendix 4, and some of the scores will be highlighted in the next part.

Additionally, it is possible to figure out what the effect is on the FRL when indicators within a certain location are adapted. This could be used in multiple cases. One of these cases would be if the considered area has a fairly high FRL. It can be tested what changes to the spatial aspects would help to significantly decrease the FRL. Another case would be if there are plans to make adaptations at a certain location, it can then be checked what the influence of these adaptations is on the FRL.

To show how the changes to the urban environment can be tested for potential adjustments one raster cell with a relatively high FRL is taken as an example. The example raster cell (id: 238278) is located in the city center of Tilburg, at the corner of the building where the Stadhuisstraat and Alexanderstraat meet (Figure 4.8). The area has an FRL score of 7.1 which is perceived as high risk (Table 3.8). Looking at the indicator scoring, which can be seen in Table 4.3, it is immediately noticeable that the land cover scoring is fairly high due to the share of building and pavement, and there is almost no vegetation present and no water surface present within the area. Additionally, the geographical location is not the most optimal, however, the capacity does somewhat compensate for the high runoff score.

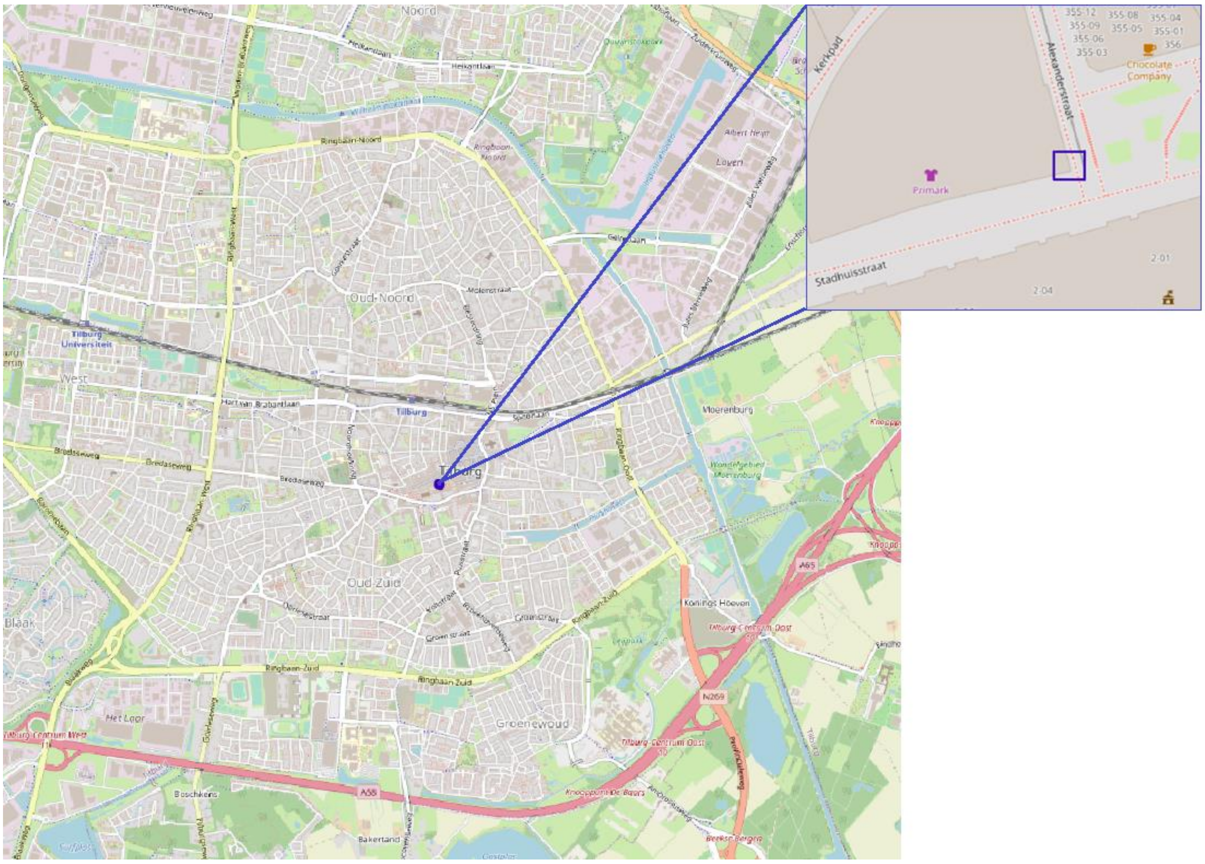


Figure 4.8 Location of raster cell 238278

The flood risk at the considered location can be decreased by making adjustments to multiple indicators. In potential, the runoff category score could be decreased the most compared to the capacity category score. Within the runoff category, it is possible to make adjustments to the indicators within the land cover or geography sub-category.

Table 4.3 Scoring of raster cell (238278)

ID	BuildingScore	TreesScore	BushesScore	GrassScore	VegetationScore	PavementScore	WaterScore	LandCoverScore	ElevationScore	SlopeScore	GeographyScore	RunoffScore	GroundwaterlevelScore	SewageSystemScore	SoilScore	CapacityScore	FloodRiskLevel
238278	8.3	7.0	8.0	8.0	7.7	2.0	10.0	6.7	7.0	10.0	8.0	7.4	6.3	9.8	1.0	5.3	6.7

Starting with the possible adjustments within the sub-category land cover, adjustments could be made to the indicators building, vegetation, pavement, and water. In the current situation, a large share of the surface is covered by a building. The building score of 8.3 (Table 4.3) and less space available for vegetation or open water, also have a high score, resulting in a high land cover sub-category score. A possibility to reduce the FRL is to remove the building. When the building would be removed the building score would be 0, resulting in a FRL of 6.4 (see

Table 4.4). Additionally, the FRL could be further decreased with the implementation of vegetation or open water at the vacated surface. There is no higher (trees) or medium (bushes) vegetation present within the current situation, and only a small proportion of lower (grasses) vegetation. This results in a vegetation score of 9.7 (Table 4.3). A possibility at the location would be to include more vegetation. However, including more vegetation would only be possible if more space would become available by removing the building or reducing the paved surface. For example, reducing the paved surface to 25% allows for the implementation of vegetation coverage of 17%. This could be divided over the implementation of medium and lower vegetation, and higher vegetation could be included. In this example, 10% lower vegetation coverage, 7% medium vegetation coverage, and one deciduous tree with a diameter of 0.7 meters will be added. This results in a vegetation score of 7.1, and a decrease in the FRL of 0.4 (from 7.1 to 6.7) (see Table 4.4). The pavement at the considered location consists of pervious pavement and has a reasonable pavement density. This results in a pavement score of 4.2 (Table 4.3). It would be possible to decrease the pavement density and/or change the pavement type that is used at the location. Changing the pavement type to permeable pavement and reducing the pavement density to 25% could reduce the pavement score to 1.3, which results in a decrease in the FRL of 0.2 (from 7.1 to 6.9) (see Table 4.4). Additionally, the decrease in the pavement density allows for the implementation of vegetation or open water, which could further decrease the FRL. In the current situation, there is no water at the considered location, which is shown by the water score of 10 (Table 4.3). A possibility for the municipality could be to include water at the location. This could be done by replacing a part of the paved surface with open water. Reducing the pavement density to 25% allows for the implementation of open water to 17%, resulting in a decrease in the FRL of 0.1 (from 7.1 to 7.0) (see Table 4.4).

The possible adjustments within the sub-category geography could be made to the indicators' elevation and slope. From a practical point of view, changing the elevation or slope within the considered area is probably not the most feasible adjustment for execution. Nevertheless, the effect of adjusting the elevation or slope will be shown in this part. The current situation has an elevation of 8.9 meters relative to N.A.P., which is represented by an elevation score of 7.0 (Table 4.3). Increasing the elevation would decrease the elevation score. For example, the elevation could be increased to 9.5 meters relative to N.A.P., which results in an elevation score of 6.7. This would eventually result in a decrease of the FRL by 0.1 (7.1 to 7.0) (see Table 4.4). Another possibility is to adjust the slope in the considered location. The current slope is 15 degrees, which is represented by a slope score of 10 (Table 4.3). Decreasing the slope would decrease the slope score. For example, the slope could be decreased to 10 degrees, which results in a slope score of 6.7. This would eventually result in a decrease of the FRL by 0.4 (from 7.1 to 6.7) (see Table 4.4).

Other than adjusting indicators within the runoff category, it is also possible to make adjustments to the indicators within the capacity category. The indicators within the capacity category concern the groundwater level, sewage system, and soil. The groundwater level at the considered location is 925 mm below ground level, which is represented by a score of 6.3 (Table 4.3). A possibility would be to decrease the groundwater level to 1200 mm below ground level, which reduces the groundwater level score to 5.6. This would result in a decrease of the FRL by 0.1 (from 7.1 to 7.0) (see Table 4.4). In the current situation, there is a considerably low sewage system density, which is shown by the sewage system score of 9.8

(Table 4.3). A possible adjustment could be to include more sewage system pipes at the considered location, this could result in a higher sewage system density. For example, if the sewage system density would be increased to 0.2 m/m^2 the sewage system score would decrease to 8.3. This would result in a decrease of the FRL by 0.1 (from 7.1 to 7.0) (see Table 4.4). At the considered location the soil type already consists of sand, therefore it is not possible to adjust the soil type to a more permeable soil type.

Table 4.4 Possible adjustments to improve the FRL of location (238278)

Potential adjustment to raster cell 238278	BuildingScore	TreesScore	BushesScore	GrassScore	VegetationScore	PavementScore	WaterScore	LandCoverScore	ElevationScore	SlopeScore	GeographyScore	RunoffScore	GroundwaterlevelScore	SewageSystemScore	SoilScore	CapacityScore	FloodRiskLevel
Original scores	8.3	10.0	10.0	9.0	9.7	4.2	10.0	8.0	7.0	10.0	8.0	8.0	6.3	9.8	2.5	5.3	7.1
Building	0.0	10.0	10.0	9.0	9.7	4.2	10.0	5.9	7.0	10.0	8.0	7.0	6.3	9.8	2.5	5.3	6.4
Vegetation	8.3	4.0	9.3	8.0	7.1	3.7	10.0	6.9	7.0	10.0	8.0	7.5	6.3	9.8	2.5	5.3	6.7
Pavement	8.3	10.0	10.0	9.0	9.7	1.3	10.0	7.3	7.0	10.0	8.0	7.6	6.3	9.8	2.5	5.3	6.9
Water	8.3	10.0	10.0	9.0	9.7	3.7	8.3	7.7	7.0	10.0	8.0	7.8	6.3	9.8	2.5	5.3	7.0
Elevation	8.3	10.0	10.0	9.0	9.7	4.2	10.0	8.0	6.7	10.0	7.8	7.9	6.3	9.8	2.5	5.3	7.0
Slope	8.3	10.0	10.0	9.0	9.7	4.2	10.0	8.0	7.0	6.7	6.9	7.5	6.3	9.8	2.5	5.3	6.7
Groundwater level	8.3	10.0	10.0	9.0	9.7	4.2	10.0	8.0	7.0	10.0	8.0	8.0	5.6	9.8	2.5	5.1	7.0
Sewage system	8.3	10.0	10.0	9.0	9.7	4.2	10.0	8.0	7.0	10.0	8.0	8.0	6.3	8.3	2.5	4.9	7.0
Combined	0.0	4.0	9.3	8.0	7.1	4.2	10.0	5.0	7.0	6.7	6.9	5.9	6.3	9.8	2.5	5.3	5.7

Based on the possible adjustments that can be made to the indicators within the considered location (raster cell id: 238278), it can be concluded that adjusting the building density has the largest effect on the reduction of the FRL within the considered location, followed by the indicators vegetation and slope. Combining the effect of these indicators would lead to a reduction in the FRL of 1.4 (from 7.1 to 5.7) (see Table 4.4, *Combined*). Additionally, the capacity score could also be further reduced based on changes to the groundwater level or sewage system. However, these adjustments would be of smaller effect on the reduction of the FRL within the considered location.

4.5 Evaluation of the tool

The final Flood Risk Level (FRL) is highly dependent on the indicators that are chosen for inclusion, weighting, scale of analysis, and data sources (Woodruff et al., 2017). Consequently, it is important to conduct validation to understand how well the tool represents the concept of flood risk. Validation of the FRL can be achieved by comparing the FRL scores to an independent dataset (external validation) (Ramspek et al., 2021). The indicators applied in the tool have been selected based on international evidence that they contribute to the relationship between the urban environment and flood risk. Therefore, this part will only focus on validating the FRL and does not include the indicator selection.

The map that will be used for validation of the FRL is the flood risk map that indicates the water depth which has been developed by Deltares & ROR (2018). This map indicates the water depth based on a rainfall event of 140 mm precipitation and a duration of two hours, which is recognized as a short-term heavy rainfall event. A computer simulation was used to indicate the maximum water depth as a result of heavy rainfall. A couple of principles were used for the simulation, including sewage system capacity, superficial runoff, infiltration, and elevation. Comparing the final FRL with the water depth map can provide an objective guideline to support the weighting and indicator inclusion for the flood risk assessment tool (FRAT).

The map of Deltares & ROR (2018) indicates the water depth in centimeters with a pixel size of 2.5-by-2.5 meters. The water depth of the Deltares map can be compared to the FRL, as the greater the water depth the higher the FRL. The maps will be compared to see whether the FRL provided a valid representation for the case study of Tilburg.

Figure 4.9 FRL map weighted

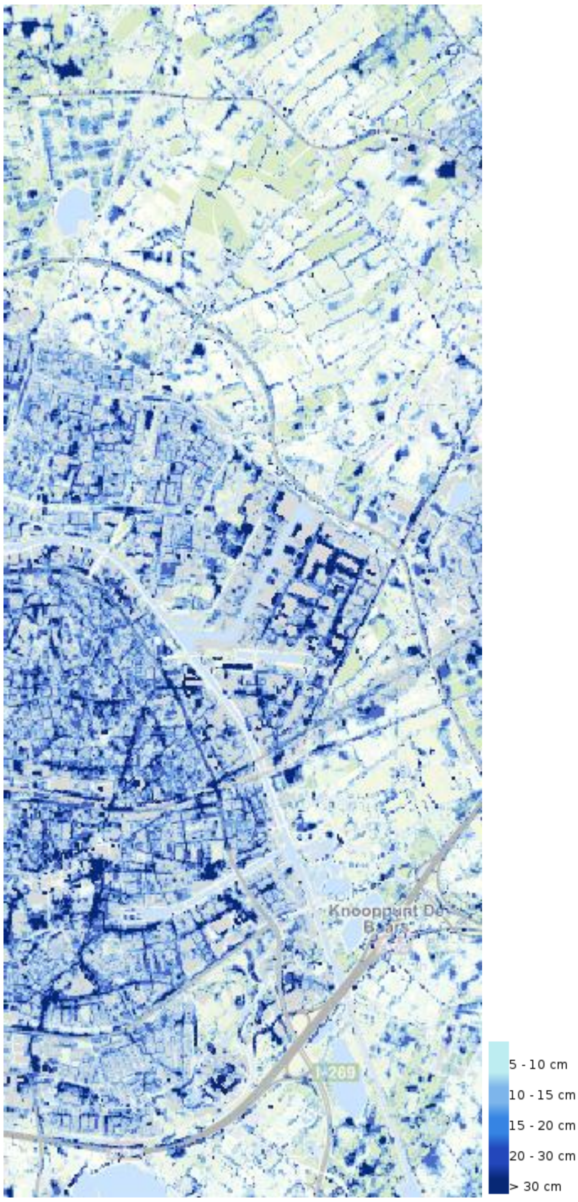


Figure 4.10 Deltares map indicating the water depth (Deltares & ROR, 2018)

Comparing the FRL map (Figure 4.9) to the Deltares map (Figure 4.10) it is also seen that the FRL is highest in the city center, relatively high in the industrial area, and lower but nevertheless present in the surrounding neighborhoods. The city center in the FRL map does not contain as many deviations as the map of Deltares & ROR (2018), however, a slight differentiation is seen where the FRL is low or very high. Areas of open water have a very low risk of flooding and at the agricultural lands on the North side of the city, a very low to low flood risk occurs.

Based on this comparison it can be concluded that the generated FRL map, including weights, shows significant similarities to the water depth map of Deltares & ROR (2018) to show its accuracy.

4.6 Conclusion

In this chapter, a case study was conducted for the municipality of Tilburg to illustrate the practical application of the tool. During the case study, the data sources had to be adjusted to match the scoring as described in the methodology. However, at the end data were obtained for all indicators to show the functioning of the tool.

In general, most data was easily accessible through the use of municipal data via open data platforms, national data, or data sources via the QGIS plugins. However, as not all available data contained the preferred data input some of the sources had to be adjusted to match the tool, which makes it less easy to apply. Changing the input for scoring could help overcome this problem, however, the scoring would be less preferred.

When applying the tool in the case study, the difference between the scores with equal weights and the weighted scores becomes evident. For example, the capacity score was suppressed by the low soil score that had higher importance in the weighted approach. This effect was also noticeable in the weighted FRL, as the overall FRL was lower than the applied weights.

Overall, the municipality of Tilburg has a nicely spread distribution of the FRL and does not show specific problematic locations with an enhanced flood risk. The FRL in the city center is higher compared to its surroundings. Other neighborhoods and the industrial area show a moderate FRL and the surrounding agricultural lands have a low to very low FRL. Additionally, some smaller spots show a higher FRL.

During the case study, the tool showed its practicability for the implementation of potential adjustments. The tool provides a link between the flood risk level and green infrastructure aspects. Thereby, the tool also showed its capability of providing insight into potential adjustments for the support of urban planners and policy makers in decision-making. Additionally, the tool has been compared to the water depth map of Deltares to validate the representation of the flood risk.

5. Conclusion and Recommendations

Climate change has become a global threat and is putting stress on various sectors, such as the economy and biodiversity. Because of climate change more events of extreme rainfall are occurring, which increases the chances of flooding. In the Netherlands, rainfall events cause water nuisance on local and regional levels, which possibly result in damages and disturbances for residents and authorities in the affected areas. Therefore, cities are preparing themselves to keep up with climate change by implementing adaptation efforts, such as Green Infrastructure (GI) alternatives. GI in the Netherlands has mostly been implemented in newly developed neighborhoods and revived neighborhoods, however, research about the effect of GI on flood risk reduction in the Dutch context is relatively limited. An understanding of where an enhanced risk of flooding is present, and which indicators drive the perceived risk level, becomes valuable for the support of urban planners and policy makers in decision-making.

5.1 Conclusion

Urban areas are particularly vulnerable to flooding events driven by intense rainfall. More frequent and extensive floods are inevitable, but this does not mean that floods are accepted. When the precepted flood risk probability is too high, different measures can be taken to reduce the flood risk and/or to keep the risk low. One of these measures is the use of Green Infrastructure (GI) alternatives. GI are strategically designed and managed networks of natural structures. GI alternatives can range to a wide variety of types and open up opportunities for sustainable development. Thereby, the inclusion of GI in urban areas is of effect under both flood and non-flood conditions. Additionally, GI alternatives contribute to ecological, social, and economic benefits. These benefits are seen in multiple studies when assessing the implementation of GI.

A literature review has been performed to assess studies based on their methodology for the determination of the flood risk probability. Where computational models mainly focus on the hydrological performance of the GI alternative and Bayesian Network (BN) assesses the relationship between factors influencing the flood risk, the flood risk assessment allows for the identification of areas prone to flood risk incorporating the indicator relations and suitability mapping. Thereby, flood risk assessments do not involve complicated calculations and are often easily interpretable. Consequently, the indicators for the determination of the flood risk probability used in the assessed studies were compared, and different GI alternatives were examined based on their functioning and included aspects to include GI alternatives in the flood risk assessment. GI alternatives help to restore and recreate a more natural flood response, through the processes of interception, evaporation, infiltration, and depression. A large part of this matter is fulfilled by vegetation.

Assessing available methodologies for the determination of the flood risk probability and the effect of GI helped to understand how an assessment tool for determining the flood risk probability in Dutch urban areas can be developed. Based on the indicators and GI aspects applied throughout the assessed studies the framework for flood risk determination (FFRD) has been developed. This framework forms the decision model in the newly developed GIS-based multi-criteria flood risk assessment tool (FRAT). The FRAT combined commonly applied indicators to form a comprehensive indicator set and thereby provides a detailed calculation of all indicator scores to come to the overall score, the Flood Risk Level (FRL). The eventual

FRL provides better insight into how to adapt to the urban environment using GI alternatives to reduce flood risk.

The functioning of the FRAT was illustrated in a case study of the municipality of Tilburg. During the case study, the data sources had to be adjusted to match the scoring as described in the methodology. Ultimately, data was obtained for all indicators to show the functioning of the tool. In general, most data was easily accessible. During the case study, the tool showed its practicability for the implementation of potential adjustments. The tool provides a link between the flood risk level and green infrastructure aspects, while it supports urban planners and policy makers in decision-making.

The purpose of the thesis has been to develop a FRAT that is able to determine the flood risk in urban areas and captures the contribution of Green Infrastructure (GI) alternatives through the use of indicators that cover the aspects of GI. Dutch municipalities do recognize the risk of pluvial flooding but do not yet incorporate the needed measures when (re-)developing urban areas. Providing Dutch municipalities with a simple and straightforward method helps them to gain insight into the areas within the municipality that have an enhanced risk of flooding. Understanding the conditions within certain locations can help municipalities guide and assess the possible adjustments to reduce the flood risk. The developed tool provides a methodology for the support of decision-making in urban planning, in which different indicators can be evaluated based on their contribution to the reduction of the flood risk probability. Because the aspects of Green Infrastructure (GI) alternatives are also taken into consideration, it can also clarify the influence of the adaptations that will be made for the implementation of a GI alternative. Thereby, the tool contributes to the understanding of the effect of flood risk when changing urban aspects.

5.2 Limitations

One of the drawbacks of this study is the lack of detailed open data sources, to gain the necessary information on the indicators. The lack of the preferred data results in the need to translate this data into the preferred ranking method, this means that the performed case study is adapted to the existing data. The soil, for example, in the case study is represented by the geological formation. Although this seems like a fine source to indicate the soil type, it does not provide detailed information about the top soil layers which mostly affect the infiltration capacity.

Another drawback of this study was the limited computer processing capacity when performing the case study. As a result, the case study area had to be limited to one-fourth of its size. In addition, some indicator data when performing the vector overlay analysis had to be performed on a cell size of 10-by-10 meters instead of 5-by-5 meters, which affected the accuracy of the outcome.

The flood risk assessment tool (FRAT) does not take into account neighboring cells. Within the tool, raster cells are assessed based on the conditions involved in the considered location. However, the impact of other cells that are next to one another or nearby one another is not taken into account. This is considered to be a limitation, as the response to the flood risk of one raster cell also can impact other raster cells.

Other than this the weights applied in the FRAT were based on findings from the literature. This has been recognized as a limitation, based on the abstract strategy that was used to apply weights to the categories and indicators included in the FRAT.

A shortcoming of this research is that the validation that has been applied to the tool was based on a comparison to a map of a computer-based simulation. The indicators applied in the tool were selected based on national or international evidence that they contribute to the relationship between the urban environment and flood risk perception. However, the outcome of the tool has not been validated based on comparative assessments.

Despite these limitations, the tool and the associated research offer a foundation for decision support in urban planning for the Dutch urban environment. Supporting urban planners and policy makers in decision-making when certain locations have an enhanced risk of flooding, is determined based on the indicators included in the framework for flood risk determination.

5.3 Recommendations

While this study presented an attempt in supporting the decision-making for urban planning in Dutch urban environments based on the precepted flood risk, there is still room for improvement of the tool. Future research could further investigate the inclusion of the effect of neighboring cells within the raster, to gain a better understanding of the stormwater runoff that is handled within the cell, or redirected towards neighboring cells.

Subsequently, it is recommended to look further into the chosen weights for the indicators and categories. The weights used for the flood risk assessment tool (FRAT) have been based on findings from the literature. However, other research has used different methodologies, such as pairwise comparison, to assign relative importance to indicators and categories. Using a method like pairwise comparison would provide a more comprehensive contrast between the assigned weights.

Future research could focus on conducting more comprehensive research on the sub-base of green infrastructure (GI) alternatives. This could improve the inclusion of the soil type, as only the four most common soil types within the Netherlands have now been included in the assessment. The implementation of GI alternatives often includes soil improvements. Including a more extensive representation of soil types that can be used for infiltration improvement, would give an even better representation of GI alternatives in the FRAT. Similarly, water surfaces now only contain locations that are permanently filled with water. An additional part for future improvements could be to include places that can temporarily store rainwater, as this is an important feature of many GI alternatives.

Dutch municipalities do recognize the risk of pluvial flooding but do not always incorporate the needed measures when (re-)developing urban areas. Therefore, rules are set by the national government, which now forces all governmental bodies, including municipalities, to undertake action for climate adaptation. For example, the Delta Program of spatial adaptation should help in the realization of climate adaptation measures in the long term. It is recommended that more guidance from national and regional governments should help to encourage the local governments (municipalities) for the implementation of adaptation measures when (re-)developing urban areas, especially with a focus on the pluvial flood risk.

Additionally, it is recommended for municipalities to better record and keep data registration up-to-date about the urban environment. For example, the map including medium vegetation (bushes) in the case study did not include all locations that contain bushes. In order to gain a more representative perspective of the medium vegetation, this map should be upgraded and kept up-to-date by the municipality. Thereby, the medium and low vegetation has now only been assessed based on the density of surface coverage. However, additional distinctions between types of medium and lower vegetation, such as the difference between mosses and grasses or the leaf density of bushes, could be made to create a more representative presentation of the effect on flood risk mitigation.

Finally, the assumption has been made that buildings are always directly discharging the stormwater onto other surfaces. Supplementary features of roofs, such as green roofs or temporary storage of stormwater on roofs, have not been taken into account. For future research, it is recommended to include a more comprehensive perspective on the type of roofs that can be distinguished in Dutch urban areas.

Although future research is required, the current study has contributed to the understanding of the conditions within urban areas that cause an enhanced risk of flooding. Additionally, the aspects of GI alternatives are included in the FRAT. The newly developed tool can give municipalities insight into the areas within an urban area with an enhanced risk of flooding. The FRAT allows urban planners and decision-makers to determine the FRL when adjustments are made to the urban area. Thereby, the FRAT supports local Dutch authorities in the implementation of GI alternatives for flood risk reduction in urban areas.

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Appendix 1. Flood risk level codebook

1. Flood risk level (equal weights)

Table A1.1 Codebook of the FRL with equal weights

Flood Risk Level																					
Runoff																Capacity					
Land cover												Geography									
Building		Vegetation						Pavement		Water		Elevation		Slope		Groundwater level		Sewage system		Soil	
		Trees		Bushes		Grasses															
Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score
0%	0	10	10	0%	10	0%	10	0	0.00	0%	10	2	10.00	0	0.00	0	10	0	10.00	High	1
10%	1	9	9	10%	9	10%	9	50	1.25	10%	9	3	9.57	0.5	0.33	50	9.8	5	9.17	Moderate	2
20%	2	8	8	20%	8	20%	8	100	2.50	20%	8	4	9.13	1	0.67	100	9.6	10	8.33	Low	3
30%	3	7	7	30%	7	30%	7	150	3.75	30%	7	5	8.70	2	1.33	250	9	15	7.50	Very low	4
40%	4	6	6	40%	6	40%	6	200	5.00	40%	6	7	7.83	4	2.67	500	8	20	6.67		
50%	5	5	5	50%	5	50%	5	250	6.25	50%	5	9	6.96	5	3.33	750	7	30	5.00		
60%	6	4	4	60%	4	60%	4	300	7.50	60%	4	10	6.52	7	4.67	1000	6	40	3.33		
70%	7	3	3	70%	3	70%	3	350	8.75	70%	3	15	4.35	10	6.67	2500	0	45	2.50		
80%	8	2	2	80%	2	80%	2	400	10.00	80%	2	20	2.17	15	10.00			50	1.67		
90%	9	1	1	90%	1	90%	1			90%	1	25	0.00					55	0.83		
100%	10	0	0	100%	0	100%	0			100%	0							60	0.00		
$Building_{score}$		$Vegetation_{score} = \frac{\sum vegetation\ score}{3}$						$Pavement_{score}$		$Water_{score}$		$Elevation_{score}$		$Slope_{score}$		$Groundwater_{score}$		$Sewage\ system_{score}$		$Soil_{score}$	

$$Land\ cover_{score} = \frac{Buildin\ g_{score} + Vegetation_{score} + Pavement_{score} + Water_{score}}{4}$$

$$Geography_{score} = \frac{Elevation_{score} + Slope_{score}}{2}$$

$$Capacity_{score} = \frac{Groundwater_{scoe} + Sewage\ system_{score} + Soil_{score}}{3}$$

$$Runoff_{score} = \frac{Land\ cover_{score} + Geography_{score}}{2}$$

$$Flood\ Risk\ Level = \frac{Runoff_{score} + Capacity_{score}}{2}$$

2. Flood risk level (weighted)

Table A1.2 Codebook of the FRL including weights

Flood Risk Level (Weighted)																					
Runoff																Capacity					
Land cover												Geography									
Building		Vegetation						Pavement		Water		Elevation		Slope		Groundwater level		Sewage system		Soil	
		Trees		Bushes		Grasses															
Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score	Performance	Score
0%	0	10	10	0%	10	0%	10	0	0.00	0%	10	2	10.00	0	0.00	0	10	0	10.00	High	1
10%	1	9	9	10%	9	10%	9	50	1.25	10%	9	3	9.57	0.5	0.33	50	9.8	5	9.17	Moderate	2
20%	2	8	8	20%	8	20%	8	100	2.50	20%	8	4	9.13	1	0.67	100	9.6	10	8.33	Low	3
30%	3	7	7	30%	7	30%	7	150	3.75	30%	7	5	8.70	2	1.33	250	9	15	7.50	Very low	4
40%	4	6	6	40%	6	40%	6	200	5.00	40%	6	7	7.83	4	2.67	500	8	20	6.67		
50%	5	5	5	50%	5	50%	5	250	6.25	50%	5	9	6.96	5	3.33	750	7	30	5.00		
60%	6	4	4	60%	4	60%	4	300	7.50	60%	4	10	6.52	7	4.67	1000	6	40	3.33		
70%	7	3	3	70%	3	70%	3	350	8.75	70%	3	15	4.35	10	6.67	2500	0	45	2.50		
80%	8	2	2	80%	2	80%	2	400	10.00	80%	2	20	2.17	15	10.00			50	1.67		
90%	9	1	1	90%	1	90%	1			90%	1	25	0.00					55	0.83		
100%	10	0	0	100%	0	100%	0			100%	0							60	0.00		
		Weight	*1*	*Weight*	*1*	*Weight*	*1*														
$Building_{score}$		$Vegetation_{score} = \frac{\sum Sub\text{-}indicator_{score} * Weight}{\sum Weights}$						$Pavement_{score}$		$Water_{score}$		$Elevation_{score}$		$Slope_{score}$		$Groundwater_{score}$		$Sewage\ system_{score}$		$Soil_{score}$	
Weight	*2*	*Weight*	*3*					*Weight*	*2*	*Weight*	*1*	*Weight*	*2*	*Weight*	*1*	*Weight*	*1*	*Weight*	*1*	*Weight*	*2*
$Land\ cover_{score} = \frac{\sum Indicator_{score} * Weight}{\sum Weights}$												$Geography_{score} = \frac{\sum Indicator_{score} * Weight}{\sum Weights}$				$Capacity_{score} = \frac{\sum Indicator_{score} * Weight}{\sum Weights}$					
Weight	*1*											*Weight*	*1*								
$Runoff_{score} = \frac{\sum Sub\text{-}category_{score} * Weight}{\sum Weights}$																					
Weight	*2*															*Weight*	*1*				
$Flood\ Risk\ Level = \frac{\sum Category_{score} * Weight}{\sum Weights}$																					

Appendix 2. Steps in QGIS

1. Data Sources

For all map layers of the indicators, different data sources were used as base maps. An overview of the files that were used as base maps can be found in the table below.

Table A3 Data sources of base maps

Indicator	Layer type	Data file	Source
Building	Vector	Bebouwing kadaster gegevens (BGT)	PDOK (services pluging QGIS)
Vegetation - Trees	Vector	Bomen Tilburg	https://www.dataplatform.nl/#/data/96b46ab5-7638-46bb-b416-c480170b9a84
- Bushes	Vector	Kernregistratie Topografie (KRT)	https://data.overheid.nl/dataset/kernregistratie-topografie-tilburg
- Grasses	Vector	Kernregistratie Topografie (KRT)	https://data.overheid.nl/dataset/kernregistratie-topografie-tilburg
Pavement	Vector	Kernregistratie Topografie (KRT)	https://data.overheid.nl/dataset/kernregistratie-topografie-tilburg
Water	Vector	Natural water	QuickOSM query
Elevation	Raster / 5 m	AHN3 DTM 5m	PDOK https://app.pdok.nl/rws/ahn3/download-page/
Slope	Raster / 5 m	AHN3 DTM 5m	PDOK https://app.pdok.nl/rws/ahn3/download-page/
Groundwater level	Raster / 250 m	Berging in de grond	Atlas Leefomgeving https://www.atlasleefomgeving.nl/
Sewage system	Vector	Riolering Tilburg	https://www.dataplatform.nl/#/data/ff417681-302e-4466-aa90-7574171678be
Soil	Vector	Geologische kaart	Dinoloket https://www.dinoloket.nl/geologische-kaart

2. Preparing the map

Before all data sources could be added to the map in QGIS, the file had to be prepared. This preparation was done by setting the right project CRS and adding a base map and the municipal boundary.

The projection that is used throughout the creation of the tool is Amersfoort / RD New (ESPG: 28992). This projection is chosen as it is a specifically suitable projection for working on project areas within the Netherlands, and the tool focuses on Dutch urban areas.

As a base map the map 'Opentopoachtergrondkaart' was used, which was retrieved from PDOK services plugin. Additionally, the municipal boundary of Tilburg was included in the map using the OSM Place Search plugin. The boundary was included as a vector layer named 'Municipal Boundary Tilburg'.

3. Steps in QGIS per indicator

Below the steps performed in QGIS per indicator are elaborated on. The steps indicate how each indicator was retrieved from its data source until the indicator was translated to the raster layer including the indicator score.

3.1 Building

First, the 'Building' vector layer was retrieved from the PDOK services plugin, which is accessible via QGIS. This map is made available by the Dutch land register and was subtracted from the Basisregistratie Grootschalige Topografie (BGT).

Before processing the map, the layer was clipped to the 'Municipal Boundary Tilburg'. This was done using the vector geoprocessing tool 'clip', the clip tool allows to perform an overlay analysis on two layers, in which the output contains the areas of the input layer that intersect with the clip layer. In this case, the input layer was 'Building' and the clip layer was the 'Municipal Boundary Tilburg'.

Once the building layer was prepared, the process to gain the raster representing the building density could start. The first step in this process was to generate a vector grid of five-by-five meters that is aligned with the output raster files. This was done by using the vector research tool 'create grid'. Using this tool a rectangular polygon grid was created within the boundary of the Municipality of Tilburg with a horizontal and vertical spacing of five meters. This vector grid was aligned with the raster layers by using the rasterized 'Municipal Boundary Tilburg' as the grid extent. The second step was to calculate the overlap percentage between the 'Building' and 'Vector Grid' layers. In doing so, the vector geometry tool 'collect geometries' was performed on the 'Building' layer to combine all attributes into one. To check whether the right output was generated the attribute tables of 'Building' and 'BuildingCollected' could be compared, in the attribute table of the 'BuildingCollected' layer only one row should be left in the table. After this, the vector geometry tool 'fix geometries' was used, which helps to create a valid representation of an invalid geometry. The layer 'BuildingFixed' was then used to perform the overlap analysis with the 'VectorGrid'. This was done using the vector analysis tool 'overlap analysis' that calculates the area and percentage cover by which features from the input layer 'VectorGrid' are overlapped by features from the overlay layer 'BuildingFixed'. However, due to the limited processing capacity of the available technologies, it was unable to generate the output within a realistic amount of time. Therefore, the vector grid was clipped to a fourth of its size, using the third quarter 'Q3'. As much of the urban area is covered by buildings this vector grid was also converted to a ten-by-ten meters cell size. These adaptations were made by creating a new vector grid with a vertical and horizontal spacing of ten meters, and then selecting the third quarter of the grid cells using 'Select by Expression' after which the selection was saved to a new file ‘VectorGrid_10m_Q3’. The overlap analysis output file was generated based on the input layer ‘VectorGrid_10m_Q3’ overlapped by the features from the overlay layer ‘BuildingFixed_Q3’. The overlay layer was generated by using the vector geoprocessing tool ‘clip’, therefor the layer ‘BuildingFixed’ was clipped to the layer ‘VectorGrid_10m_Q3’. Within this output vector layer, the building score was calculated using the ‘field calculator’, therefore the following formula was used: ‘’10*((building percentage-0)/(100-0))’’.

After this, the final step that remains for generating a raster layer that represents the building density is converting the vector layer ‘BuildingOverlap_10m_Q3’ to a raster layer. This is done through the raster conversion tool ‘rasterize (raster to vector)’, for this command, the input layer is ‘BuildingOverlap_10m_Q3’ for which the score field is used as the burn-in value, and the pixel size is set to five-by-five meters. The ‘Building’ output raster layer contains the building density with a score of 0 to 10 for every pixel within the raster.

To generate the final raster layer the raster tool ‘fill nodata cells’ is used. This tool allows resetting the no data values of the ‘Building’ raster layer, which will be represented by a value of zero. This is done as the cells that contain no data are the cells that have no building within their area, so a value of 0 represents these cells. The range within the raster layer is now 0 to 10 and the raster layer was styled to show ranges of densities in a pseudocolor spectrum using the properties dialog of the layer.

3.2 Vegetation

As mentioned in Section 3.3.2 of the research the indicator vegetation was sub-divided into three sub-indicators. These sub-indicators are trees, bushes, and grasses, which were separately processed in QGIS.

3.2.1 Trees

The trees were retrieved from ‘Bomen Tilburg’, which is a file that provides insight into the locations of trees within the Municipality of Tilburg on a map. Opening the attribute table, the map contains different tree types which can be separated into the types ‘pine’ and ‘deciduous’. The trees are divided into two types by opening the ‘field calculator’ and using the following expression:

‘’CASE

WHEN "nederlands" = 'atlasceder' OR "nederlands" = 'himalayaceder' OR "nederlands" = 'libanonceder' OR "nederlands" = 'blauw spar' OR "nederlands" = 'blauw spar (cv)' OR "nederlands" = 'colorado spar' OR "nederlands" = 'douglasspar' OR "nederlands" = 'edele zilverspar' OR "nederlands" = 'fijnspar' OR "nederlands" = 'kaukasische spar' OR "nederlands" = 'koreaanse zilverspar' OR "nederlands" = 'nordmannzilverspar' OR "nederlands" = 'oostelijke hemlockspar' OR "nederlands" = 'reuzenzilver spar' OR "nederlands" = 'servische spar' OR "nederlands" = 'spar' OR "nederlands" = 'westelijke hemlockspar' OR "nederlands" = 'californische cipres' OR "nederlands" = 'japanse cipres' OR "nederlands" = 'moerascipres' OR "nederlands" = 'watercipres' OR "nederlands" = 'den' OR "nederlands"= 'grove den' OR "nederlands" = 'slangenden' OR "nederlands" = 'weymouthden' OR "nederlands" = 'zwarte den' OR "nederlands" = 'europese lork' OR "nederlands" = 'japanse lariks' OR "nederlands" = 'lariks' OR "nederlands" = 'perzische slaapboom' OR "nederlands" = 'reuzenlevensboom' OR "nederlands" = 'westerse levensboom' OR "nederlands" = 'venijnboom'

THEN'naaldboom'

ELSE'loofboom

END''

After the tree type is added using the field calculator, the score per tree can be calculated. This is done by opening the 'field calculator' and using the following expression:

''CASE

WHEN "diameter_i" < 40 AND "Type tree" = 'naaldboom' THEN 9
WHEN "diameter_i" < 40 AND "Type tree" = 'loofboom' THEN 8
WHEN "diameter_i" >= 40 AND "diameter_i" < 60 AND "Type tree" = 'naaldboom' THEN 7
WHEN "diameter_i" >= 40 AND "diameter_i" < 60 AND "Type tree" = 'loofboom' THEN 6
WHEN "diameter_i" >= 60 AND "diameter_i" < 80 AND "Type tree" = 'naaldboom' THEN 5
WHEN "diameter_i" >= 60 AND "diameter_i" < 80 AND "Type tree" = 'loofboom' THEN 4
WHEN "diameter_i" >= 80 AND "diameter_i" < 100 AND "Type tree" = 'naaldboom' THEN 3
WHEN "diameter_i" >= 80 AND "diameter_i" < 100 AND "Type tree" = 'loofboom' THEN 2
WHEN "diameter_i" >= 100 AND "Type tree" = 'naaldboom' THEN 1
WHEN "diameter_i" >= 100 AND "Type tree" = 'loofboom' THEN 0

END''

Once all attributes were added to the 'Tree' layer to determine the tree category score, the 'Tree' layer was combined with a vector grid. Before doing so, a vector grid had to be created. This was done by using the vector research tool 'create grid'. Using this tool a rectangular polygon grid was created within the boundary of the Municipality of Tilburg with a horizontal and vertical spacing of five meters. This vector grid was aligned with the raster layers by using the rasterized 'Municipal Boundary Tilburg' as the grid extent. After the vector grid was created, the 'Tree' layer and 'Vector Grid' could be joined using the vector data management tool 'join attributes by location'. This algorithm takes 'Tree' as the input vector layer and creates a new vector layer that is an extended version of the input vector layer. This extended version is extended based on the intersecting features with the layer for comparison 'Vector Grid'. The extended version of the 'Tree' layer shows per tree in which cell of the 'Vector Grid' this tree is located. This extended version is saved to a Microsoft Excel File, for further analysis.

In Excel, the duplicates in the id-value of the 'Vector Grid' are highlighted, which easily shows in which grid cells multiple trees are located. The eventual goal in Excel will be to calculate the score per grid cell. The first step in achieving this goal is to sum the tree scores based on the location. So, all trees that are within the same grid cell are summed, this is done using the formula 'SUMIF'. Then, the average score of the trees within one grid cell is to be calculated.

This is done by calculating the number of trees per grid cell, using the formula 'COUNTIF'. The summed value of the trees that are within one grid cell is then divided by the number of trees, resulting in the average score of trees within one grid cell. The final step in calculating the score per grid cell is to calculate the eventual score. This score is calculated by dividing the average score by the number of trees, where the maximum number of trees is two, this is done using the 'IF' formula. Once this is calculated in the Excel file, the file is saved as a CSV file.

The CSV file is added to the GIS map using the data source manager 'delimited text'. The file that is generated by entering the CSV file as a vector point layer is converted to a raster layer. This is done using the raster conversion tool 'rasterize (vector to raster)'. For this command, the input layer is 'Trees' for which the score field is used as the burn-in value and the pixel size is set to five-by-five meters. The 'Trees' output raster layer contains the pavement type as a category score for every cell within the raster. Based on the category score the raster is styled using a pseudocolor spectrum.

3.2.2 Bushes

First, the 'Bushes' vector layer was retrieved from the 'Kernregistratie Topografie (KRT)', which is a file that contains the central registration of all geometrical objects in the municipality of Tilburg. These geometrical objects also contain the bushes that are present within the municipality of Tilburg. The bushes were retrieved by selecting all concerned objects in the attribute table using the expression: "FYS_BGT"='struiken' OR "TYPE_PLUS"='haag'. Once the concerned objects were selected, the export option 'save selected features as…' was used. Using this option all bushes were saved to a new layer, which could be used for further analysis.

Before processing, the map the layer was clipped to the 'Municipal Boundary Tilburg'. This was done using the vector geoprocessing tool 'clip', the clip tool allows to perform an overlay analysis on two layers, in which the output contains the areas of the input layer that intersect with the clip layer. In this case, the input layer was 'Bushes' and the clip layer was the 'Municipal Boundary Tilburg'.

Once the bushes layer was prepared, the process to gain the raster representing the bush density could start. The first step in this process was to generate a vector grid of five-by-five meters that is aligned with the output raster files. This was done by using the vector research tool 'create grid'. Using this tool a rectangular polygon grid was created within the boundary of the Municipality of Tilburg with a horizontal and vertical spacing of five meters. This vector grid was aligned with the raster layers by using the rasterized 'Municipal Boundary Tilburg' as the grid extent. The second step was to calculate the overlap percentage between the 'Bushes' and 'Vector Grid' layers. In doing so, the vector geometry tool 'collect geometries' was performed on the 'Bushes' layer to combine all attributes into one. To check whether the right output was generated the attribute tables of 'Bushes' and 'BushesCollected' could be compared, in the attribute table of the 'BushesCollected' layer only one row should be left in the table. After this, the vector geometry tool 'fix geometries' was used, which helps to create a valid representation of an invalid geometry. The layer 'BushesFixed' was then used to perform the overlap analysis with the 'VectorGrid'. This was done using the vector analysis tool 'overlap analysis' that calculates the area and percentage cover by which features from the input layer 'VectorGrid' are overlapped by features from the overlay layer 'BushesFixed'. Within this output vector layer, the bushes score was calculated using the 'field calculator', therefore the following formula was used: ''10*((bushes percentage-100)/(0-100))''. Based on the adapted analysis area, the layer 'BushesOverlap' was clipped using the vector geoprocessing tool 'clip', to the new size of the area 'VectorGrid_Q3'.

After this, the final step that remains for generating a raster layer that represents the bush density is converting the vector layer 'BushesOverlap_Q3' to a raster layer. This is done through the raster conversion tool 'rasterize (raster to vector)', for this command, the input layer is 'BushesOverlap_Q3' for which the score field is used as the burn-in value, and the pixel size is set to five-by-five meters. The 'Bushes' output raster layer contains the bush density with a score of 0 to 10 for every pixel within the raster.

To generate the final raster layer the raster tool 'fill nodata cells' is used. This tool allows resetting the no data values of the 'Bushes' raster layer, which will be represented by a value of zero. This is done as the cells that contain no data are the cells that have no bushes within their area, so a value of 0 represents these cells. The range within the raster layer is now 0 to 10 and the raster layer was styled to show ranges of densities in a pseudocolor spectrum using the properties dialog of the layer.

3.2.3 Grasses

First, the 'Grasses' vector layer was retrieved from the 'Kernregistratie Topografie (KRT)', which is a file that contains the central registration of all geometrical objects in the municipality of Tilburg. These geometrical objects also contain the areas covered in grass that are present within the municipality of Tilburg. The grassed areas were retrieved through selecting all concerned objects in the attribute table using the expression: "FYS_BGT"='grasland agrarisch' OR "FYS_BGT"='grasland overig' OR "FYS_BGT"='groenvoorziening' OR "FYS_BGT"='heide' OR "FYS_BGT"='rietland'. Once the concerned objects were selected, the export option 'save selected features as…' was used. Using this option all grassed areas were saved to a new layer, which could be used for further analysis.

Once the grasses layer was prepared, the process to gain the raster representing the grass density could start. The first step in this process was to generate a vector grid of five-by-five meters that is aligned with the output raster files. This was done by using the vector research tool 'create grid'. Using this tool a rectangular polygon grid was created within the boundary of the Municipality of Tilburg with a horizontal and vertical spacing of five meters. This vector grid was aligned with the raster layers by using the rasterized 'Municipal Boundary Tilburg' as the grid extent. The second step was to calculate the overlap percentage between the 'Grasses' and 'Vector Grid' layers. In doing so, the vector geometry tool 'collect geometries' was performed on the 'Grasses' layer to combine all attributes into one. To check whether the right output was generated the attribute tables of 'Grasses' and 'GrassesCollected' could be compared, in the attribute table of the 'GrassesCollected' layer only one row should be left in the table. After this, the vector geometry tool 'fix geometries' was used, which helps to create a valid representation of an invalid geometry. The layer 'GrassesFixed' was then used to perform the overlap analysis with the 'VectorGrid'. This was done using the vector analysis tool 'overlap analysis' that calculates the area and percentage cover by which features from the input layer ‘VectorGrid’ are overlapped by features from the overlay layer ‘GrassesFixed’. However, due to the limited processing capacity of the available technologies, it was unable to generate the output within a realistic amount of time. Therefore, the vector grid was clipped to a fourth of its size, using the third quarter ‘Q3’. As much of the urban area is covered by grassed areas this vector grid was also converted to a twenty-by-twenty meters cell size. These adaptations were made by creating a new vector grid with a vertical and horizontal spacing of twenty meters, and then selecting the third quarter of the grid cells using ‘Select by Expression’ after which the selection was saved to a new file ‘VectorGrid_20m_Q3’. The overlap analysis output file was generated based on the input layer ‘VectorGrid_20m_Q3’ overlapped by the features from the overlay layer ‘GrassesFixed_Q3’. The overlay layer was generated by using the vector geoprocessing tool ‘clip’, therefor the layer ‘GrassesFixed’ was clipped to the layer ‘VectorGrid_20m_Q3’. Within this output vector layer, the grasses score was calculated using the ‘field calculator’, therefore the following formula was used: ‘’10*((grasses percentage-100)/(0-100))’’.

After this, the final step that remains for generating a raster layer that represents the grass density is converting the vector layer ‘GrassesOverlap_20m_Q3’ to a raster layer. This is done through the raster conversion tool ‘rasterize (raster to vector)’, for this command, the input layer is ‘GrassesOverlap_20m_Q3’ for which the score field is used as the burn-in value, and the pixel size is set to five-by-five meters. The ‘Grasses’ output raster layer contains the grass density with a score of 0 to 10 for every pixel within the raster.

To generate the final raster layer the raster tool ‘fill nodata cells’ is used. This tool allows resetting the no data values of the ‘Grasses’ raster layer, which will be represented by a value of zero. This is done as the cells that contain no data are the cells that have no grass within their area, so a value of 0 represents these cells. The range within the raster layer is now 0 to 10 and the raster layer was styled to show ranges of densities in a pseudocolor spectrum using the properties dialog of the layer.

3.3 Pavement

The pavement was retrieved from the ‘Kernregistratie Topografie (KRT)’, which is a file that contains the central registration of all geometrical objects in the municipality of Tilburg. These geometrical objects also contain the paved surfaces that are present within the municipality of Tilburg. The paved surfaces were retrieved through selecting all concerned objects in the attribute table using the expression: "FYS_BGT"='erf' OR "FYS_BGT"='gesloten verharding' OR "FYS_BGT"='half verhard' OR "FYS_BGT"='onverhard' OR "FYS_BGT"='open verharding' OR "FYS_BGT"='zand'. Once the concerned objects were selected, the export option ‘save selected features as…’ was used. Using this option all paved surfaces were saved to a new layer, which could be used for further analysis.

Opening the attribute table of the ‘Pavement’ layer, the ‘field calculator’ is used to generate scores per type of pavement based on the classification that is considered. A total of five fields are added. In the first attribute, the pavement types with a score of 1 are considered, which is achieved by using the expression ‘’if("FYS_BGT" = 'onverhard' OR "FYS_BGT" = 'zand' ,1,NULL)’’. In the second attribute the pavement types with a score of 2 are considered, which is achieved by using the expression ‘’if("FYS_BGT" = 'half verhard' ,2,NULL)’’. In the third attribute, the pavement types with a score of 3 are considered, which is achieved by using the expression ‘’if("FYS_BGT" = 'open verharding' OR "FYS_BGT" = 'erf' ,3,NULL)’’. In the fourth attribute, the pavement types with a score of 4 are considered, which is achieved by using the expression ‘’if("FYS_BGT" = 'gesloten verharding' ,4,NULL)’’. In the fifth and final attribute, the scores are combined using the expression ‘’concat("Score 1" , "Score 2" , "Score 3" , "Score 4")’’.

Once the pavement layer was prepared, the process to gain the raster representing the pavement score could start. The first step in this process was to generate a vector grid of five-by-five meters that is aligned with the output raster files. This was done by using the vector search tool ‘create grid’. Using this tool a rectangular polygon grid was created within the boundary of the Municipality of Tilburg with a horizontal and vertical spacing of five meters. This vector grid was aligned with the raster layers by using the rasterized ‘Municipal Boundary Tilburg’ as the grid extent. The second step was to calculate the overlap percentage between the ’Pavement’ and ‘Vector Grid’ layer. In doing so, the vector geometry tool ‘collect geometries’ was performed on the ‘Pavement’ layer to combine all attributes into one. To check whether the right output was generated the attribute tables of ‘Pavement’ and ‘PavementCollected’ could be compared, in the attribute table of the ‘PavementCollected’ layer only one row should be left in the table. After this, the vector geometry tool ‘fix geometries’ was used, which helps to create a valid representation of an invalid geometry. The layer ‘PavementFixed’ was then used to perform the overlap analysis with the ‘VectorGrid’. This was done using the vector analysis tool ‘overlap analysis’ that calculates the area and percentage cover per pavement type which features from the input layer ‘VectorGrid’ are overlapped by features from the overlay layer ‘PavementFixed’. However, due to the limited processing capacity of the available technologies, it was unable to generate the output within a realistic amount of time. Therefore, the vector grid was clipped to a fourth of its size, using the third quarter ‘Q3’. This adaptation was made by selecting the third quarter of the grid cells using ‘Select by Expression’ after which the selection was saved to a new file ‘VectorGrid_Q3’. The overlap analysis output file was generated based on the input layer ‘VectorGrid_Q3’ overlapped by the features from the overlay layer ‘PavementFixed_Q3’. The overlay layer was generated by using the vector geoprocessing tool ‘clip’, therefor the layer ‘PavementFixed’ was clipped to the layer ‘VectorGrid_Q3’. Within this output vector layer, the pavement score was calculated using the ‘field calculator’, therefore the following formula was used: ‘’10*(((%score1*1+%score2*2+%score3*3+%score4*4)-0)/(400-0))’’.

After this, the final step that remains for generating a raster layer that represents the pavement score is converting the vector layer ‘PavementOverlap_Score1+2+3+4_Q3’ to a raster layer. This is done through the raster conversion tool ‘rasterize (raster to vector)’, for this command the input layer is ‘PavementOverlap_Score1+2+3+4_Q3’ for which the score field is used as the burn-in value and the pixel size is set to five-by-five meters. The ‘PavementScore’ output raster layer contains the pavement score with a range of 0 to 10 for every pixel within the raster.

To generate the final raster layer the raster tool ‘fill nodata cells’ is used. This tool allows resetting the no data values of the ‘PavementScore’ raster layer, which will be represented by a value of zero. This is done as the cells that contain no data are the cells that have no paved areas within their area, so a value of 0 represents these cells. The range within the raster layer is now 0 to 10 and the raster layer was styled to show ranges of densities in a pseudocolor spectrum using the properties dialog of the layer.

3.4 Water

First, the 'Water' vector layer was retrieved from the Quick OSM query plugin in QGIS. For the query the key 'natural' was used with the value 'water', using the layer extent of the 'Municipal Boundary Tilburg'.

Once the water layer was prepared, the process to gain the raster representing the open water density could start. The first step in this process was to generate a vector grid of five-by-five meters that is aligned with the output raster files. This was done by using the vector research tool 'create grid'. Using this tool a rectangular polygon grid was created within the boundary of the Municipality of Tilburg with a horizontal and vertical spacing of five meters. This vector grid was aligned with the raster layers by using the rasterized 'Municipal Boundary Tilburg' as the grid extent. The second step was to calculate the overlap percentage between the 'Water' and 'Vector Grid' layer. In doing so, the vector geometry tool 'collect geometries' was performed on the 'Water' layer to combine all attributes into one. To check whether the right output was generated the attribute tables of 'Water' and 'WaterCollected' could be compared, in the attribute table of the 'WaterCollected' layer only one row should be left in the table. After this, the vector geometry tool 'fix geometries' was used, which helps to create a valid representation of an invalid geometry. The layer 'WaterFixed' was then used to perform the overlap analysis with the 'VectorGrid'. This was done using the vector analysis tool 'overlap analysis' that calculates the area and percentage cover by which features from the input layer 'VectorGrid' are overlapped by features from the overlay layer 'WaterFixed'. However, due to the limited processing capacity of the available technologies, it was unable to generate the output within a realistic amount of time. Therefore, the vector grid was clipped to a fourth of its size, using the third quarter 'Q3'. This adaptation was made by selecting the third quarter of the grid cells using 'Select by Expression' after which the selection was saved to a new file 'VectorGrid_Q3'. The overlap analysis output file was generated based on the input layer 'VectorGrid_Q3' overlapped by the features from the overlay layer 'WaterFixed_Q3'. The overlay layer was generated by using the vector geoprocessing tool 'clip', therefor the layer 'WaterFixed' was clipped to the layer 'VectorGrid_Q3'. Within this output vector layer, the water score was calculated using the 'field calculator', therefore the following formula was used: ''10*((water percentage-100)/(0-100))''.

After this, the final step that remains for generating a raster layer that represents the open water density is converting the vector layer 'WaterOverlap_Q3' to a raster layer. This is done through the raster conversion tool 'rasterize (raster to vector)', for this command the input layer is 'WaterOverlap_Q3' for which the score field is used as the burn-in value and the pixel size is set to five-by-five meters. The 'Water' output raster layer contains the open water density with a score of 0 to 10 for every pixel within the raster.

To generate the final raster layer the raster tool 'fill nodata cells' is used. This tool allows resetting the no data values of the 'Water' raster layer, which will be represented by a value of ten. This is done as the cells that contain no data are the cells that have no open water within their area, so a value of 10 represents these cells. The range within the raster layer is now 0 to 10 and the raster layer was styled to show ranges of densities in a pseudocolor spectrum using the properties dialog of the layer.

3.5 Elevation

The elevation map was first retrieved from the PDOK AHN3 download page. On this page, the AHN3 map sheets that match the considered area of the study can be downloaded. For this case study the following sheets were downloaded:

- M5_44GZ1
- M5_44GZ2
- M5_44HZ1
- M5_44HZ2
- M5_45CZ1
- M5_50EN1
- M5_50EN2
- M5_50EZ1
- M5_50EZ2
- M5_50FN1
- M5_50FN2
- M5_50FZ1
- M5_50FZ2
- M5_51AN1
- M5_51AZ1

These sheets were all added to the GIS map and merged so the separate sheets would form one map layer. As the digital terrain model (DTM), instead of the digital surface model (DSM), was used the building heights were not included in the maps. Because the building heights were not included within the map some spots do not contain any data. To fill these empty spaces in the map the raster analysis tool 'fill nodata' was used. The tool enabled interpolating the surrounding elevations to fill the empty raster cells.

The layer was converted to a vector layer, so the score of the elevation could be calculated. This was done using the 'field calculator' and performing the following formula: ''if("Elevation" <= 25 ,10*(("Elevation" -25)/(2-25)), 0)''. With this formula, the score of the elevation was converted to a scale of 0 to 10. With this scoring the layer was converted back to a raster layer, using the raster conversion tool 'rasterize (raster to vector)', for this command, the input layer is 'Elevation' for which the score field is used as the burn-in value, and the pixel size is set to five-by-five meters. This layer was clipped to the area of analysis using the raster extraction algorithm 'clip raster by mask layer'. The 'Elevation_Q3' output raster layer contains the elevation with a score of 0 to 10 for every pixel within the raster.

Once the full map was filled with data, the elevation map could be aligned with the other raster maps, using the raster tool 'align raster'. To align the elevation map the rasterized version of the 'Municipal Boundary Tilburg' layer was used as the reference layer. After this, the only step that was left to do was to style the layer and determine the classification of the range of the layer. The range was used to style the layer in a pseudocolor spectrum.

3.6 Slope

The slope map was generated based on the output map of the elevation. This was done using the raster analysis tool 'slope', which enables to performance of a translation from an elevation raster layer to a slope through executing a raster terrain analysis. The resulting layer could either be set to result in the slope as degrees or percentages. In this project, the slope is considered as degrees. After the elevation map was translated to the slope map, The layer was converted to a vector layer, so the score of the slope could be calculated. This was done using the 'field calculator' and performing the following formula: ''if("Slope" <= 15 ,10*(("Slope" -0)/(15-0)), 10)''. With this formula, the score of the slope was converted to a scale of 0 to 10. With this scoring the layer was converted back to a raster layer, using the raster conversion tool 'rasterize (raster to vector)', for this command the input layer is 'Slope' for which the score field is used as the burn-in value, and the pixel size is set to five-by-five meters. This layer was clipped to the area of analysis using the raster extraction algorithm 'clip raster by mask layer'. The 'Slope_Q3' output raster layer contains the slope with a score of 0 to 10 for every pixel within the raster. The final step remaining was to classify and style the range of the layer in a pseudocolor spectrum.

3.7 Groundwater level

The groundwater level map was imported to the GIS map as a raster layer with a pixel size of 250 meters by 250 meters, as subtracted from the source. As this file was already a raster layer there were only three steps that needed to be performed.

The first step was to align the raster with the other raster maps. This step was performed using the raster tool 'align raster', and the groundwater level map was aligned using the rasterized version of the 'Municipal Boundary Tilburg' layer as the reference layer.

Once the imported map was aligned with the other raster maps, the pixel size could be changed to five by five meters, to allow comparison with the other layers. The pixel size was adjusted using the raster projections tool 'warp (reproject)', which enables to change the target georeferenced units of the outputs file resolution.

The layer was converted to a vector layer, so the score of the groundwater level could be calculated. This was done using the 'field calculator' and performing the following formula: ''10*(("Groundwater level" -2500)/(0-2500))''. With this formula, the score of the groundwater level was converted to a scale of 0 to 10. With this scoring the layer was converted back to a raster layer, using the raster conversion tool 'rasterize (raster to vector)', for this command, the input layer is 'Groundwater level' for which the score field is used as the burn-in value, and the pixel size is set to five-by-five meters. This layer was clipped to the area of analysis using the raster extraction algorithm 'clip raster by mask layer'. The 'GroundwaterlevelScore_Q3' output raster layer contains the elevation with a score of 0 to 10 for every pixel within the raster.

Once the full map was filled with data, the groundwater level map could be aligned with the other raster maps, using the raster tool 'align raster'. To align the groundwater level map the rasterized version of the 'Municipal Boundary Tilburg' layer was used as the reference layer. After this, the only step that was left to do was to style the layer and determine the classification of the range of the layer. The range was used to style the layer in a pseudocolor spectrum.

3.8 Sewage system

The sewage system was imported to the GIS map as a DWG file. Before the DWG file was imported the redundant layers that were included in the file were turned off in AutoCAD. The file was then saved and imported to QGIS. Once the sewage system file was imported into the GIS map the vector line layers were merged to represent one layer. This was done using the vector data management tool ‘merge vector layers’.

The merged vector layers formed the layer ‘Sewage system’, which is represented as a line vector. Because the ‘Sewage system’ was represented as a line vector the interpolation tool ‘line density’ could be performed to calculate the drainage density. In this tool, the ‘Sewage system’ was used as the input line layer. The tool algorithm calculates a density measure for the linear features which are obtained in a circular neighborhood within each raster cell. The output file, a raster layer, shows the sewage system density per raster cell.

The layer was converted to a vector layer, so the score of the sewage system could be calculated. This was done using the ‘field calculator’ and performing the following formula: ‘’if(10*(("Density"-60)/(0-60))’’. With this formula, the score of the sewage sytem was converted to a scale of 0 to 10. With this scoring the layer was converted back to a raster layer, using the raster conversion tool ‘rasterize (raster to vector)’, for this command, the input layer is ‘Sewagesystem_Density’ for which the score field is used as the burn-in value, and the pixel size is set to five-by-five meters. This layer was clipped to the area of analysis using the raster extraction algorithm ‘clip raster by mask layer’. The ‘Sewagesystem_Density_Score_Q3’ output raster layer contains the elevation with a score of 0 to 10 for every pixel within the raster.

Once the map was filled with data, the sewage system map could be aligned with the other raster maps, using the raster tool ‘align raster’. To align the sewage system map the rasterized version of the ‘Municipal Boundary Tilburg’ layer was used as the reference layer. After this, the only step that was left to do was to style the layer and determine the classification of the range of the layer. The range was used to style the layer in a pseudocolor spectrum.

3.9 Soil

A geological map was used as the basis to subtract the soil type. As the map’s extent was the Netherlands, the first step was to decrease the map’s extent to the ‘Municipal Boundary Tilburg’. This was done using the vector geoprocessing tool ‘clip’, in which the geological map was used as the input layer and ‘Municipal Boundary Tilburg’ was used as the overlay layer.

In order to make use of the geological map, the described soil types had to be converted to the four soil types included in this research (sand, loess, peat, and clay). This was done by selecting the different described soil types and categorizing these into the four designated soil types. Appointing each layer feature with the designated soil type was achieved using the ‘field calculator’. Using the field calculator an expression was prepared to create a new field (named ‘Soil type’) in which the designated soil type was linked to the described soil type.

After each feature was assigned a designated soil type, the soil types were divided into categories. This was done similarly to appointing the soil types. The algorithm 'field calculator' was used to create a new attribute field for appointing the category score to the soil types. After this was performed the vector layer could be rasterized using the raster conversion tool 'rasterize (vector to raster)'. For this command, the input layer is 'Soil' for which the category score field is used as the burn-in value, and the pixel size is set to five-by-five meters. This layer was clipped to the area of analysis using the raster extraction algorithm 'clip raster by mask layer'. The 'Soil_Q3' output raster layer contains the soil type as a category score for every cell within the raster.

Finally, the soil raster is styled using a pseudocolor spectrum. The classification of the layer is based on the soil type classification that was assigned earlier to each separate soil type.

4. Generating the Flood Risk Level

After the raster layers of all indicators were generated using QGIS the layers could be combined to form the sub-category scores, category scores, and Flood Risk Level (FRL). To perform these tasks the equations as mentioned in Chapter 3 of the research had to be inserted using the raster analysis algorithm 'raster calculator'. In this algorithm, the expression could be inserted, and a reference layer was inserted to automate the generation of the output extent, cell size, and CRS. The output file was saved and created in the GIS map. The following expressions were used to generate the output.

Expression for the vegetation score (equal weights):

''("Trees_score_Q3_filled_@1"+"BushesScore_filled_@1"+"GrassesScore_20m_Q3_filled@1")/3''

Expression for the land cover score (equal weights):

''("BuildingScore_10m_Q3_@1"+"VegetationScore_@1"+"PavementScore_@1"+"WaterScore_@1")/4''

Expression for the geography score (equal weights):

'' ("ElevationScore_@1"+"SlopeScore_@1")/2''

Expression for the runoff score (equal weights):

'' ("LandCoverScore@1"+"GeographyScore@1")/2''

Expression for the capacity score (equal weights):

''("GroundwaterlevelScore@1"+"Sewagesystem_Density_Score@1"+"SoilScore+weight@1")/3''

Expression for the FRL (equal weights):

‘’("RunoffScore@1"+"CapacityScore@1")/2’’

Expression for the vegetation score (weighted):

‘’("Trees_score_Q3_filled_@1"+"BushesScore_filled_@1"+"GrassesScore_20m_Q3_filled@1")/2’’

Expression for the land cover score (weighted):

‘’("BuildingScore_10m_Q3_@1"*2+"VegetationScore_@1"*3+"PavementScore_@1"*2+"WaterScore_@1"*1)/(2+3+2+1)’’

Expression for the geography score (weighted):

‘’("ElevationScore_@1"*2+"SlopeScore_@1"*1)/(2+1)’’

Expression for the runoff score (weighted):

‘’("LandCoverScore_Weighted@1"*1+"GeographyScore_Weighted@1"*1)/(1+1)’’

Expression for the capacity score (weighted):

‘’("GroundwaterlevelScore@1"*1+"Sewagesystem_Density_Score@1"*1+"SoilScore+weight@1"*2)/(1+1+2)’’

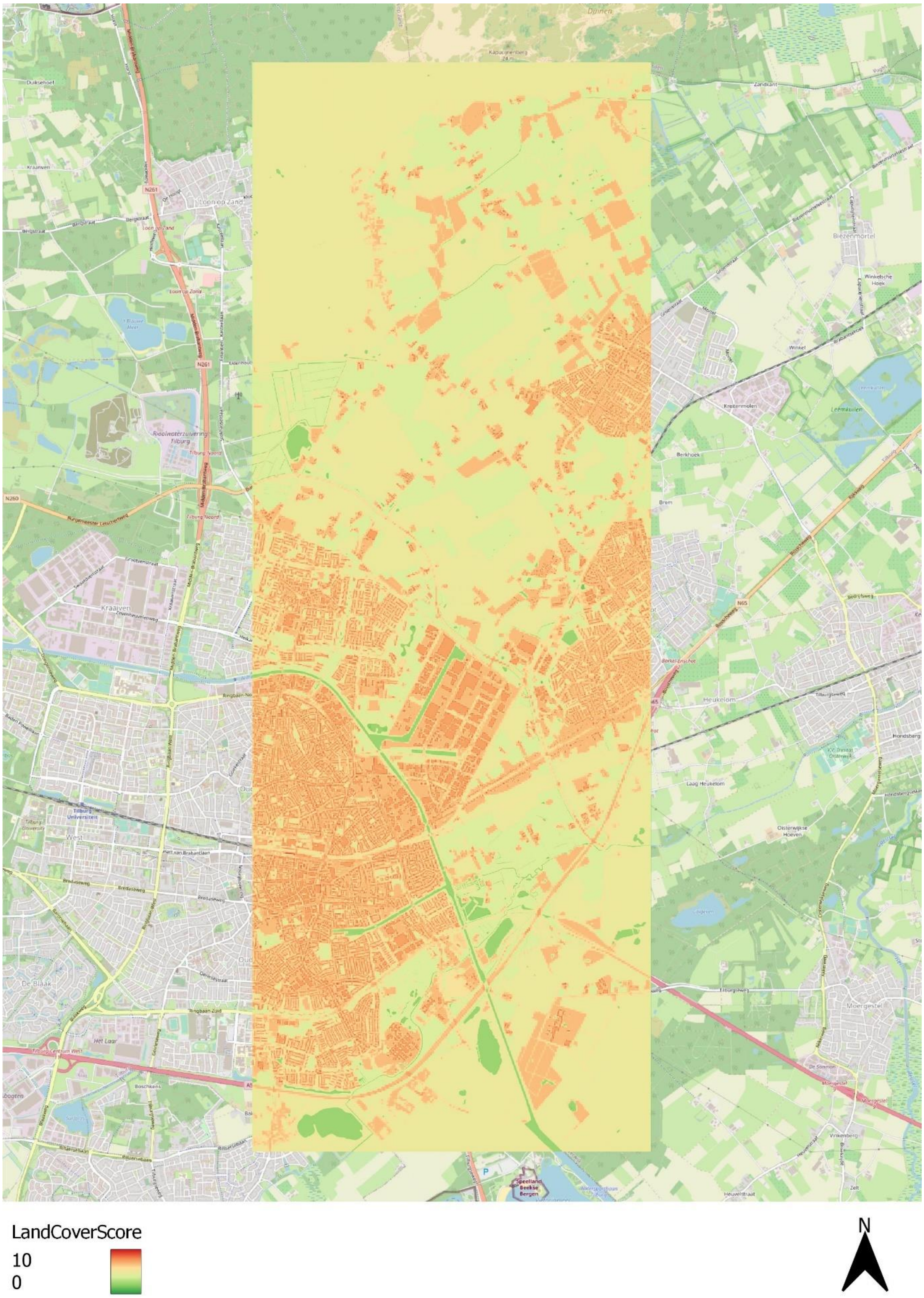
Expression for the FRL (weighted):

("RunoffScore_Weighted@1"*2+"CapacityScore_Weighted@1"*1)/(2+1)

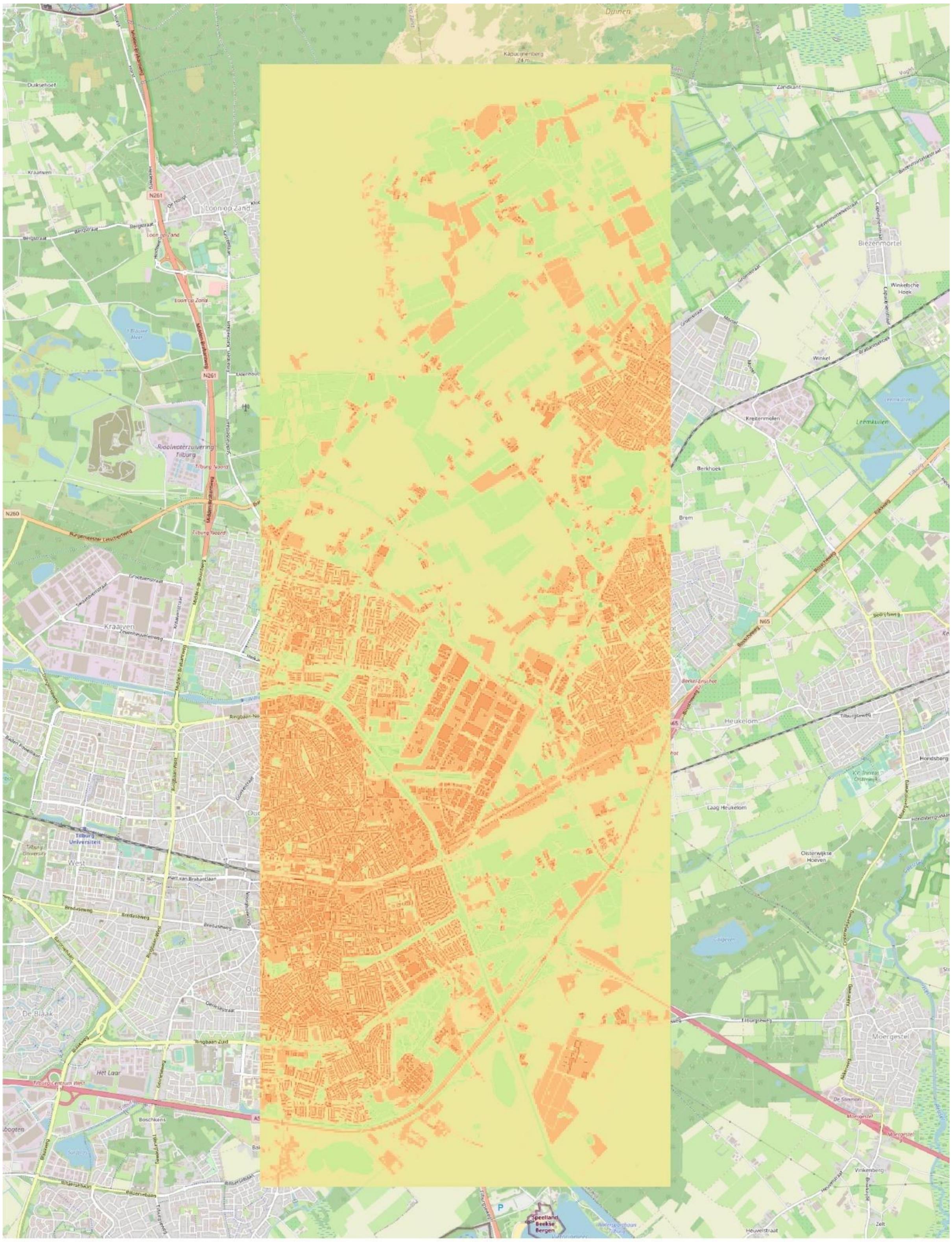
In order to provide a comprehensive overview of all values that resulted in the eventual FRL, the data of the raster maps was combined using the raster analysis algorithm ‘Sample raster values’. This algorithm allowed to add the raster cell value of each layer into an attribute table. The attribute table was generated twice, once for the FRL based on equal weights, and once for the weighted FRL. To use the ‘Sample raster value’ algorithm a point layer was created that had a point in the center of each raster cell. This layer was used as the input layer when the algorithm was performed for the first time. Step by step each raster layer was included, and the column prefix was set to the indicator or category score (for example ‘TreesScore’ or ‘CapacityScore’). The newly created layer was then used as the input layer to include the next raster layer, and so on. Eventually resulting in the two attribute tables for the FRL with equal weights and the weighted FRL.

Appendix 3. Maps of the case study

1. Land cover score (equal weights)



2. Land cover score (weighted)



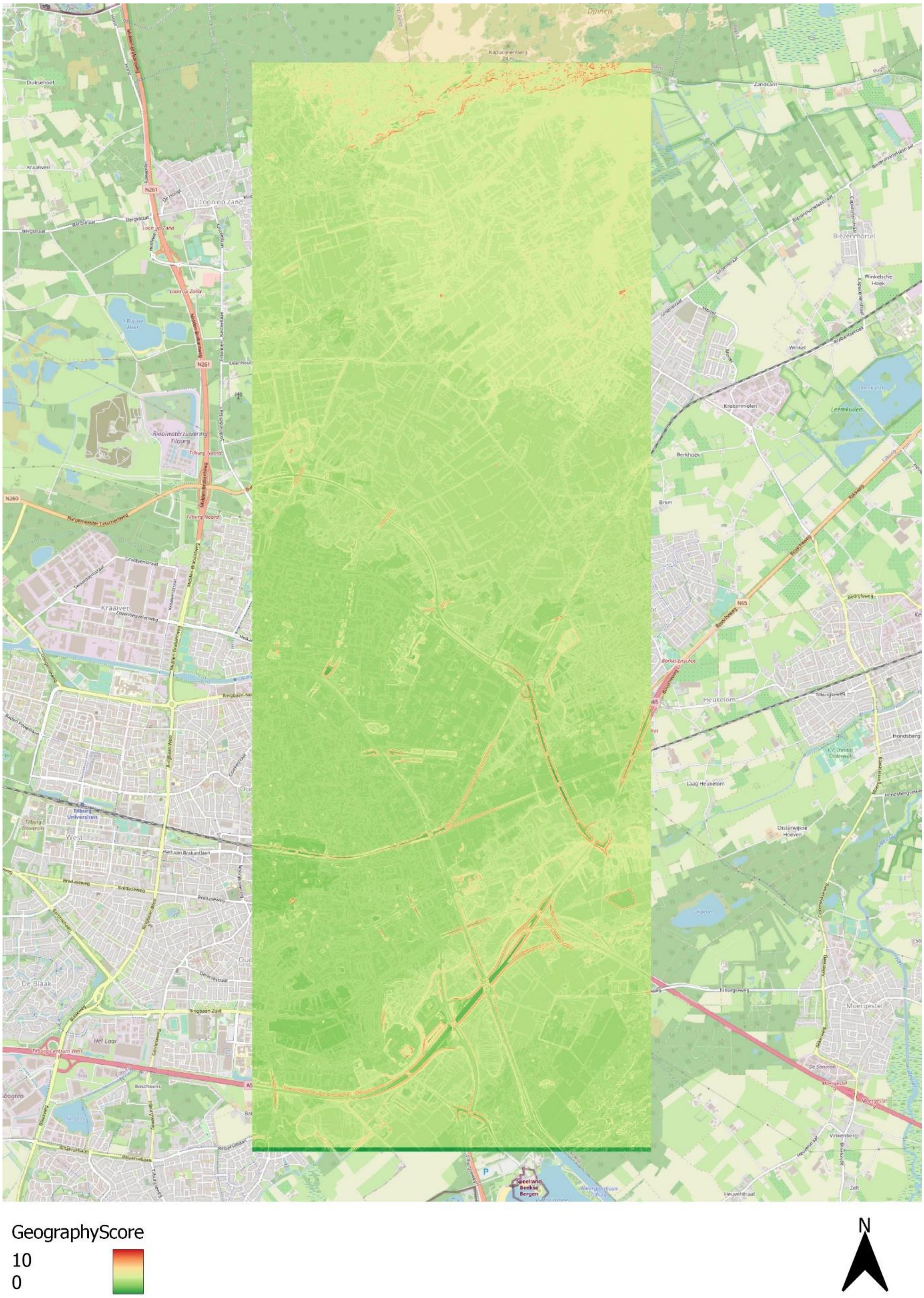
LandCoverScore_Weighted

10

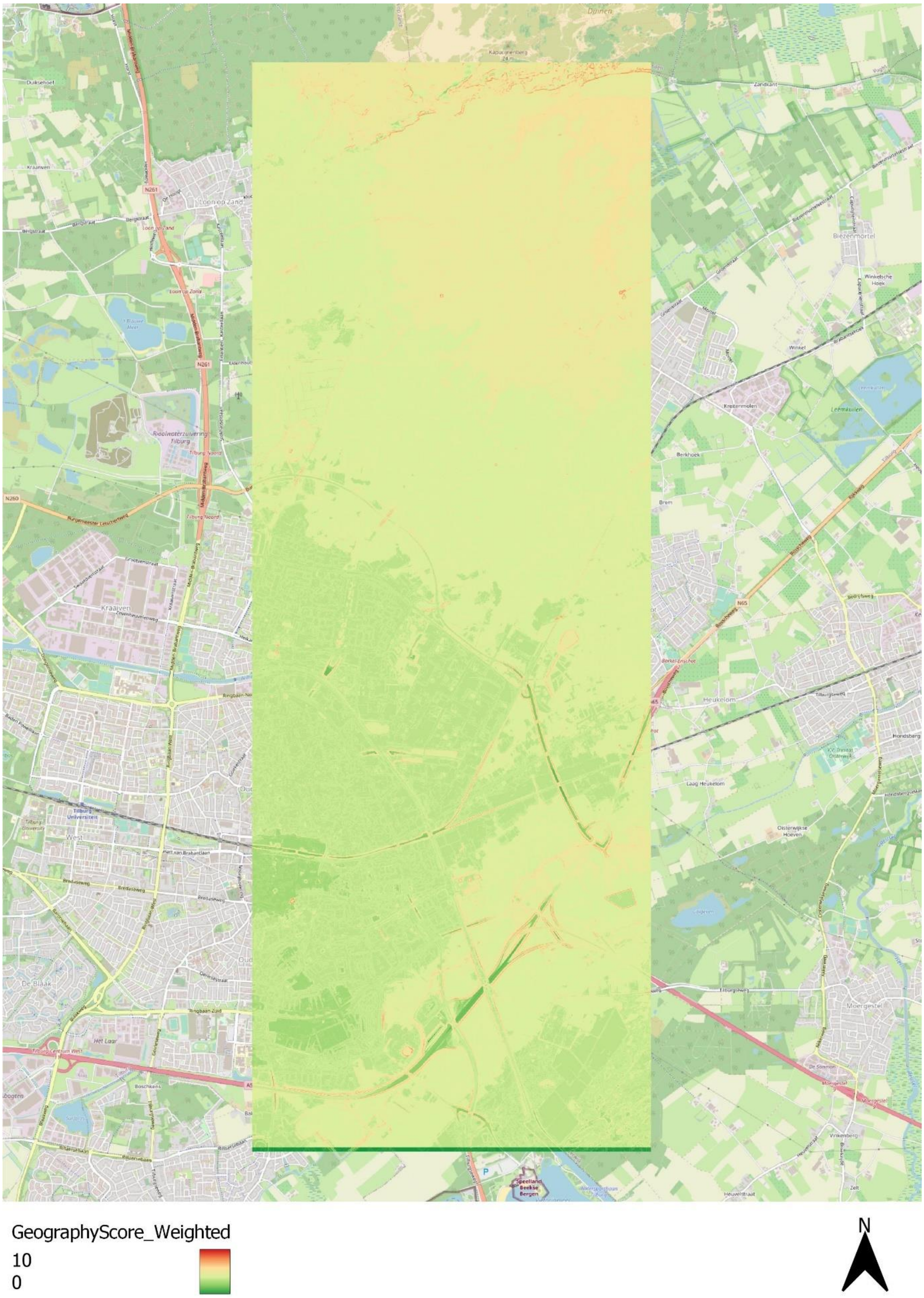
0

N

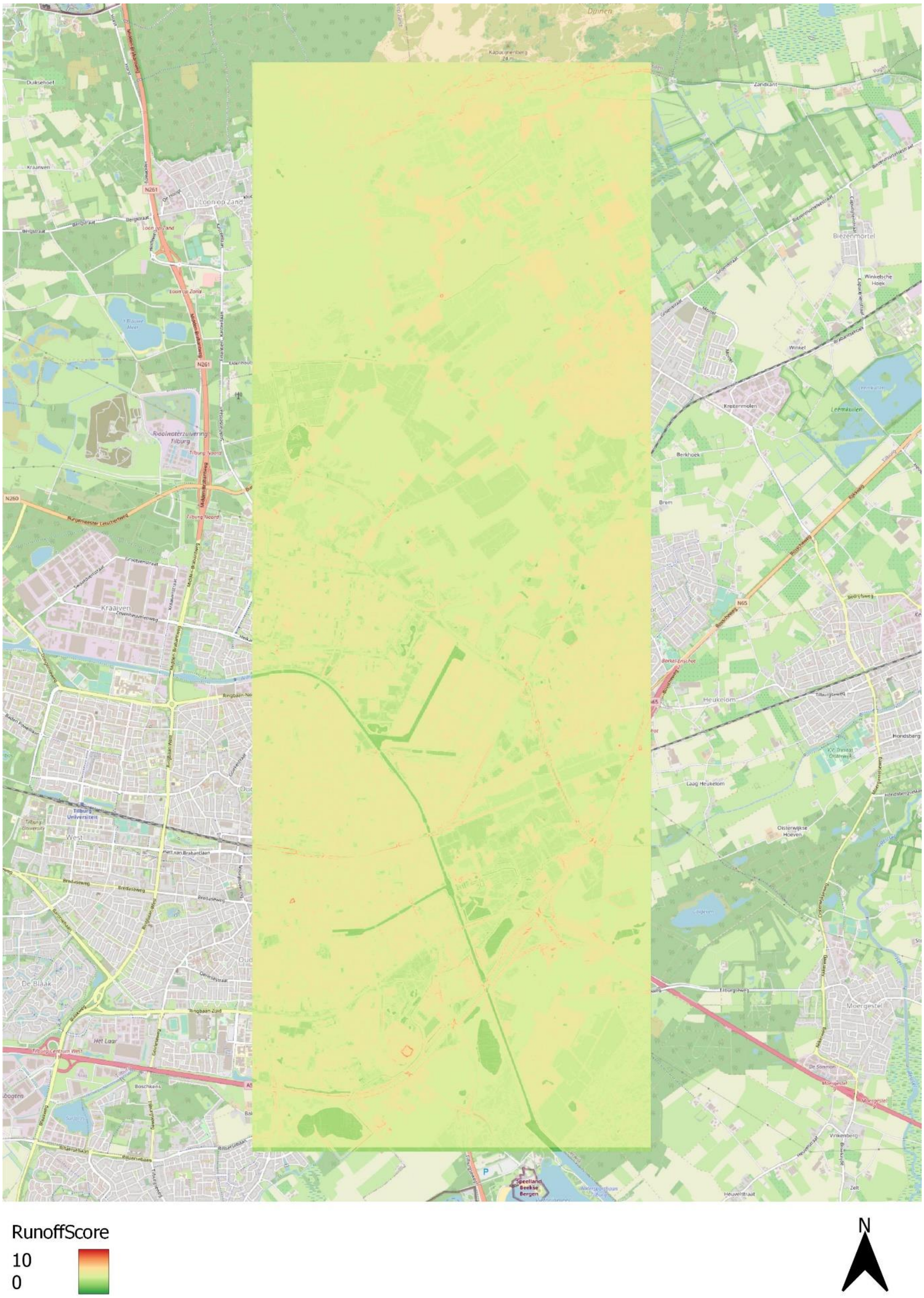
3. Geography score (equal weights)



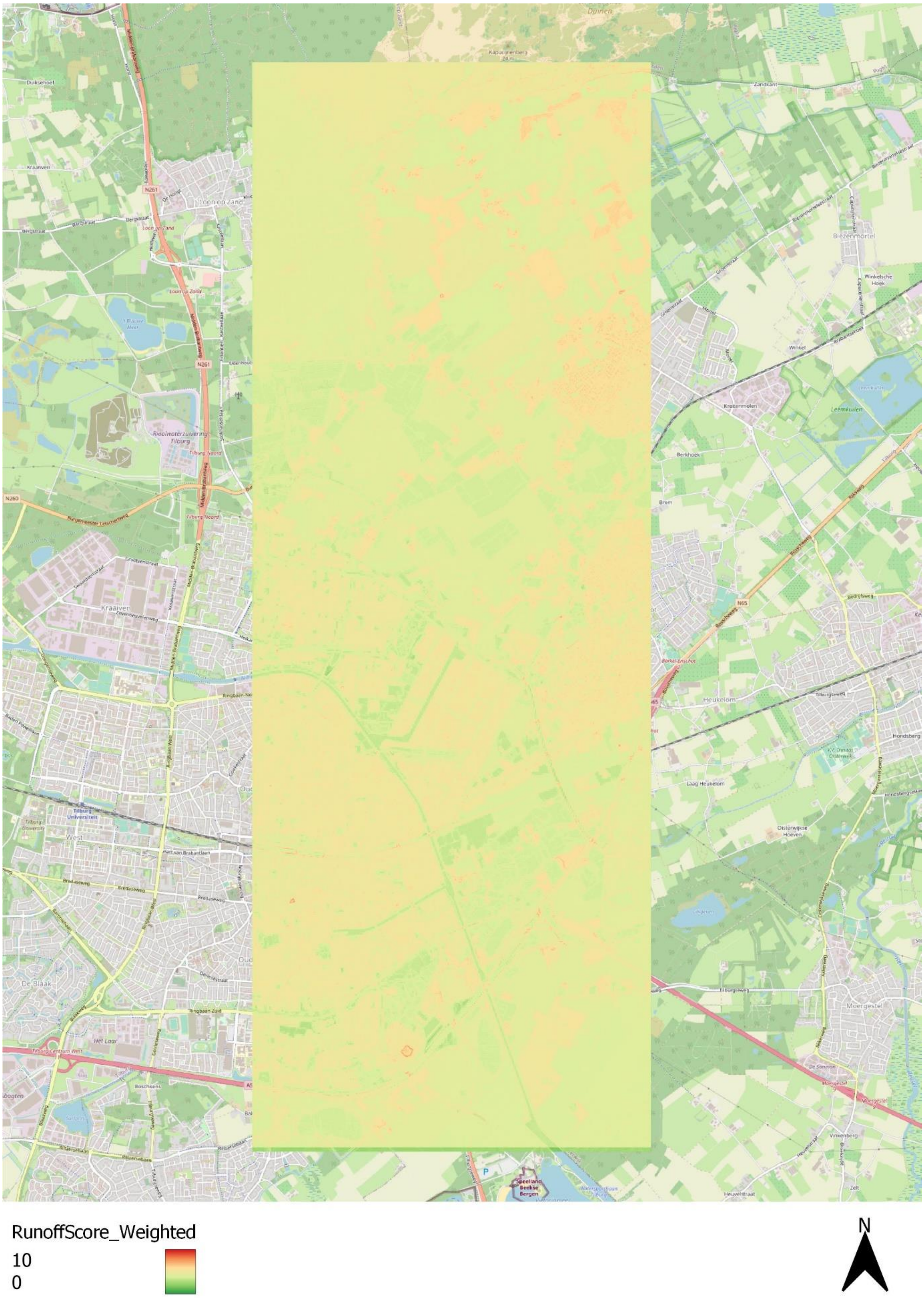
4. Geography score (weighted)



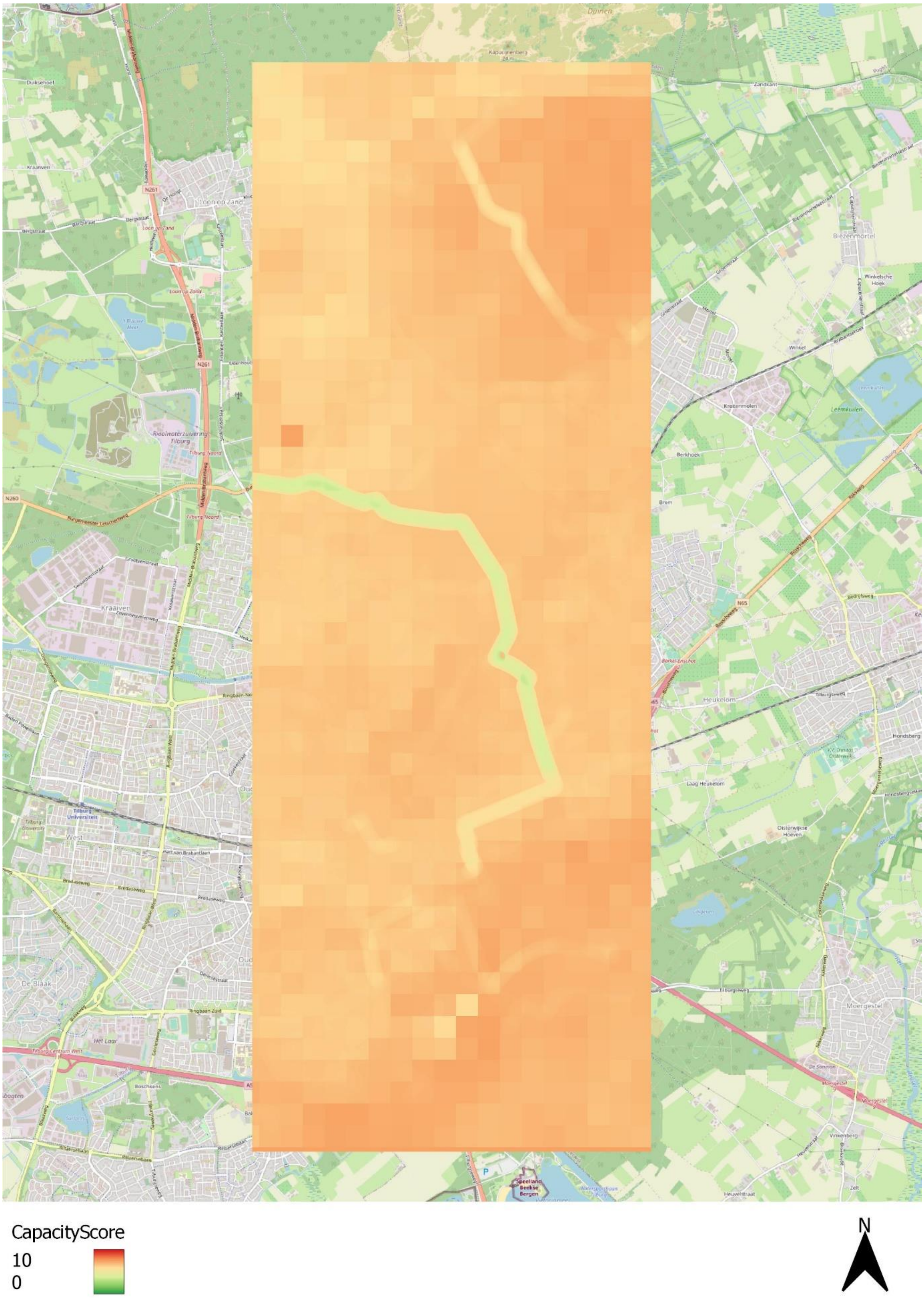
5. Runoff score (equal weights)



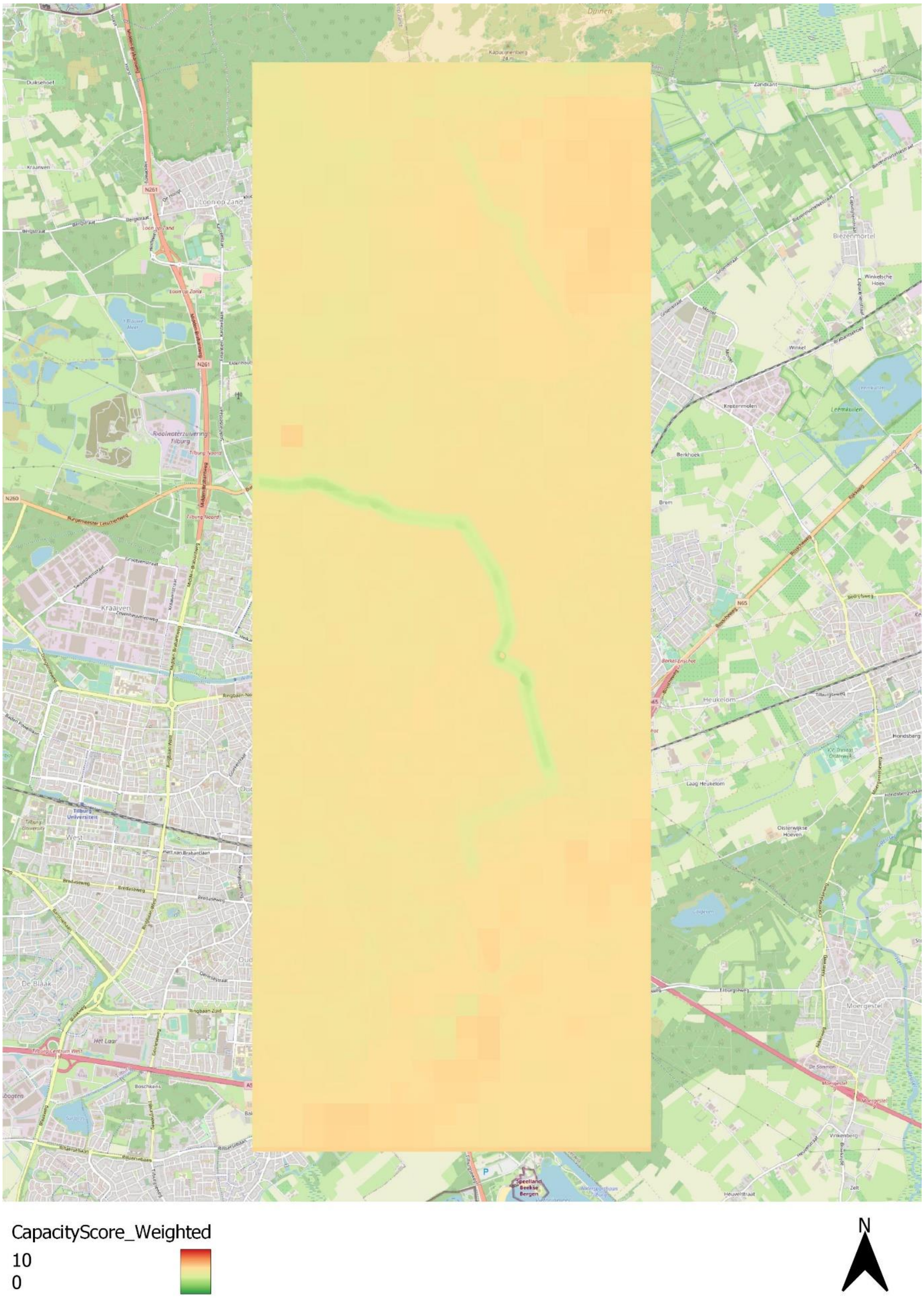
6. Runoff score (weighted)



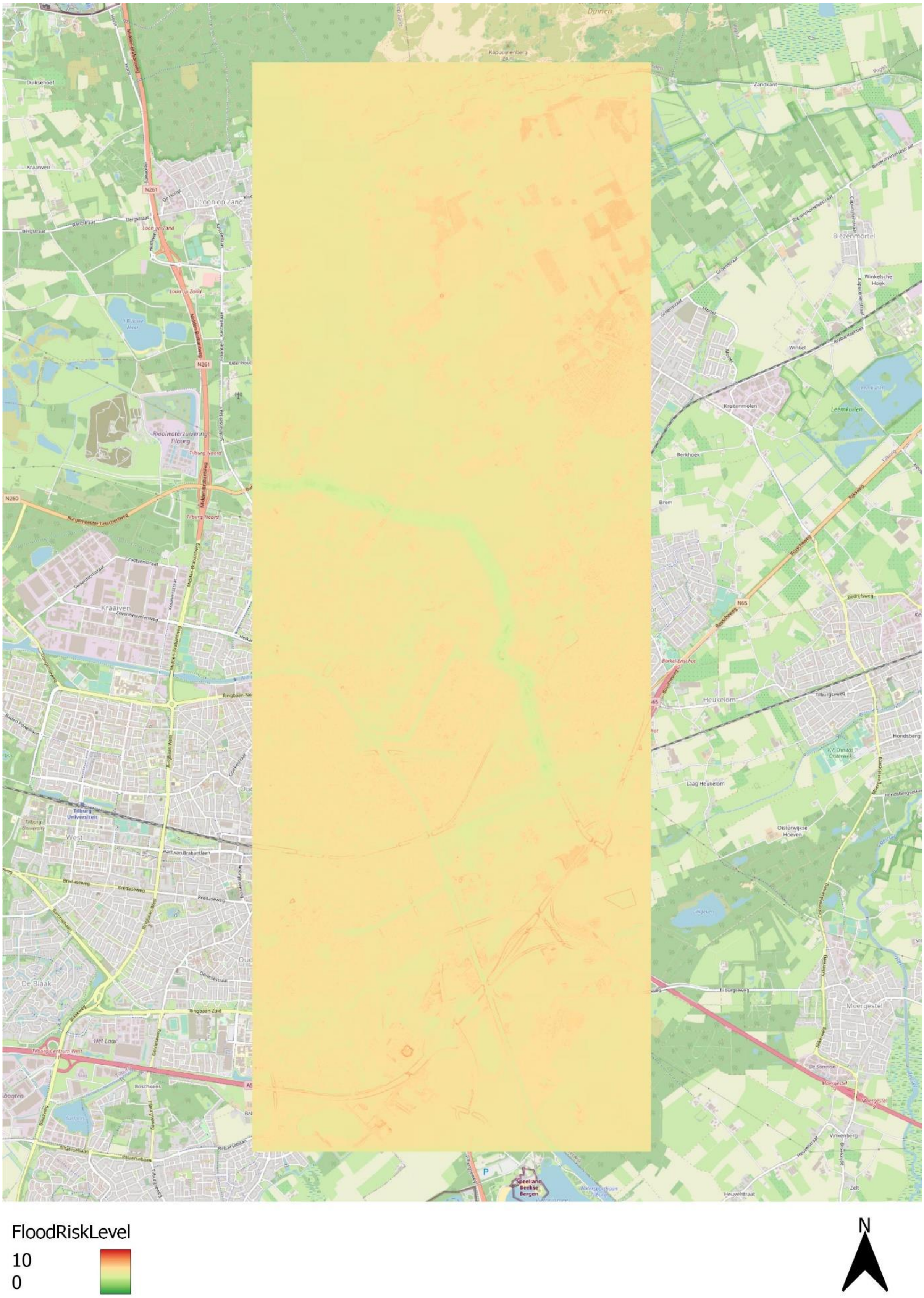
7. Capacity score (equal weights)



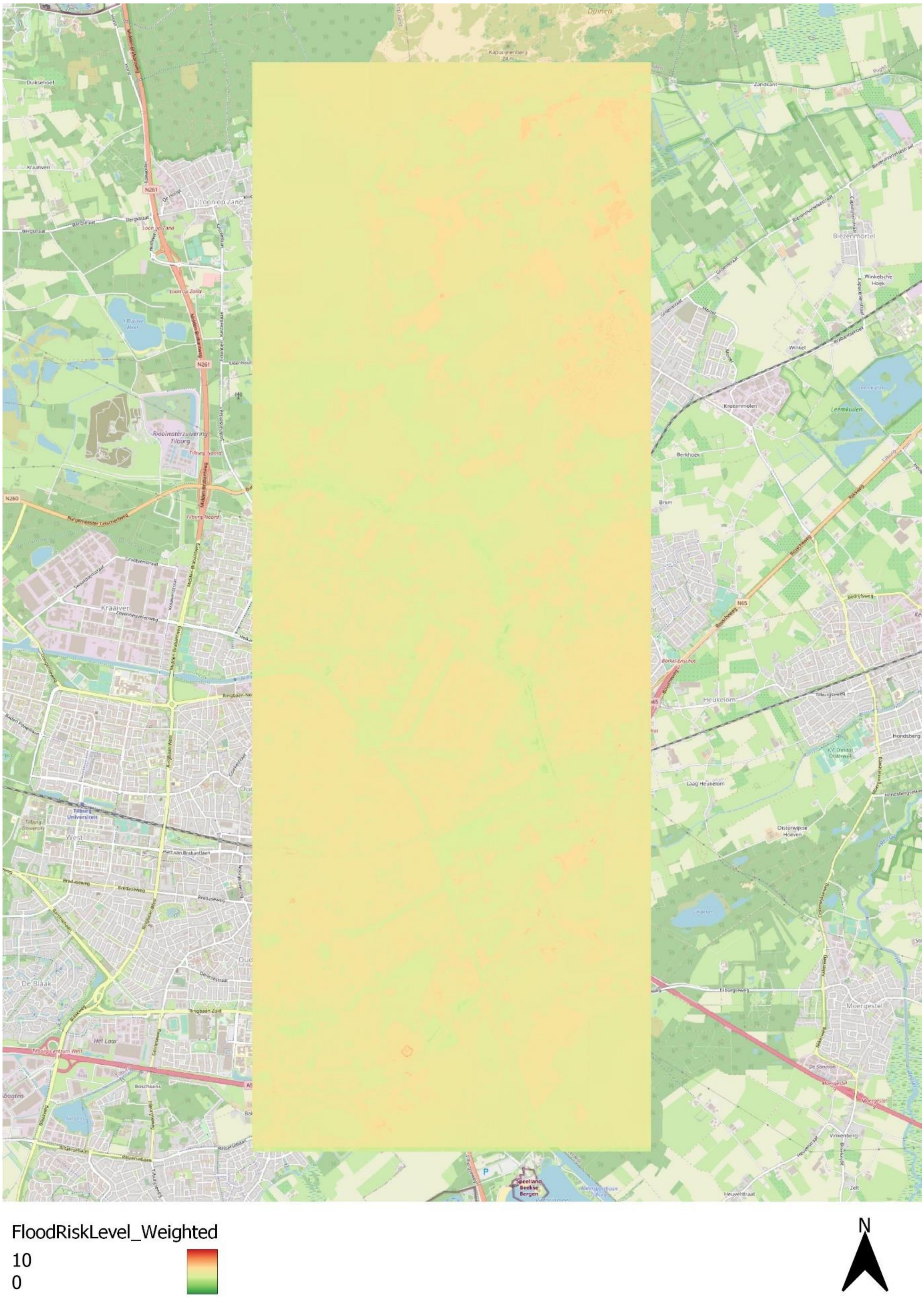
8. Capacity score (weighted)



9. Flood risk level (equal weights)



10. Flood risk level (weighted)



Appendix 4. Features of the flood risk level

1. Selection of FRL scoring with equal weights

Table A4.1 Overview of scoring with equal weights

fid	BuildingScore	TreesScore	BushesScore	GrassScore	VegetationScore	PavementScore	WaterScore	LandCoverScore	ElevationScore	SlopeScore	GeographyScore	RunoffScore	GroundwaterlevelScore	SewageSystemScore	SoilScore	CapacityScore	FloodRiskLevel
1249	0.0	10.0	10.0	10.0	10.0	6.0	10.0	6.5	5.0	0.0	2.5	4.5	6.8	9.8	1.0	6.4	5.4
1269	4.9	10.0	10.0	10.0	10.0	2.3	10.0	6.8	5.0	0.0	2.5	4.7	6.8	9.8	1.0	6.4	5.5
39809	0.0	10.0	10.0	10.0	10.0	0.0	10.0	5.0	6.0	0.0	3.0	4.0	4.8	10.0	1.0	5.8	4.9
59217	0.0	3.7	10.0	1.0	4.9	0.4	10.0	3.8	5.0	1.0	3.0	3.4	8.1	10.0	1.0	6.9	5.1
176499	0.0	10.0	10.0	7.0	9.0	5.2	10.0	6.0	5.0	10.0	7.5	6.8	8.9	10.0	1.0	7.1	6.9
238278	8.3	10.0	10.0	9.0	9.7	4.2	10.0	8.1	7.0	10.0	8.5	8.3	6.3	9.8	1.0	6.2	7.2
238700	0.0	1.5	10.0	6.0	5.8	4.9	10.0	5.2	5.0	4.0	4.5	4.8	8.9	9.8	1.0	7.1	6.0
357319	0.0	1.5	10.0	7.0	6.2	5.6	10.0	5.4	5.0	0.0	2.5	4.0	7.8	9.8	1.0	6.7	5.3
370667	0.0	10.0	10.0	10.0	10.0	0.0	8.4	4.6	6.0	10.0	8.0	6.3	9.4	10.0	1.0	7.3	6.8
443827	0.0	10.0	10.0	8.0	9.3	1.7	7.0	4.5	6.0	1.0	3.5	4.0	5.6	3.8	1.0	4.0	4.0
584890	0.0	10.0	10.0	10.0	10.0	0.4	10.0	5.1	6.0	1.0	3.5	4.3	5.2	10.0	1.0	5.9	5.1
646715	0.0	10.0	10.0	3.0	7.7	0.5	4.4	3.1	6.0	1.0	3.5	3.3	8.5	10.0	1.0	7.0	5.2
687697	0.0	8.0	10.0	2.0	6.7	1.4	10.0	4.5	5.0	1.0	3.0	3.8	7.1	1.7	1.0	3.8	3.8
695160	0.0	10.0	10.0	10.0	10.0	7.5	10.0	6.9	5.0	1.0	3.0	4.9	7.1	1.7	1.0	3.8	4.4
722535	10.0	10.0	10.0	10.0	10.0	1.4	10.0	7.8	5.0	1.0	3.0	5.4	7.1	2.2	1.0	3.9	4.7
737456	0.0	10.0	10.0	3.0	7.7	0.0	0.0	1.9	6.0	1.0	3.5	2.7	7.1	2.7	1.0	4.1	3.4
742436	0.0	10.0	10.0	9.0	9.7	0.0	0.0	2.4	6.0	0.0	3.0	2.7	7.1	2.5	1.0	4.0	3.4
781182	0.0	10.0	10.0	10.0	10.0	7.5	10.0	6.9	5.0	10.0	7.5	7.2	9.5	10.0	1.0	7.3	7.3
798025	6.3	10.0	10.0	6.0	8.7	3.3	10.0	7.1	5.0	0.0	2.5	4.8	7.7	9.8	1.0	6.7	5.7
798117	0.0	8.0	10.0	8.0	8.7	4.7	5.8	4.8	5.0	1.0	3.0	3.9	7.9	9.2	1.0	6.5	5.2
798479	0.0	10.0	6.0	10.0	8.7	0.0	10.0	4.7	6.0	4.0	5.0	4.8	8.6	10.0	1.0	7.0	5.9
799173	0.0	10.0	10.0	6.0	8.7	4.7	10.0	5.8	6.0	0.0	3.0	4.4	7.5	10.0	1.0	6.7	5.5
804975	1.5	10.0	10.0	4.0	8.0	2.8	10.0	5.6	5.0	0.0	2.5	4.0	6.9	10.0	1.0	6.5	5.3
805124	0.0	8.0	10.0	6.0	8.0	4.2	10.0	5.6	5.0	1.0	3.0	4.3	8.2	9.8	1.0	6.8	5.6
805210	0.0	4.0	10.0	10.0	8.0	7.0	10.0	6.3	5.0	1.0	3.0	4.6	7.7	9.8	1.0	6.7	5.7
807405	3.4	10.0	10.0	4.0	8.0	2.4	10.0	6.0	5.0	0.0	2.5	4.2	6.9	9.8	1.0	6.4	5.3
807962	10.0	10.0	10.0	4.0	8.0	0.5	10.0	7.1	5.0	1.0	3.0	5.1	7.7	9.8	1.0	6.7	5.9
814587	0.0	10.0	10.0	7.0	9.0	4.9	8.4	5.6	6.0	1.0	3.5	4.5	7.4	9.8	1.0	6.6	5.6
820862	0.0	1.3	10.0	4.0	5.1	1.5	10.0	4.2	5.0	1.0	3.0	3.6	8.6	10.0	1.0	7.0	5.3
824553	0.0	10.0	10.0	6.0	8.7	1.0	0.0	2.4	6.0	2.0	4.0	3.2	7.4	3.3	1.0	4.4	3.8
878047	10.0	10.0	10.0	10.0	10.0	2.8	10.0	8.2	6.0	10.0	8.0	8.1	8.5	10.0	1.0	7.0	7.5
895443	10.0	10.0	10.0	10.0	10.0	0.9	10.0	7.7	7.0	10.0	8.5	8.1	8.5	10.0	1.0	7.0	7.6
905232	0.0	1.3	10.0	2.0	4.4	1.6	10.0	4.0	5.0	0.0	2.5	3.3	8.3	9.8	1.0	6.9	5.1
924573	0.0	10.0	10.0	10.0	10.0	7.0	2.8	4.9	5.0	0.0	2.5	3.7	8.6	10.0	1.0	7.0	5.4
937269	0.0	1.5	10.0	8.0	6.5	5.3	10.0	5.4	5.0	5.0	5.0	5.2	7.4	9.8	1.0	6.6	5.9
942744	0.0	10.0	1.0	1.0	4.0	0.0	10.0	3.5	6.0	5.0	5.5	4.5	9.3	10.0	1.0	7.3	5.9
951644	0.0	10.0	10.0	7.0	9.0	4.5	3.8	4.3	5.0	1.0	3.0	3.7	7.3	10.0	1.0	6.6	5.1

2. Selection of FRL scoring weighted

Table A4.2 Overview of scoring with weights

fid	BuildingScore	TreesScore	BushesScore	GrassScore	VegetationScore	PavementScore	WaterScore	LandCoverScoreWeighted	ElevationScore	SlopeScore	GeographyScoreWeighted	RunoffScoreWeighted	GroundwaterlevelScore	SewageSystemScore	SoilScore	CapacityScoreWeigthed	FloodRiskLevelWeigthed
1249	0.0	10.0	10.0	10.0	10.0	6.0	10.0	6.5	5.0	0.0	3.3	4.9	6.8	9.8	2.5	5.4	5.1
1269	4.9	10.0	10.0	10.0	10.0	2.3	10.0	6.8	5.0	0.0	3.3	5.1	6.8	9.8	2.5	5.4	5.2
39809	0.0	10.0	10.0	10.0	10.0	0.0	10.0	5.0	6.0	0.0	4.0	4.5	4.8	10.0	2.5	4.9	4.6
59217	0.0	3.7	10.0	1.0	4.9	0.4	10.0	3.2	5.0	1.0	3.7	3.4	8.1	10.0	2.5	5.8	4.2
176499	0.0	10.0	10.0	7.0	9.0	5.2	10.0	5.9	5.0	10.0	6.7	6.3	8.9	10.0	2.5	6.0	6.2
238278	8.3	10.0	10.0	9.0	9.7	4.2	10.0	8.0	7.0	10.0	8.0	8.0	6.3	9.8	2.5	5.3	7.1
238700	0.0	1.5	10.0	6.0	5.8	4.9	10.0	4.7	5.0	4.0	4.7	4.7	8.9	9.8	2.5	5.9	5.1
357319	0.0	1.5	10.0	7.0	6.2	5.6	10.0	5.0	5.0	0.0	3.3	4.2	7.8	9.8	2.5	5.7	4.7
370667	0.0	10.0	10.0	10.0	10.0	0.0	8.4	4.8	6.0	10.0	7.3	6.1	9.4	10.0	2.5	6.1	6.1
443827	0.0	10.0	10.0	8.0	9.3	1.7	7.0	4.8	6.0	1.0	4.3	4.6	5.6	3.8	2.5	3.6	4.2
584890	0.0	10.0	10.0	10.0	10.0	0.4	10.0	5.1	6.0	1.0	4.3	4.7	5.2	10.0	2.5	5.1	4.8
646715	0.0	10.0	10.0	3.0	7.7	0.5	4.4	3.5	6.0	1.0	4.3	3.9	8.5	10.0	2.5	5.9	4.6
687697	0.0	8.0	10.0	2.0	6.7	1.4	10.0	4.1	5.0	1.0	3.7	3.9	7.1	1.7	2.5	3.4	3.7
695160	0.0	10.0	10.0	10.0	10.0	7.5	10.0	6.9	5.0	1.0	3.7	5.3	7.1	1.7	2.5	3.4	4.7
722535	10.0	10.0	10.0	10.0	10.0	1.4	10.0	7.8	5.0	1.0	3.7	5.8	7.1	2.2	2.5	3.6	5.0
737456	0.0	10.0	10.0	3.0	7.7	0.0	0.0	2.9	6.0	1.0	4.3	3.6	7.1	2.7	2.5	3.7	3.6
742436	0.0	10.0	10.0	9.0	9.7	0.0	0.0	3.6	6.0	0.0	4.0	3.8	7.1	2.5	2.5	3.7	3.8
781182	0.0	10.0	10.0	10.0	10.0	7.5	10.0	6.9	5.0	10.0	6.7	6.8	9.5	10.0	2.5	6.1	6.6
798025	6.3	10.0	10.0	6.0	8.7	3.3	10.0	6.9	5.0	0.0	3.3	5.1	7.7	9.8	2.5	5.6	5.3
798117	0.0	8.0	10.0	8.0	8.7	4.7	5.8	5.1	5.0	1.0	3.7	4.4	7.9	9.2	2.5	5.5	4.8
798479	0.0	10.0	6.0	10.0	8.7	0.0	10.0	4.5	6.0	4.0	5.3	4.9	8.6	10.0	2.5	5.9	5.2
799173	0.0	10.0	10.0	6.0	8.7	4.7	10.0	5.7	6.0	0.0	4.0	4.8	7.5	10.0	2.5	5.6	5.1
804975	1.5	10.0	10.0	4.0	8.0	2.8	10.0	5.3	5.0	0.0	3.3	4.3	6.9	10.0	2.5	5.5	4.7
805124	0.0	8.0	10.0	6.0	8.0	4.2	10.0	5.3	5.0	1.0	3.7	4.5	8.2	9.8	2.5	5.7	4.9
805210	0.0	4.0	10.0	10.0	8.0	7.0	10.0	6.0	5.0	1.0	3.7	4.8	7.7	9.8	2.5	5.6	5.1
807405	3.4	10.0	10.0	4.0	8.0	2.4	10.0	5.7	5.0	0.0	3.3	4.5	6.9	9.8	2.5	5.4	4.8
807962	10.0	10.0	10.0	4.0	8.0	0.5	10.0	6.9	5.0	1.0	3.7	5.3	7.7	9.8	2.5	5.6	5.4
814587	0.0	10.0	10.0	7.0	9.0	4.9	8.4	5.7	6.0	1.0	4.3	5.0	7.4	9.8	2.5	5.6	5.2
820862	0.0	1.3	10.0	4.0	5.1	1.5	10.0	3.6	5.0	1.0	3.7	3.6	8.6	10.0	2.5	5.9	4.4
824553	0.0	10.0	10.0	6.0	8.7	1.0	0.0	3.5	6.0	2.0	4.7	4.1	7.4	3.3	2.5	3.9	4.0
878047	10.0	10.0	10.0	10.0	10.0	2.8	10.0	8.2	6.0	10.0	7.3	7.8	8.5	10.0	2.5	5.9	7.1
895443	10.0	10.0	10.0	10.0	10.0	0.9	10.0	7.7	7.0	10.0	8.0	7.9	8.5	10.0	2.5	5.9	7.2
905232	0.0	1.3	10.0	2.0	4.4	1.6	10.0	3.3	5.0	0.0	3.3	3.3	8.3	9.8	2.5	5.8	4.1
924573	0.0	10.0	10.0	10.0	10.0	7.0	2.8	5.9	5.0	0.0	3.3	4.6	8.6	10.0	2.5	5.9	5.0
937269	0.0	1.5	10.0	8.0	6.5	5.3	10.0	5.0	5.0	5.0	5.0	5.0	7.4	9.8	2.5	5.6	5.2
942744	0.0	10.0	1.0	1.0	4.0	0.0	10.0	2.8	6.0	5.0	5.7	4.2	9.3	10.0	2.5	6.1	4.8
951644	0.0	10.0	10.0	7.0	9.0	4.5	3.8	5.0	5.0	1.0	3.7	4.3	7.3	10.0	2.5	5.6	4.7