Urban water resilience

Understanding the effects of climate change and urban densification to plan the future of urban water systems : urban planning water resilience measures, groundwater management, climate adaptation, urban densification, spatial measures

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Award date:
2024

Colophon

Technische Universiteit Eindhoven
Master Architecture, Building and Planning
Architectural Urban Design and Engineering [AUDE]
Urbanism register track
Graduation studio: ‘Density and other matters’
[February 2023- January 2024]

Graduation project:
Urban water resilience: Understanding the effects of climate change and urban densification to plan the future of urban water systems

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Acknowledgements

This project marks the end of my studies. Having a complete year for the finalisation of a project has finally given the time to go a bit further than just scratching the surface of some concepts. One thing is certain, I can never work on a future project again without considering the water system.

Thanks to Dena and Gamze for trying to organise the ideas which were clear in my mind, but a chaos on paper. Thanks to Tijn and Merijn for enduring the same struggle. Thanks to friends and family for providing much needed distraction. Thanks to peanut butter, coffee and music.

I am looking forward to future endeavours.

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Wilco Verpoorten

15-01-2023

Abstract

Climate change and urban densification influence the physical state of the natural and urban water cycle, resulting in negative impacts such as ecological damage, land subsidence or water supply depletion. This paper contains an overview on the functioning of urban water, specifically groundwater level categorised in a Driver-Pressure-State-Impact-Response (DPSIR) framework to better understand the implications of water in cities into the future and how water resilient urban planning could improve upon the impacts caused by climate change and urban densification.

Through a literature review, the current development of methods used in groundwater estimation techniques will become apparent. The spatial determinants used in the literature is structured and recommendations are analysed. Groundwater level is formed by geological, topographical, meteorological, hydro-infrastructural and land use determinants, of which the final two can be altered through urban planning.

Results also include a collection of case studies and strategy documents selected on the similar circumstances as soil type, climate zone and landscape accidentation. The policies regarding water management in Eindhoven, Enschede, Hannover, Münster and Norwich are analysed and compared to the results of the literature review, uncovering the gaps between theory and practice.

Findings include: Re/detention measures should form an integrated whole between the scales of seasonal wet periods and singular precipitation events. Artificial recharge should only be considered in areas which do not have sufficient natural recharge potential. And while the effects of climate change on water are universally covered in urban planning strategies, the effects of densification on water management are often neglected.

These findings are applied in practice. A redesign proposal is made for Limbeek-Zuid and Fellenoord, two neighbourhoods in central Eindhoven, with the goal of increasing water resilience while increasing urban land use intensity and being subject to climate change. The redesign proposal is based on the findings in literature and spatial analysis. It serves as an exploration of taking water resilience principles as a leading guideline can still be fitted in a city to make it a functioning whole.

Part I: Literature

Introduction

1.1. Problem field

The effects of climate change (CC) and urban densification (UD) need to be addressed for the city and its surroundings to function adequately. This article will investigate the effects of these two trends in relation to the urban water cycle. Further explanation is given in chapter 2.

Because the urban water cycle is too complex to fully cover, the focus of this article is the quantity of groundwater. Groundwater level is difficult to accurately predict as it is dependent on many variables and changes within an aquifer have implications over large areas while being invisible to humans. These make it difficult to plan for, while sustainable management is needed for this vulnerable resource [1][2]. Increasing pressure from climate change and urban land use intensity have additional consequences for groundwater quantity.

Stable groundwater level is necessary for the functioning of ecologic systems and to provide for water demand in urban systems [3][4]. If the water balance is disrupted, the groundwater table rises or lowers [5]. This results in an imbalance in ecologic and urban systems. The natural water balance is based on the formula:

$$P = Q + E + \Delta S$$
$$S(in) - S(out) = P - Q - E$$

where P is Precipitation, Q is runoff, E is evapotranspiration and ΔS the change in storage in the aquifer [6].

Hence the added storage into the aquifer, groundwater recharge, is based on precipitation, runoff and evapotranspiration. A negative ΔS would indicate larger withdrawal than recharge. This is a simplified version of groundwater level estimation as it does not account for lateral flow of groundwater, water exchange between aquifers, interception of precipitation and surface water interactions.

Large changes in groundwater level create impacts, as explained in chapter 2.7. Most impacts are negative for either public health, financial or ecological reasons [7], [8].

1.2. State of the art

1.2.1. Structuring current situation

To accurately give overview into the complex interactions of groundwater level within the urban water cycle, the DPSIR framework is used. UD and CC can be identified as drivers in this framework. They pose as external influences on the balance of the groundwater level.

A compilation of consequences of the introduction of UD and CC to the urban water cycle is shown in figure 1. Further explanation of the sequence of DPSIR steps is discussed in chapter 2.4 – 2.8.

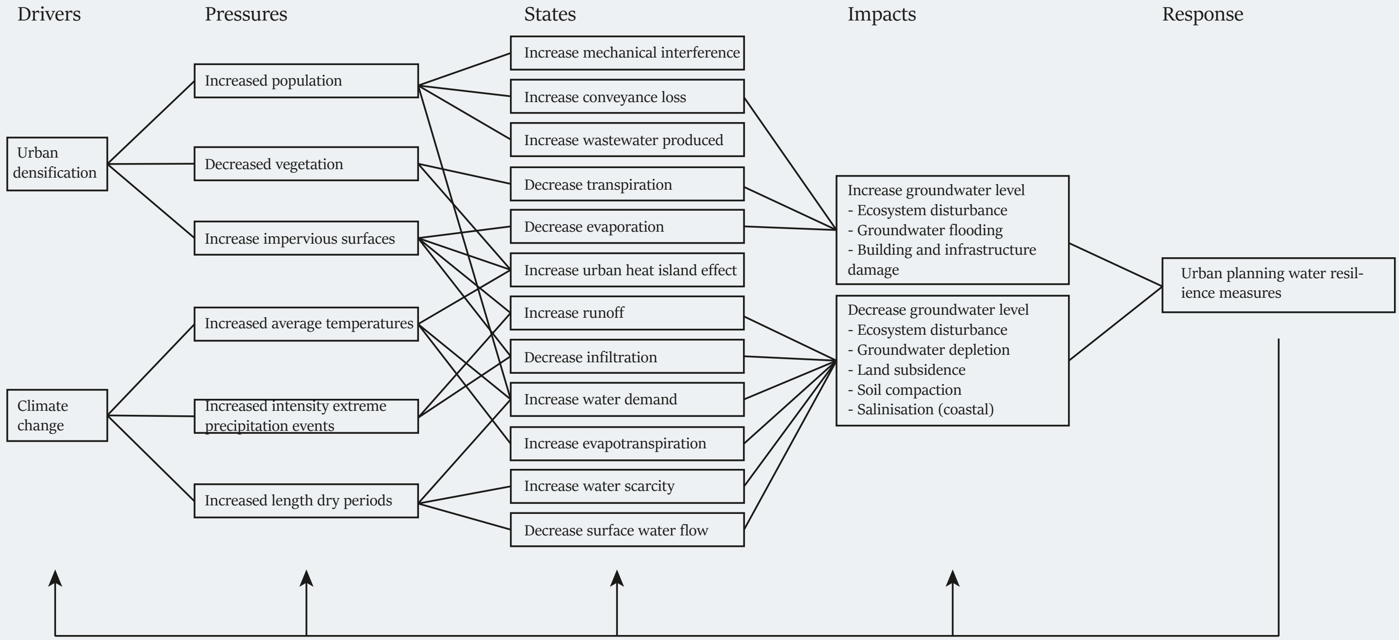


Figure 1: Impacts caused by UD and CC following the DPSIR framework steps as compiled from sources explained in chapter 2.4 – 2.8

1.2.2. Interactions found

Figure 1 shows the complex nature of effects of UD and CC on the urban water cycle. Some pressures reinforce each other, such as urban heat island effect intensification through decrease in vegetation and increase in impervious surface cover and average temperatures. Other pressures create contradictory states, for example, the decrease in transpiration and evaporation caused by impervious surfaces and decreased vegetation, while increased temperatures increase transpiration and evaporation. Finally, some states do not have direct effect on groundwater level, however indirect effects are not ruled out.

Many variables act upon groundwater level. There have been difficulties in quantifying (changes in) flows. As UD and CC cause a multitude of effects which can increase and decrease the groundwater level, there is no standard prediction of net rise or lowering of the phreatic surface. Accurately modelling of (geo)hydrological systems is therefore still difficult to achieve [9]. The rate of change caused by UD and CC is highly dependent on locational context and regional hydrology. As aquifers often extend over large areas, predictions and strategies that confine to city limits may not be sufficient.

The pressures causing imbalances of the groundwater table can have negative impacts. A response to negate these impacts is to create water resilience. This can be done by implementing preventative measures in urban planning that soften imbalances of the urban water cycle [10].

1.3. Research gaps

By intending to undertake hydrological challenges through urban planning, both fields of research need to be linked. The connection between the practices has been established since urban water management started to become an integrated academic topic in urban planning in the 20th century [11]. With the introduction of UD and CC to the system, new solutions are needed to manage water levels and create water resilience. A review of current steps taken in academic works is needed to provide a perspective in the changing conditions of the combination of hydrology and urban planning. This can form the foundation for densifying cities to base their development strategy on, as will be exemplified in chapter 6-8.

1.4. Objectives

The goal of this article create an overview in the current methods and spatial determinants used in (ground)water research and what recommendations are made to create water resilience. Additionally, current urban planning policy is reviewed to discern differences between theoretical and practical responses to the effects created by UD and CC on the urban water cycle. To summarise; *how can urban planning affect the groundwater level in a densifying city to improve water resilience?*

1.5. Relevance

In the past decade, technological development in remote sensing and data storage contributed to geospatial data availability [12]. Research articles often use remote sensing datasets to support in their investigations. The application of big data especially helps research over large areas, which is needed for groundwater management. The methods used in emergence of remote sensing data to groundwater management can provide an overview of how technological advancements can help identify spatial determinants and how they can be used in performance-based planning.

CC is a phenomenon experienced globally and many cities experience pressure of densification through ongoing urbanisation. The effects of both drivers create negative impacts in society through financial costs, public health risks and ecological damage [7]. Natural hazards occur more frequently with increased intensity. Urban centres are an accumulation of people and economic assets. Therefore, urban areas are more at risk of health and financial damages experienced by natural hazards [8]. The results of this article can be used in urban strategies to lower the impacts of natural hazards.

1.6. Chapter overview

The introduction has given a short overview of the scope, gaps and aim of the research. A background chapter follows with explanations of the urban water cycle and terminology used. In the methodology chapter, the steps taken in the research are given, which are followed by the results where the outcome of the analysis is provided. Trends and key findings are addressed in the conclusion, including implications for future research and future application in urban planning. The second part of this booklet consists of the spatial analysis and strategy of a city following the findings of the preceding research. A design proposal on the neighbourhood scale ensues completes this booklet.

Background

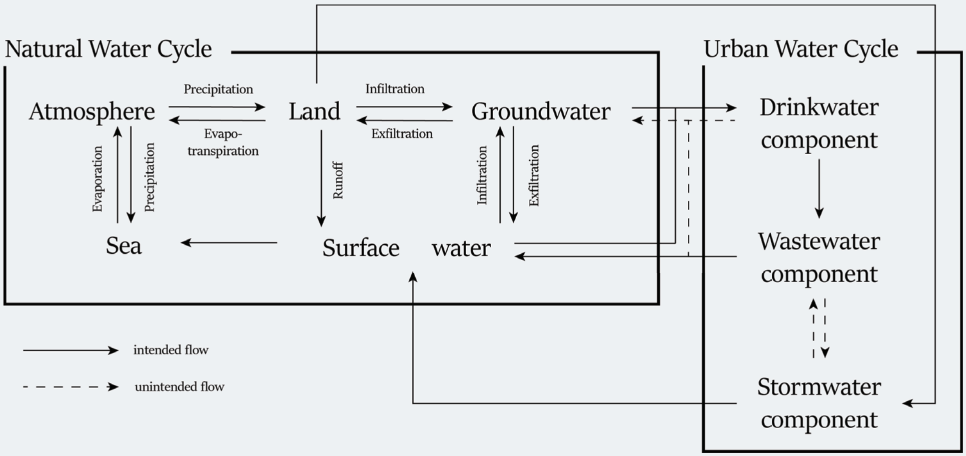


Figure 2: Urban and natural water cycle, based on [13]

2.1. Water cycle and urban component

The water cycle is a concept explaining the natural process of water circulation. With the development of civilisation, infrastructure was needed to provide access to potable water, removal of wastewater and prevention of flooding through drainage. These three additional components of drinkwater, wastewater and stormwater infrastructure are part of the urban water cycle. Figure 1 shows the interaction between the components of the urban water cycle and the natural water cycle.

Civilisation needs water to function, therefore water is extracted from aquifers and/or surface waters. The water is treated and filtered to make it potable. After this, it is used for domestic, industrial and irrigation processes. Ensuing the use of the water, it has become a waste product. Sewage infrastructure is used to collect it, after which it is treated and released downstream. Drainage from stormwater can use the same infrastructure as sewage, however, there can be separate stormwater systems in place to prevent combined sewage overflows [14].

In clusterings of civilisation, the urban water cycle components needed for day to day function create large flows. This results in the destabilisation of the natural water cycle [15]. The effects on the water system caused by the city have effects on the whole of the surface and subsurface watersheds. Therefore, it is interesting to look at the city and its surroundings as a whole.

2.2. Trend population density

Spatially speaking, the change in flows of the water cycle are caused by population growth, climate change and land use change [16]. Global city population share will grow from 50% in 2020 to 58% in 2070 [17]. City densification is the main source of city population growth [18]. The reason for densification of urban centres is twofold: In unplanned environments, densification during population growth is a natural process. The cities are a centre of opportunity which attract people to move in. In places where spatial planning procedures are in place, densification is also the preferred method of urban development as it provides an efficient city layout without large distances to travel for amenities [19].

An additional advantage is the limitation of urban sprawl. For example, in the EU, future policy shows densification is preferred over sprawl, as to improve the functioning of their cities and to preserve the rural and natural identity outside of cities [20].

Solely addressing population growth and its resulting densification is insufficient to indicate the changes in the urban water cycle. Physical changes to the environment as a consequence of population density are also related to water behaviour [21].

In this article, the term UD is used for the process of increasing urban land use intensity, where land use intensity is: an indication of the amount and degree of population growth and urban development of the land in an area, and a reflection of the effects and environmental impacts generated by that development [22].

2.3. Trend climate change

Having combined land use and population growth in the definition of UD, climate change remains to be covered as a spatial factor affecting water cycle changes. Part of the consequences of the climate change directly affect the (urban) water cycle [23]. Overall, weather extremes will become more common[24]. For the cities to remain habitable places, the urban water system and infrastructure will need to accommodate for these changes [25]. This is necessary as especially urban population is vulnerable for the effects of climate change [26]. The effects caused by UD and CC will be explained along the structure of the DPSIR framework in the following subchapter.

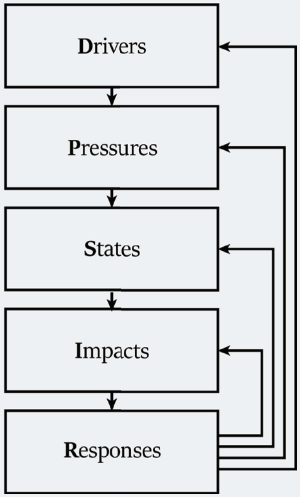


Figure 3: DPSIR framework, based on[21], [27]

2.4. DPSIR framework

The Driver-Pressure-State-Impact-Response (DPSIR) framework, shown in figure 3, is used in this article to explain the impacts of UD and CC on the urban water cycle to identify the need for certain responses. Developed in the 1990s by the European Environment Agency, it was mostly used as a comprehensive method to integrate natural and social challenges into one framework [27]. The integration of multiple problems into a simplified causal framework was used to make decision making easier [21], [28].

Chapter 1.2.1 introduced UD and CC as drivers, as they act as independent variables upon the environment. In this case, as the research investigates groundwater level, this environment entails the aquifer underneath a densifying city. The characteristics of UD change the environment. Impervious land cover and population increase while vegetation decreases [29], see subchapter 2.5. The pressures of CC are intensification in droughts and peak precipitation events and increase in average temperatures as explained in subchapter 2.6.

2.5. Urban densification states

In turn, these pressures cause well-established fluctuations of flow in the urban water cycle. The increase in impervious surfaces largely prevents infiltration of precipitation. Rather, it flows over the impenetrable surface, increasing runoff. Because of the sealed layer on top of the soil, evaporation is also diminished [29]. Materials used in urban developments are often heat retentive, causing heat stress. This contributes to the urban heat island effect [30].

Decreased vegetation through urban land use intensification causes decreased total transpiration. Together with the decrease of shaded surfaces, this also contributes to heat stress [31]. An increase in population increases withdrawals for residential and industrial activities. This could result in highly locational depletion of groundwater supplies. Also, more subsurface structures are built and mechanical interference through pumping is applied to prevent groundwater nuisance in certain locations. This disturbs and fragments the natural flow of groundwater [32].

Additionally, increase in water usage results in larger volumes wastewater produced. An infrastructural network with high capacity is needed, causing higher conveyance loss. Depending on location and circumstances, conveyance loss can even outweigh suppressing groundwater recharge factors to create more recharge in urban areas than its surroundings [33].

Although UD is a form of development that concentrates and increases fluctuations of the groundwater level, research shows it is a more efficient form of urban development over horizontal sprawl, decreasing the per capita water use and decreasing amount of infrastructure needed [34], [35].

2.6. Climate change states

Increased length of dry periods causes the replenishment of water supply to be postponed, resulting in water scarcity. Especially as during dry periods, water consumption for residential and agricultural usage rises [36]. Due to a lack of precipitation, volumetric flow rate of surface waters shrinks. Groundwater tables lower, inverting the interaction with surface water from seepage to infiltration.

Drier periods are interspersed with more extreme precipitation events, leading to increased runoff. The volume of runoff in a short time can result in flash flooding [37]. As larger amounts of water flow into stormwater infrastructure, infiltration into the soil decreases.

Average temperature increases result in higher evapotranspiration and exacerbation of the urban heat island effect. Moreover, increased temperature leads to increased water demand [38].

2.7. Impacts

When recharge is structurally greater than groundwater withdrawal, the groundwater table rises. This causes a shift towards a wetter environment. Flora and fauna need to adapt to the new conditions, else the ecosystem will (partially) collapse and be replaced by wetter species. In urban areas, buildings and infrastructure are prone to damage through moisture penetration and changes in load-bearing behaviour [39], [40].

When withdrawal is structurally greater than recharge, the groundwater table lowers. This causes a shift towards a dryer environment: Flora and fauna need to adapt, the biodiversity of the area will change to dryer species. Urban areas will experience soil compaction, land subsidence and potential difficulties in water supply.

Coastal areas, where a large proportion of the urban population is located, experience salinisation through intrusion of saline groundwater into non-marine aquifers [41].

Table 1 shows the complete overview of Drivers, States, Pressures and Impacts.

		States		Groundwater level	
Pressures UD		Increase	Decrease	Higher	Lower
Increase impervious surfaces					
	Runoff	X			X
	Infiltration		X		X
	Evaporation		X	X	
	Urban heat island effect	X		-	-
Decreased vegetation					
	Transpiration		X		
	Urban heat island effect	X			
Increased population					
	Water demand household and industry	X			X
	Wastewater produced	X		-	-
	Conveyance loss	X		X	
	Mechanical interference	X		-	-
Pressures CC					
Increased length dry periods					
	Water scarcity	X			X
	Surface water flow		X		X
	Water demand households and agriculture	X			X
Increased frequency extreme precipitation events					
	Runoff	X			X
	Infiltration		X		X
Increased average temperatures					
	Evapotranspiration	X			X
	Urban heat island effect	X		-	-
	Water demand households and agriculture	X			X

Table 1: Overview pressures and states created by UD and CC on the groundwater level

2.7. Resilience

Urban planning is a tool which can alter these impacts by influencing the preceding elements in the DPSIR framework. It functions as a response in the DPSIR framework. This article attempts to understand how urban planning can be applied to negate negative impacts by finding methods to stabilise groundwater levels. The term often used for this is water resilience, or the ability of a water system to persist, adapt and transform under pressures to remain or find a stable equilibrium [42].

Persistence is the ability to maintain coherent function under changing conditions without altering identity. For example, increasing maximum flow capacity of current buried water infrastructure to handle the increased peak precipitation caused by CC and increased runoff caused by UD.

Adaptability is the ability to modify identity to accommodate changes. For example, creating water detention elements in public spaces to temporally spread precipitation runoff and thereby decreasing the peak of maximum runoff volume. Simultaneously, more water infiltrates, creating a buffer for drier periods through groundwater recharge.

Transformation is the ability to change identity and establish a new function in a different equilibrium. For example, accepting the new states caused by changes in UD and CC that increase flash flooding following precipitation events. This would have severe consequences for the region in terms of living conditions.

Persistence and adaptability of current conditions is favourable in urban planning, while transformation often results in negative outcomes. Hence, water resilience for the purposes of this article should be the ability of the water system to persist and adapt under pressures to remain in a stable equilibrium [10].

Methodology

3.1. Overview of methods and data used

The aim is to understand the differences between the theoretical approach in academics and the practical approach of spatial planning policy in groundwater management. To ensure relevant findings, a systematic method is used consisting of three parts.

Firstly, a literature review is conducted to discover what methods, spatial determinants and recommendations are used and given. Secondly, a policy analysis based on case studies of cities is performed to understand the current challenges undertaken in practice regarding groundwater management. Finally, the two methods are compared to analyse differences, resulting in potential for improvement in the field of water management through urban planning.

3.2. Literature review

A selection of articles is formed through a search query in the academic database Scopus. To guarantee relevancy, all selected articles must include a groundwater, climate change and urban densification aspect in combination with a spatial determinant aspect. The exact search query is shown in figure 4.

3.3. Selection criteria and method policy analyses

To understand the current advancements in the field of water management in cities, a multiscalar approach is selected. Strategy documents of the national, provincial/state, region and municipality level are analysed. Also, if applicable, strategies of water authorities and water suppliers are included as they can have large influence on the steps taken in water management, depending on location.

3.4. Comparative analysis

All scale levels per case study are compared to the overarching themes of the literature review case studies. This gives insight in the degree of application of suggested concepts. A distinction is made on the omission, mentioning or in-depth explanation of the concept. Patterns in degree of application and differences between scale levels are analysed.

Results

TITLE-ABS-KEY (
("**urban water cycle**" OR "**groundwater recharge**" OR "**groundwater level**")
AND ("**climate change**" OR "**climate resilien***" OR "**water resilien***")
AND ("**urban densification**" OR **urbani?ation** OR "**urban land use**")
AND (**paramet*** OR **variable** OR **GIS**))

Figure 4: Search string literature review

4.1. Literature review

The query used in this literature review gives 35 results. One document is unavailable, and after reading abstracts, six are not included in the review based on relevancy. This results in 28 eligible articles for review. The review includes:

1. standard information of title, location, climate and date of collected data
2. methods used
3. spatial determinants used in the articles, including a short definition and source of the data
4. (spatial) design recommendations

Both the determinants and recommendations are used to distil overarching typologies and interactions. Additional analysis includes a frequency analysis of all used concepts to understand better understand importance of use.

The climatic and locational spread of the articles assessed in the literature review is shown in figure 5 . A wide range of climates is represented, which should give a well-balanced perspective on geohydrological management in different conditions. Appendix A shows the list of reviewed articles, the entire literature review is attached in Appendix B [43]-[70].

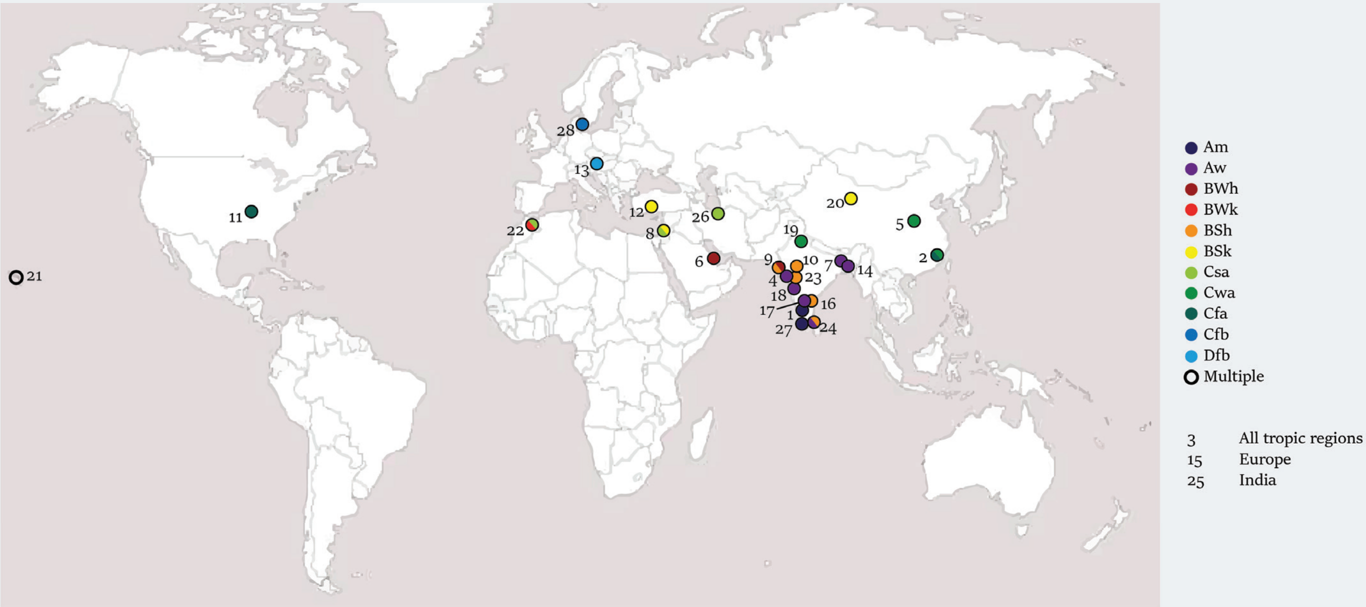


Figure 5: Location and Köppen-climate classification of reviewed articles

As the article set is selected on the requirement of spatial approaches, most use a hybrid modelling approach. This could be using existing hydrological models and applying them to different locations, like SWAT [43], [68] or VIC [56]. Other articles use analysis methods that are non-exclusive to hydrology, such as Regression Analysis [44], [49], [64], Dynamic Factor Analysis [55] or Analytical Hierarchy Process [58] to conclude findings. The data used as input for the model is often retrieved through remote sensing or provided by local governments or institutes.

A frequency analysis shows which spatial determinants are used most often in this set of articles as input for models or other analysis techniques. 57 Unique determinants are used. Most often used are precipitation -23-, land use/land use change -20-, temperature -14-, groundwater level -12- and soil type -12-. Based on this set, a categorisation can be made into 5 types of determinant or combinations thereof. This categorisation including frequency of use is shown in figure 6.

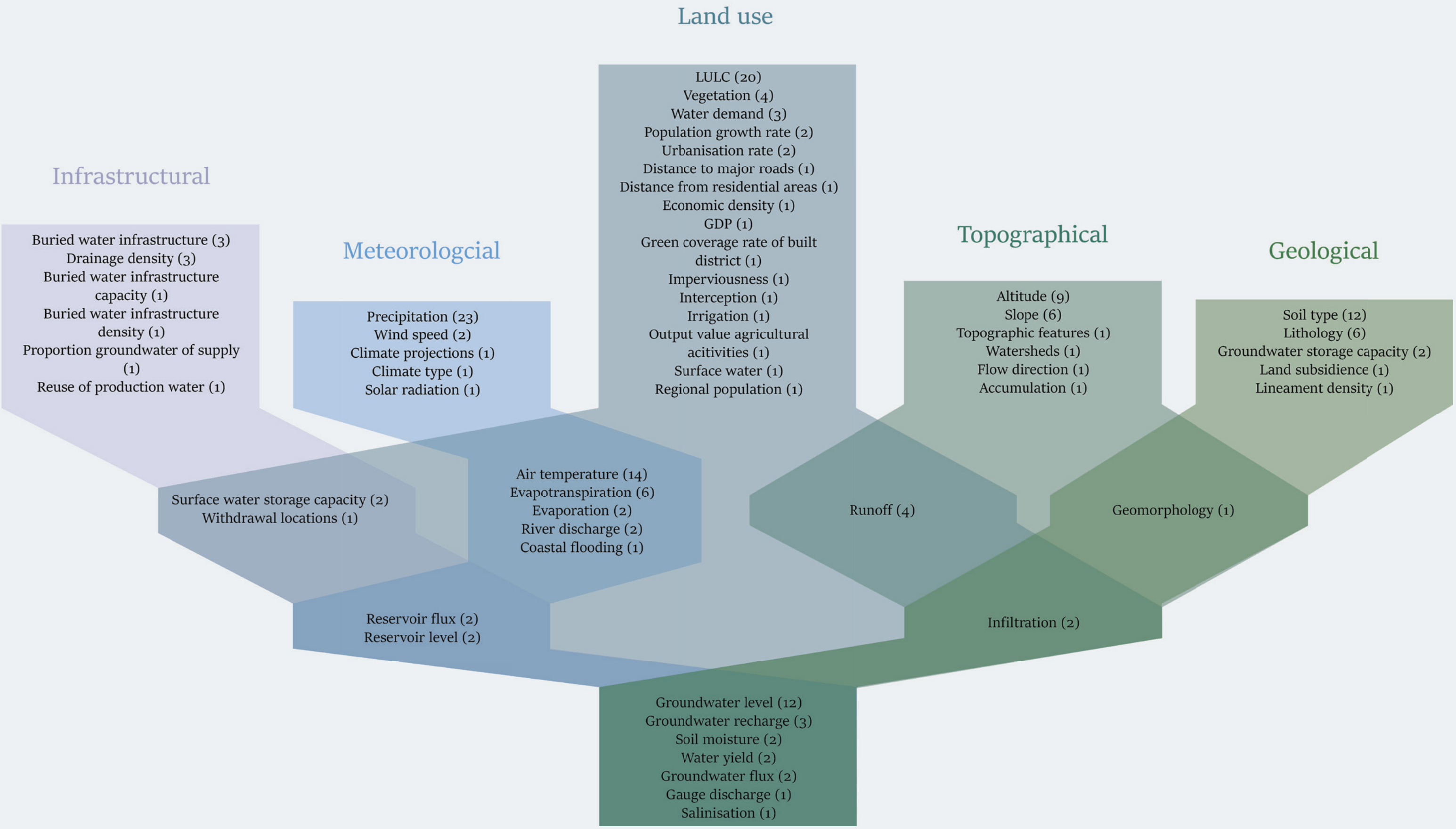


Figure 6: Euler diagram including categorisation and frequency of use of spatial determinants

The main categories are hydro-infrastructural, meteorological, land use, topographical and geological. All determinants fit to at least one category, often multiple. Influences on groundwater are discussed through the DPSIR model in the background chapter, showing that it fits all categories. Therefore, it is one of the most complex determinants.

Recommendations in the articles reveal a spread of design elements and policy strategy proposals. They are highly influenced by the differences in subject of the article, making them specific. To apply a frequency analysis, the recommendations first undergo a categorisation as shown in table 3. All recommendations fit to a category. The categorisation is provided in Appendix C.

Most frequently recommended are **re/detention measures** to let more water infiltrate, reduce runoff and prevent flooding during peak precipitation events. In this categorisation, a distinction can be made between seasonal water harvesting and precipitation event retention. The former relies on the management of large-scale infrastructure, like surface water reservoirs. The latter focusses on smaller scale interventions, such as green roofs or ponds and wadis.

Water withdrawal management revolves around finding other water sources, such as conjunctive use with surface water, or management and prioritisation of withdrawals by agriculture, industry and cities.

Land cover management largely contains the need for sustainable development of the environment, involving prevention of desertification and soil degradation, urban expansion regulation to limit impervious surfaces, and conserving or restoring/decanalising surface water. Preservation and expansion of vegetative cover is used to slow runoff to prevent flash flooding and balance urban microclimates.

Mechanical interference is used to manage areas with excess or shortage of water by pumping or retaining water. The largest subcategory in mechanical interference is artificial recharge, proposed in five instances. Four out of five studies are located in arid or seasonally arid areas in India.

Water use efficiency overlaps mostly water withdrawal management in aim. Instead of limiting existing users, water use efficiency seeks to improve the efficiency of the urban water cycle through wastewater reuse and reducing conveyance loss.

Remaining recommendations include the need for adequate policy making, based on locational contexts and in participation with relevant stakeholders and users.

Linking the recommendations to the 5 earlier deducted spatial determinant categories, the conclusion can be made all recommendations fall within the water infrastructure and/or land use categories in combination with a policy aspect. Both water infrastructure and land use categories form the spatial basis for alteration through spatial planning to create water resilience, as shown in the conceptual model in figure 7 on the next page. Alterations in meteorology, topography and geology are not within the sphere of influence of urban planning.

category	subcategory	explanation	amount	examples
re/detention		Slowing and restricting runoff to increase infiltration	21	
	precipitation event	Short-term, small-scale interventions for local scale retention	13	Green roofs [46], [52], Ponds and wadis [46], [53], [61]
	seasonal	Long-term, large-scale interventions for city or regional scale retention during raining seasons	6	Surface water reservoirs [43], [47], [50], [67]
water withdrawal management		Changing withdrawal sources or quantities based on conditions affecting water availability	15	Conjunctive use [49], [56], [62], [71], Use management and prioritisation [49], [51], [55], [59], [65], [67]
land cover management		Changes in land cover that provide a minimum of disruption to the natural water cycle	15	
	increase vegetation	Vegetation stabilises urban microclimates	7	Preservation [43], [57], Expansion [43], [45], [63]
	other	Other beneficial land cover changes	8	Limit desertification, soil degradation [43], Limit impervious surfaces [45], [50], [66], Restoring surface waters [47], [50], [61]
mechanical interference		Retaining or pumping water to keep or shift flows in the urban and natural water cycle	7	Artificial recharge [49], [56], [58], [65], [70]
water use efficiency		Decreasing losses and improve urban water cycle efficiency to reduce impact	6	Wastewater reuse [49], [51], [65], Reducing conveyance loss [65]
contextual policy		Using locational conditions to base guidelines on	4	Adaption strategies per individual system [57]
participation		Involving stakeholders to increase implementation efficiency and support base	3	Water saving programmes awareness campaign [57]

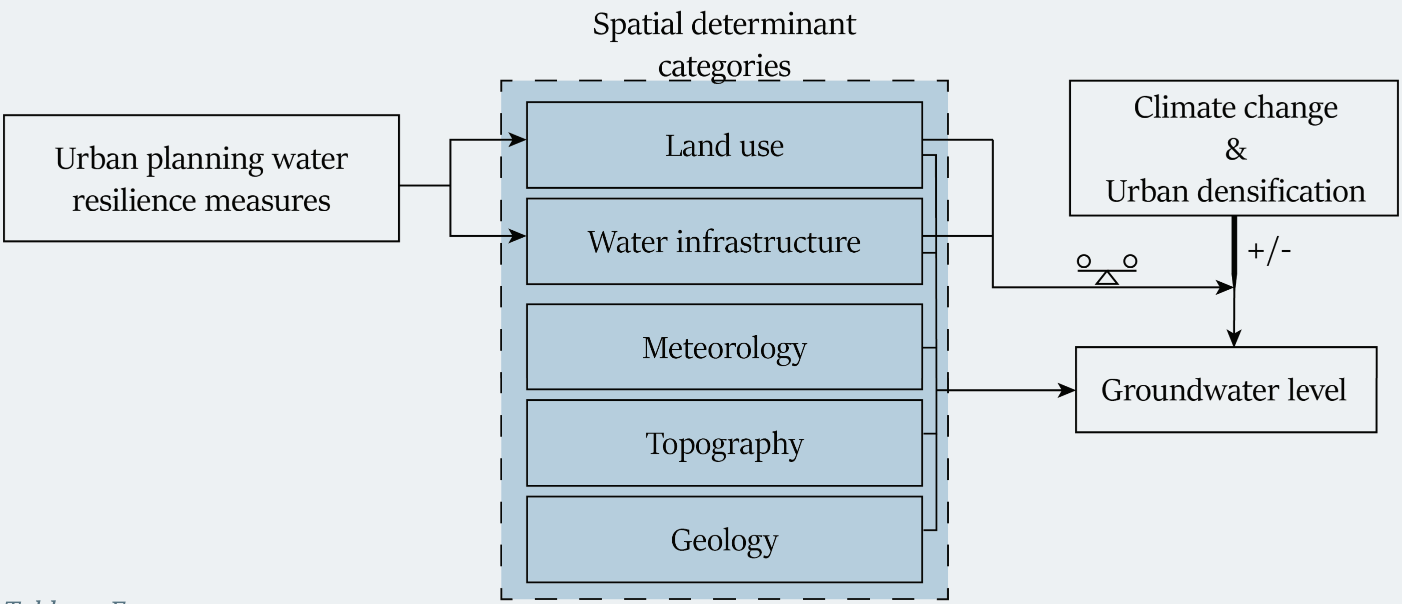


Table 2: Frequency analysis recommendation categories <<

Figure 7: Conceptual model on groundwater level changes

4.2. Policy analyses

The selection and analysis of cities is largely based on the overarching typologies of the results of the literature review. To further correspond to the aim of this article, the city must state in their spatial strategy the need for urban densification and the identification of climate change as a challenge that requires different planning strategies. Finally, selected cities must have at least 100.000 residents to guarantee proper data availability and an urban approach to its water related challenges.

The spatial determinant categories are split between adaptable through urban planning and fixed. Land use and water infrastructure could be changed with water resilience measures in mind. Meteorology, topography and geology are fixed. A selection of cities is made on these fixed categories to better explore the differences in water resilience application.

The geology, topography and meteorologic conditions should be similar. Considering these requirements, Norwich (UK), Eindhoven and Enschede (NL), Hannover and Münster (DE) were selected. All are located on a sand-loam plain with little height difference in the Cfb Köppen-climate zone [72]–[74].

EU legislation is the driving force behind the strategies of the case studies. The EU Water Framework Directive is a collection of standards for member states to comply to [75], [76]. The quality of groundwater is covered in major guidelines as the Groundwater directive and Quality of water intended for human consumption [77], [78]. Nationwide groundwater quantity regulations are not included as a protected value. The only mentions occur in the risk assessment of water withdrawal locations, causing differences in policy of overall groundwater strategies between member states [79].

	National	Provincial	Regional	Municipal	Water authority	Water supplier
Norwich	[80]	[81]	[82], [83]	[84], [85]	[86]	[87]
Eindhoven	[88], [89]	[90], [91]	[92]	[93], [94]	[95], [96]	-
Enschede	[88], [89]	[97]–[99]	-	[100], [101]	[102], [103]	[104]
Hannover	[105]	[106], [107]	[108], [109]	[110]	-	-
Münster	[105]	[111], [112]	[113]	[114]	[115]	-

Table 3: Overview sources used on scale levels per studied city

Table 3 gives an overview of sources used per scale level per city. Appendix D shows the entire policy analysis.

The forms of governance in spatial planning vary between the reviewed cities. Germany and England have a more decentralised approach compared to the Netherlands. On a national level, a framework is provided, but most planning strategy is made on the province or regional level [80], [105]. Strategies on the municipality level are rudimentary, if existing [84], [114].

The Netherlands has a more hierarchical approach to planning, providing spatial planning strategies from the national to the municipal level[88], [90], [93], [98], [100]. Besides this, water boards serve as a special governmental entity on the regional level ensuring better water management [95], [102]. In England, this set up has been emulated by the creation of a collaboration of stakeholders, started by the regional water supplier [86]. Germany does not have bodies specifically catered towards water management.

All policy documents have climate change mitigation and adaptation as one of the main priorities. While all reviewed cities want to densify, there is limited information on its relation to environmental consequences. Often the reason is the need for new housing and economic growth, while preserving the surrounding cultural and natural landscape. The changing circumstances within the city are sparingly addressed. For instance, the provincial strategy of Niedersachsen appoints preferential locations for densification, but there is no clear reasoning behind it [106]. Eindhoven seems to be frontrunner in acknowledging the challenges in relations between climate change, urban densification and water [93], [94]. Whereas Münster and Hannover are lacking severely in water management strategies, only covering the minimal necessities of EU legislation [109], [114].

4.3. Comparative analysis

The reviewed policy documents are compared to the main categories of recommendations of the literature review, a full overview is given in Appendix E. Interesting things to note are:

Due to the governmental structure, national levels in England and Germany delegate most spatial planning and water related responsibilities to their smaller scale bodies. On the national level, no specifics are given in water management or densification strategies [80], [105].

Artificial recharge is only mentioned once, as a proposal of the water supplier Vitens as a recharge measure in the Veluwe, a region without fluvial supply [104]. This is matches the literature review where artificial recharge was mostly mentioned in (seasonally) arid regions [49], [56], [58], [65].

Eindhoven and Enschede have more integration with stakeholders and initiates more participation with users [92], [93], [100]. Recommendations of the literature review state this is better for agreement on decisions over multiple scales and disciplines.

Water use efficiency through all scale levels is best addressed in Norwich, where efficiency and prioritisation practices between industrial, agricultural and residential withdrawal are in all scales of their strategy, as well as wastewater reuse [81], [82], [86], [87]. The unambiguous inclusion of water use efficiency in the policy documents can result in easier implementation. Certain strategies leaving parts out or contradictions between policy documents will slow advancements.

The subdivision of re- and detention measures into precipitation events and seasonal wet periods shows differences in implementation between scale levels. Larger scales focus on large seasonal retention strategies, while municipalities focus more on the precipitation event flood mitigation and water harvesting strategies. There is no description on how to integrate these measures into a comprehensive approach.

Discussion

This article aimed to discover what spatial measures need to be used in urban planning to influence groundwater level in a densifying city to create water resilience and if these are already in use in current urban planning policies.

The pressures created by UD and CC on the stability and availability of groundwater need to be addressed through water infrastructure and land use spatial measures. Based on the findings in this article, spatial planners can make decisions where to implement what concept to contribute to the regional water resilience.

A compilation of the methods used in the emerging field of remote sensing and GIS application to the fields of hydrology and urban planning has been made. Future research can use this summary as a base to expand their own spatial water explorations on.

Policy makers and urban planners can use the levers provided in this research for performance-based policy and design towards achieving water resilience. An example of a water resilience-based urban planning proposal will be given in the following chapters.

5.1. Findings

Spatial determinants of groundwater level used in academia can be grouped into 5 categories: Geologic, topographic, meteorological, hydro-infrastructure and land use. These define the flows of a water system.

Urban planning can provide change in the categories infrastructure and land use.

Policy and design recommendations can be grouped into seasonal and short term re/detention measures, water withdrawal management, land cover management and increasing vegetation, artificial recharge, water use efficiency, location specific measures and participation approaches.

Infrastructural approaches are withdrawal reduction through reuse of wastewater, efficiency in industrial processes, separation of waste- and stormwater, peak discharge reduction.

Land use approaches are increasing vegetation, increasing surface imperviousness, water retention on roofs, on ground level and below ground level.

Infrastructure and land use adaptation approaches have indirect consequences on the climate and topography.

Multiple differences exist between theoretic and practical methods of water resilience:

Re/detention measures could use more integration of strategy between seasonal and short term scales and artificial recharge is only considered when natural recharge measures have not enough potential. The effects of CC are universally accepted as a threat or challenge to the urban water cycle. Urban densification lacks in this regard.

5.2. Limitations and considerations

The use of a DPSIR framework to describe the effects of UD and CC on the urban water cycle is a simplification of reality. The strict causality is an abstraction of real-world relations. The selection of two drivers does not consider the rest of the context.

The comparative analysis assumes the results in academia as the base of recommendation on which the policy is measured against. Transposed, the effects have not been explored.

12/28 Articles used in the literature review are located in India, while the reviewed policies are in Western Europe. Possible explanations for the overrepresentation of India within the articles could be the combination of large population growth and arid climate, making the country susceptible to groundwater depletion, therefore making groundwater research a more pressing issue. The discrepancy between the locations of the literature review and the policy analysis should not pose as a problem as the methods applied in the articles can mostly be applied universally.

In 2020, the United Kingdom has left the European Union, making the documents in the policy analysis of Norwich not mandatory to comply to EU regulations [116]. Only the municipal strategy predates this event. However, the other policy documents are a continuation of older strategies which had to comply to EU legislation. Thus, a large overlap is assumed between current policy documents and EU regulation.

Part II: Analysis and design

Spatial analysis Eindhoven

6.1. Introduction Eindhoven

Building on the findings of the literature review, an urban planning proposal is elaborated. This will show the application of the theory into practice. Eindhoven is selected for a multitude of reasons:

- The city wants to increase its urban density and will experience the effects of climate change. The literature review has shown, this will put the urban water system under pressure. Adaptations through urban planning can be explored to alleviate this pressure.
- The policy review and comparative analysis have shown the municipality of Eindhoven is furthest in wanting to incorporate water resilient measures in its city. Therefore, making proposals for adaptation is most realistic in comparison to the other reviewed cities.
- Plenty spatial data availability and good contact with the municipality.

6.1.1. Historical context

To understand the current situation of both the city and its water system, the historical development of Eindhoven needs to be addressed.

At the confluence of the streams Dommel and Gender settlements formed that received city rights in 1232. Due to its militarily strategic position, a castle was constructed and the city was fortified. This caused the first change in the water system: the Gender was diverted to form a moat around the city [117].

The position was also favourable for trade as its location functioned as a junction between larger cities, causing the gradual growth of the city. The soil was naturally dry and unfertile, so agriculture was only practiced along the streams.

As a consequence of the industrial revolution the city changed drastically. The number of inhabitants grew and water demand for residential and industrial purposes exploded. Without proper wastewater management, the surface water quickly became polluted. Outside the city, the introduction of artificial fertiliser made the heathlands viable for agriculture, transforming the landscape to a system of irrigation and drainage [119], [120].

In the 20th century, the development of further expansions and the introduction of sewage desurfaced many smaller streams such as the Lakerloop and Lijmbeek [121], [122]. Additionally, the moat around the city centre was filled in [123]. Large scale bombings during WWII gave space for a large overhaul in infrastructure and building development.

Postwar, the already fast-growing Eindhoven even became the city with the largest population growth in the Netherlands. The third quarter of the 20th century marked the start of industrial decline. Groundwater extractions for industrial purposes plummeted. Figure 8 shows the decline for the province. The effects in Eindhoven were even larger as factories that were located within the city relocated to elsewhere out of city bounds or shut down. The groundwater level rose again in neighbourhoods that were built on dry soil during the extractions [124], [125]. This causes many areas around the streams to experience groundwater nuisance currently.

A sequence of maps in figure 9 shows the rapid development of the city over the past century.

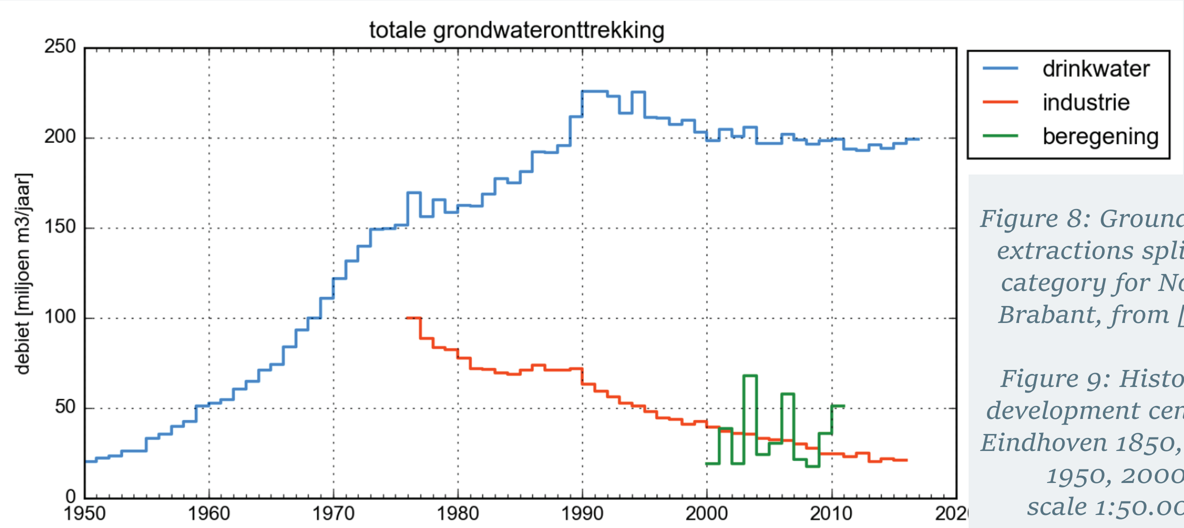


Figure 8: Groundwater extractions split per category for North-Brabant, from [126]

Figure 9: Historical development centre of Eindhoven 1850, 1900, 1950, 2000, scale 1:50.000, from [127]

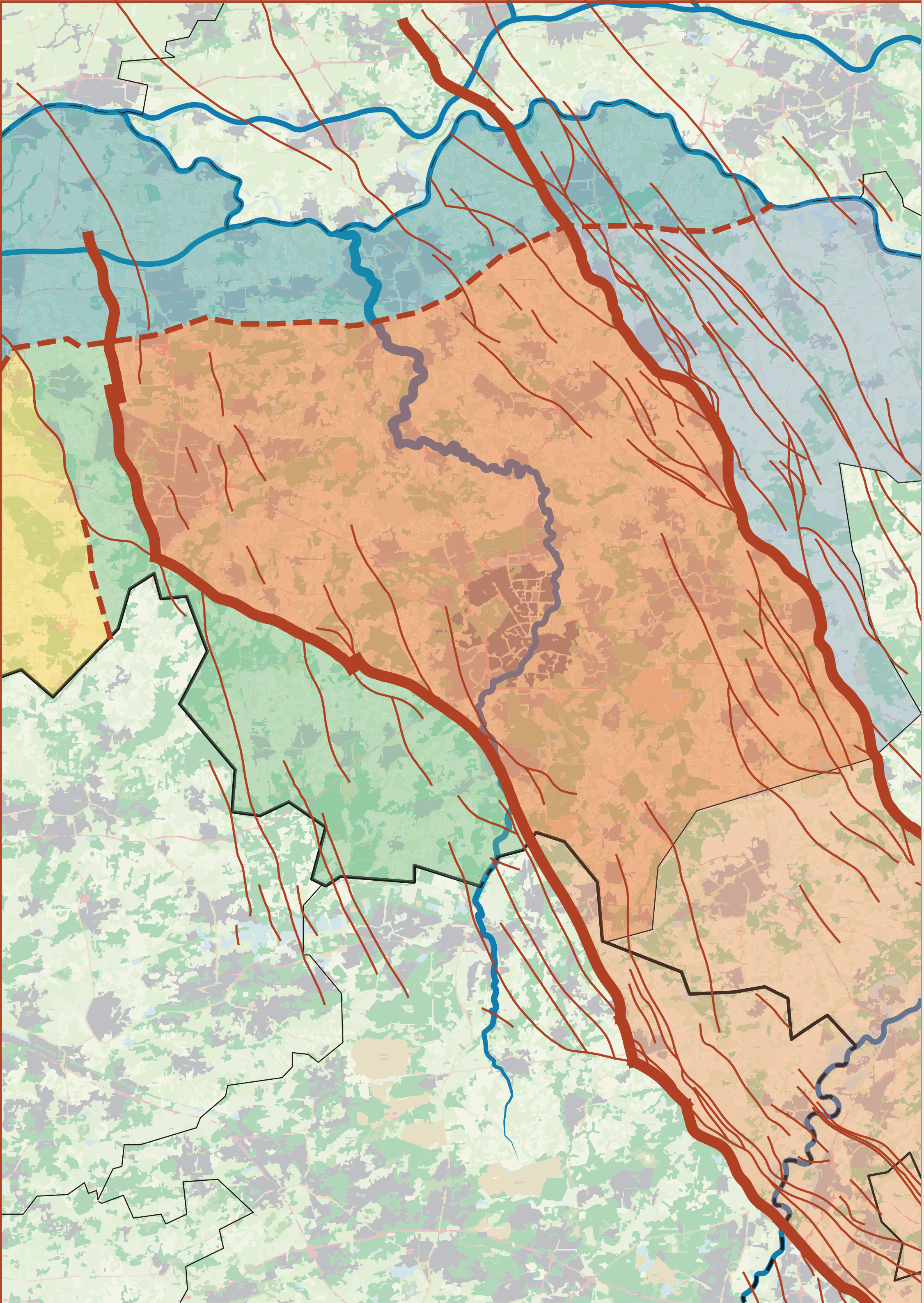


Figure 10: Aquifers eastern North-Brabant, scale 1:500.000, based on [126], [129]

Figure 11: Watershed Dommel, scale 1:500.000, based on [130]

- Surface water
- Dommel
- Watershed Dommel
- Built up areas
- Eindhoven

6.1.2. Regional context

Eindhoven is the largest city in the Dommel watershed. The watershed is located in Belgium and the Netherlands. The Dutch segment is managed by the water authority, Waterschap de Dommel, and in urban areas, land use and wastewater management are municipal responsibilities [128]. Drinkwater extraction is done by the sole water supplier in eastern Noord-Brabant, Brabant Water. Different extractions take place for industrial and agricultural purposes.

The groundwater aquifer and surface water watershed are not identical, shown in figures 10 and 11. Aquifers are delineated by geologic formations. Eindhoven is located in the Central Graben (Roerdalslenk). The western boundary is the Feldbis-faultline, the eastern boundary is the Peelrand-faultline. The graben extends from Germany towards the north-west, underneath Eindhoven, towards the centre of the Netherlands, where the groundwater level is dictated by the water levels in the rivers Meuse and Rhine. For data availability purposes, the southern border is taken as the provincial border with Limburg. Neighbouring aquifers in the west and east are the Kempisch Plateau and Peelhorst. These are both horsts, meaning they have higher elevation than grabens. The Central Graben has therefore large inflow from its neighbouring aquifers. A switch towards a dryer climate in combination with more water demand from urban densification in Eindhoven will have little effect in the Central Graben, but the Peelhorst and the Kempisch Plateau are more at risk for these changes as they have no natural geological influx [126].

6.2. Implicatons for Eindhoven

The water cycle in the region of Eindhoven is based on the yearly precipitation surplus it experiences. The amount of precipitation is higher than the evaporation and infiltration of the system. The water cycle is a closed system, so the remaining water must go somewhere. The excess is guided towards drainage and runs off through sewage and surface waters.

Effects of climate change specific to Eindhoven [131], [132]:

- The yearly precipitation will increase (mostly during winter)
- Precipitation events will become more extreme
- Dry periods will be longer and more extreme (mostly during summer)

Overall, this results in the need for more retention measures, saving the water during wetter periods in seasonal retention and detaining water during rainfall events to prevent stormwater flooding.

Effects of urban densification, see figure 1:

- There will be more paved surfaces
- There will be less vegetation
- There will be more water demand

Overall, this results in a shift towards more runoff at the expense of infiltration if there is no intervention of water resilient urban planning measures, while also increasing groundwater extraction.

The combination of the effects of urban densification and climate change on the existing water system in Eindhoven will lead to the overcapacity of the current water system during wet periods and the desiccation of the system during dry periods. These effects also result in the overall drop of the groundwater level, increasing negative impacts in places that are already experiencing drought.

To prevent damage to the living environment, we will explore the possibilities for water resilient design measures in Eindhoven.

6.2.1. Risk areas

The main principle of the analysis is to identify the risk areas in Eindhoven, with the goal of implementing water resilient urban planning measures to reduce the (negative) implications caused by urban areas being too wet or too dry.

Urban areas being too wet:

If groundwater levels are too shallow in built-up areas, the buildings and infrastructure can experience groundwater nuisance. The municipality accounts for a threshold of 70cm below the surface, with 90cm below the surface as indicator to implement preventative measures [128]. The flood risk area threshold should only count for urban areas, as high groundwater levels outside of urban development are beneficial for natural diversity.

Urban areas being too dry:

The largest risk of dry soil is land subsidience and the health of urban green. With groundwater levels that are too low or moisture content in the unsaturated zone being too low for prolonged periods, buildings can sink and the urban green will die. The municipality set a threshold of 3m below the surface as the risk limit of dry areas [133]. This is a debatable guideline, as other sources state that most vegetation on the higher sand soils feeds exclusively on the soil moisture of the unsaturated zone [134]. Figure 12 on the next page shows the locations of the risk areas.

6.2.2. Infiltration potential

Concluding the effects of urban densification and climate change in Eindhoven, the urban water cycle should shift from a runoff-based system towards an infiltration-based system. Following the spatial determinants of the literature review, the infiltration potential is based on 4 indicators, shown in figure 13:

1. Soil permeability

A more permeable soil type will let water infiltrate more easily. The k-value of the soil type is used [135], [136].

2. Relief

Water infiltrates best on surfaces with a slope below 5%. As Eindhoven is mostly flat, only manmade microrelief is steeper [137], [138]. A line density calculation shows the approximation of relative flatness of areas.

3. Imperviousness

On impervious surfaces, no water can infiltrate. Remote sensing data is used to estimate the percentage of impervious surfaces [139].

4. Vegetation

Plants will intercept and slow runoff, creating more possibility for infiltration of water. A NDVI (Normalised Difference Vegetation Index) is calculated to spatially map the relative degree of vegetation [140].

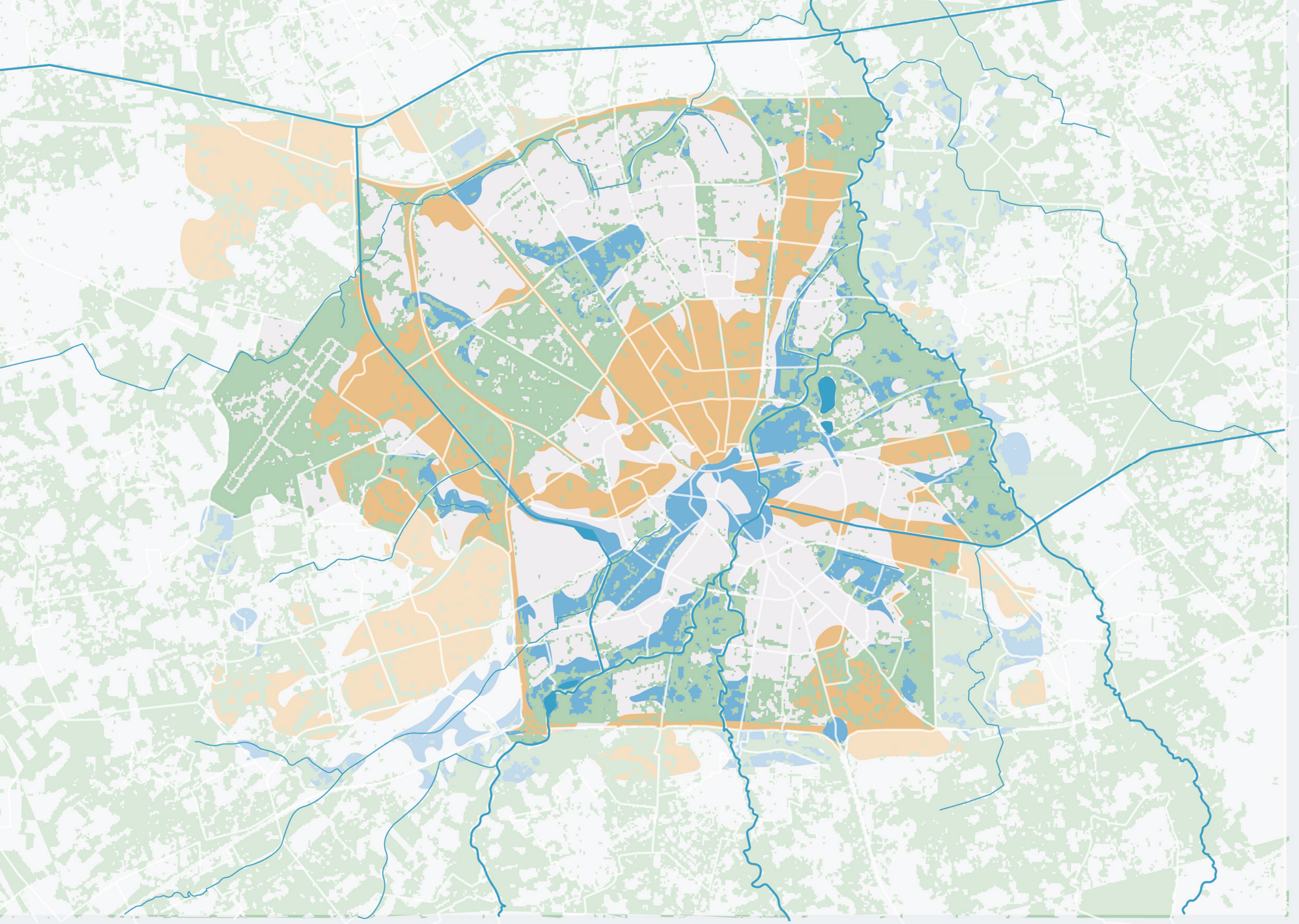


Figure 12: Groundwater risk areas, based on [128], [133], [135], scale 1:100.000

Base map

Vegetation (NDVI > 0,35)

Surface water

Risk areas

Flood risk (AHG < 0,9m)

Drought risk (ALG >3m)

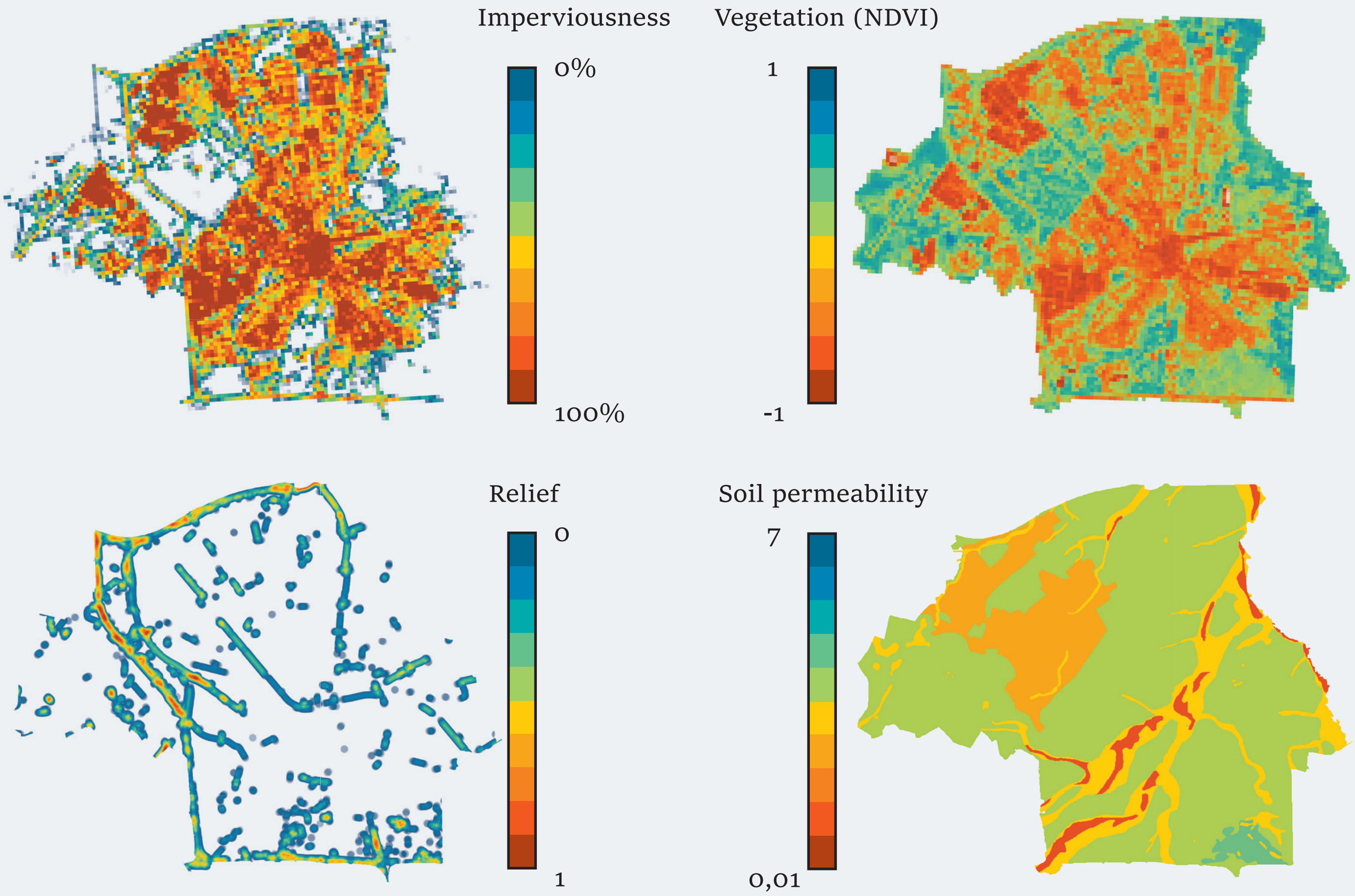


Figure 13: Infiltration potential components Eindhoven, scale 1:200.000, based on [135]-[140]

When these four are normalised and multiplicated, it equates to the total current infiltration potential. The weights of the separate indicators do differ based on locational context and are not known for this case. Therefore, all indicators are assumed to be of the same weight. Figure 14 shows the multiplication of the components.

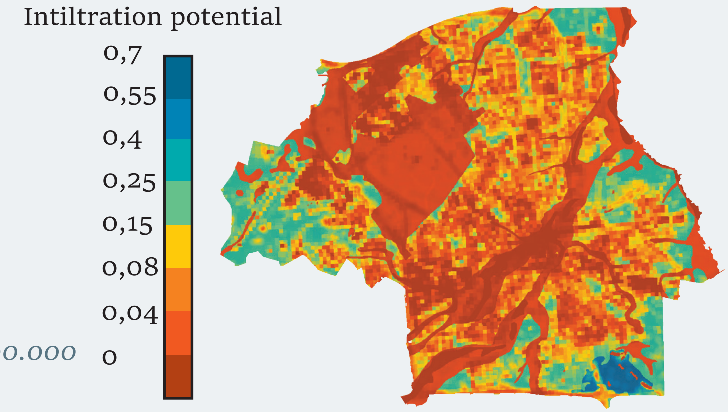


Figure 14: Infiltration potential Eindhoven, scale 1:200.000

The indicators vegetation and imperviousness are adaptable through urban planning. Soil type and slope are not. Subtracting the urban planning indicators from the given context indicators will result in the ‘infiltration potential priority’. These are the areas where implementations for infiltration would be most effective (having currently low vegetation and high imperviousness, while having little relief and highly permeable soil).

6.2.3. Other recommendations

The focus of recommendations in the literature in chapter 4.1 revolves around the integration of re/detention measures on different scales to account for seasonal wet periods on regional scale and singular rainfall events on the neighbourhood and district scale. Especially the combination of low vegetation with high imperviousness leaves much room for improvement.

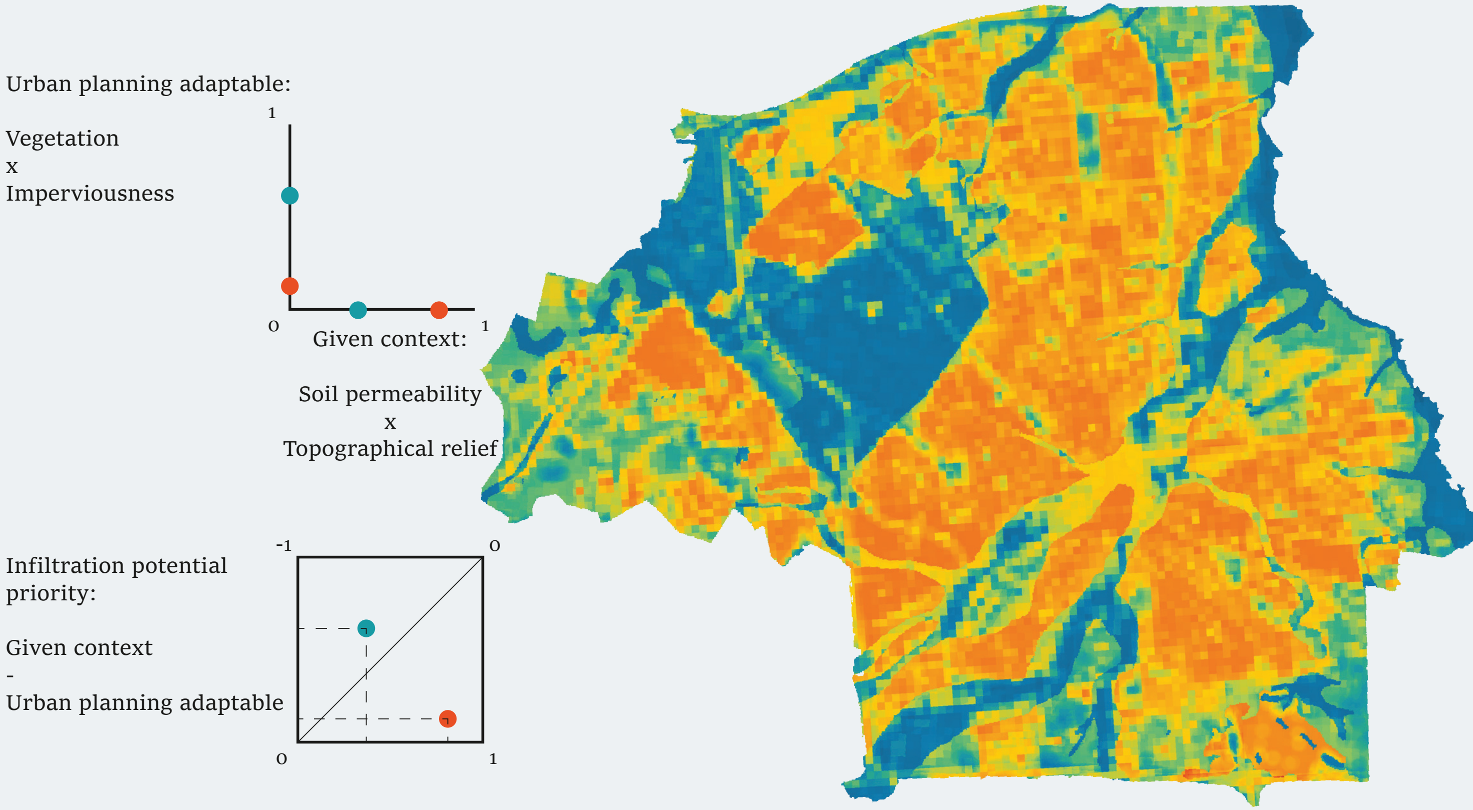


Figure 15: Infiltration potential priority Eindhoven with explanation, scale 1:100.000

Notably, areas which function as industrial estate are highlighted, as well as areas with high urban land use intensity. The latter is expected when taking the results of the DPSIR framework in chapter 1.2.2 as a guideline.

As part of land cover management, the restoration of surface waters could be beneficial for Eindhoven. Restoration in this context is meant as decanalising or resurfacing streams, restoring the flows of the natural water cycle.

Eindhoven used to have many streamlets which have disappeared over time due to urbanisation. Many of these are located in areas that are interesting regarding the risk areas. Resurfacing streams could provide drainage in flood risk areas and a source of infiltration in drought risk areas.

6.2.4. Density

Many documents state the need for more density in Eindhoven as there is a housing shortage, combined with very limited space to expand cities horizontally in fear of further deterioration of the surrounding landscape [141]–[146].

Most detailed of these visions is the Ontwikkelperspectief Centrum 2040 [147]. The extent of the vision is taken as the foundation for the densification proposal in the following chapter.

This vision does has little regard for the urban water system, especially as most areas in Fellenoord (KnoopXL, the area which has the largest proposed densification) and city centre fall within a flood risk area. The large buildings that are added to the current urban fabric will need large foundations and subsurface structures, disrupting the groundwater flows. The heavy machinery needed for such large structures also compact the soil, reducing its permeability.

Additionally, a proposition has been made for the resurfacing of the Gender with a green boulevard encircling the city centre. This idea is a good start of making a green-blue network throughout the city, focussed in densification areas. However, the execution in the drawings seems like an afterthought.

A different proposal with the water system as a base will be created, to give an opposing view from a water resilient urban planning perspective.

6.3. Conclusion

A map of all discussed aspects in this chapter is provided in figure 16.

1. Reduce risk areas

As the literature review states; the basis of the need for water resilient urban planning is to reduce the negative impact caused by UD & CC. This chapter indicates which areas experience risks in terms of groundwater level. The focus of implementations should be in these areas, attributing to a more resilient city as a whole.

2. Use the infiltration potential and context of location

Considering the effects of UD & CC on Eindhoven, the need to switch from a runoff-based system to an infiltration-based system became apparent. With the use of spatial determinants for groundwater level as found in the literature review, an infiltration potential dataset has been made. By splitting the determinants into ‘given context’ and ‘urban planning adaptable’, the infiltration potential priority map has been made. Using this dataset, areas can be assigned priority in depaving and greening, as implementing change in these areas will be most effective in terms of infiltration. Together with the context of the location, such as the current green network and the absence of streams which used to exist, this can form a city-wide network of water resilience.

3. Fit densification in

When densification occurs without taking the water system into consideration, the developments disrupt the natural state further. Densification should be taking place hand in hand with a green-blue network on all scale levels to ensure densification does not have negative consequences on the water system. Improvements could be made upon the current densification vision.

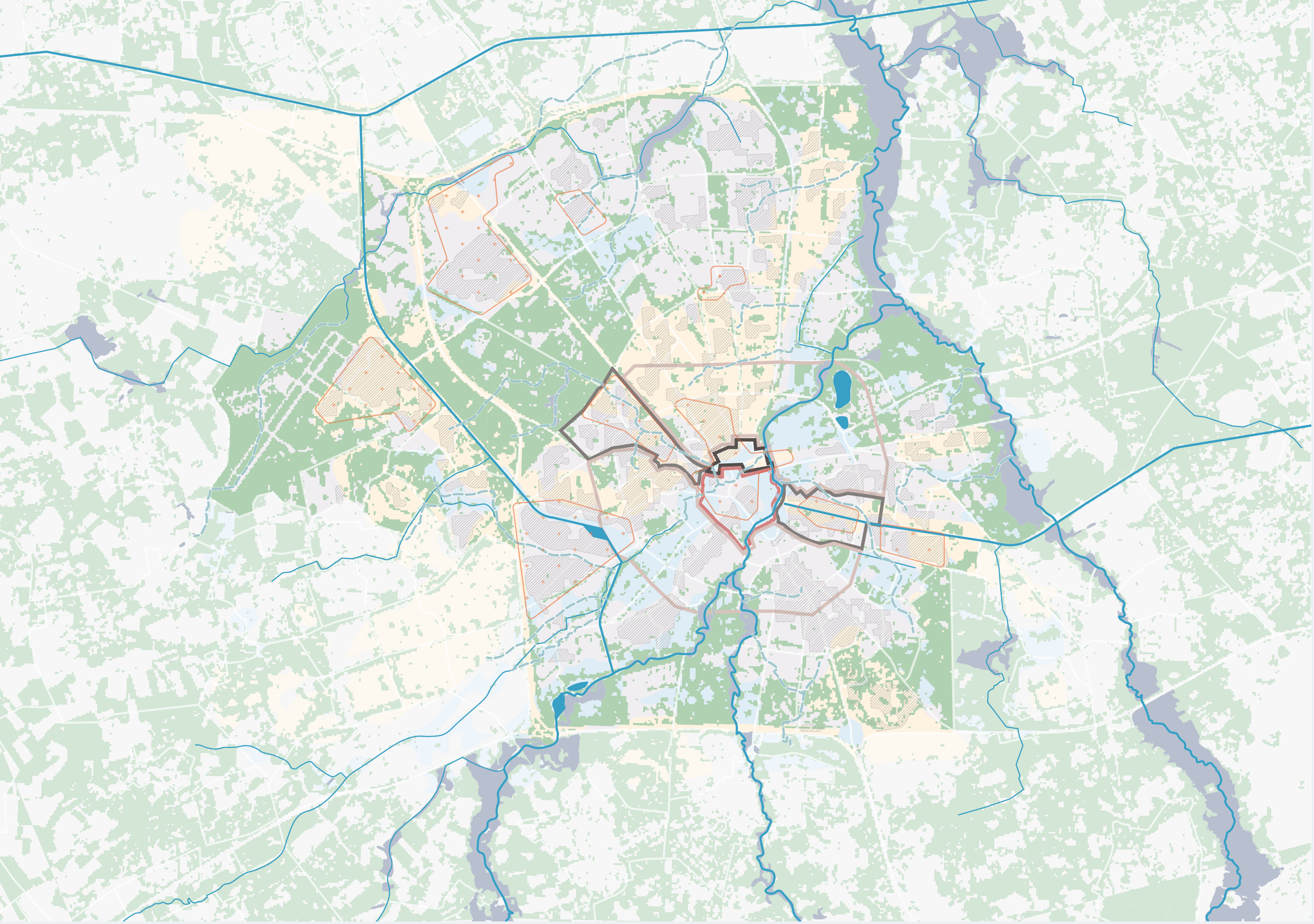


Figure 16: City analysis, scale 1:100.000

Groundwater [135]-[140]

- ALG > 3m (drought risk)
- AHG < 0,9m (flood risk)
- High effectiveness infiltrative measures ((soil * slope) - (vegetation * perviousness) > 0,3)

Surface water [130], [135]

- Surface water
- Seasonal water retention
- Historic surface water

Current densification vision [147]

- FSI 5,04
- FSI 2,92
- FSI 1,70
- FSI 1,34

Vegetation [140]

- Within municipality (NDVI>0,35)
- Outside municipality (NDVI>0,35)
- Vegetation * perviousness < 0,1)

City scale strategy Eindhoven

7.1. Main aim

1. Water resilience implementations work together on all scale levels
To create a city that can both handle large precipitation events as well as long dry seasons, together with areas prone to drought and flooding, a green-blue network starting at the building level and reaching to the regional scale should be made.

2. Infiltrate (greening, depaving, re/detention design solutions) where possible, drain where needed
To switch to an infiltration-based system, the main guideline should be to try to incorporate infiltration measures as much as possible. However, in flood risk areas this would not be beneficial. Here, an approach towards draining would help more.

3. Limit densification in unfavourable locations
Creating more density does often mean more implications for the subsoil and consequently disruptions in groundwater. Especially in locations with shallow groundwater these effects are not wanted. From a water-based perspective, it would be better to have major densification zones outside of flood risk areas.

7.2. Interventions on all scale levels

7.2.1. Regional

Outside urban development, there is space for seasonal water retention. Water management outside cities is done by the water authorities. Already certain areas are meant as 'waterberging', however, the capacity and extent could be increased to make it function as seasonal reservoirs instead of a mere overflow. These implementations should not only be spatial, but also cover policy agreements with agriculture and nature associations for regulation of surface waters.

7.2.2. City/district

To establish a blue-green network throughout the city, advantageously positioned historic streams are resurfaced to make connections. These can help in draining flood risk areas (Lakerloop in Stratum and Groote Beek in Woensel) and feed water to drought risk areas (Unknown waterloop in Woensel, Lijmbeek in Strijp). Historically, these were already the lower areas, so reintroducing blue-green space here will automatically become spaces of accumulation.

7.2.3. Neighbourhood

On the smaller scale, the focus is on the spatial differences that combine into the infiltration potential and the interventions that directly affect risk areas.

	interventions
Flood risk area	Separate sewage to increase stormwater capacity (simultaneous with street reconstruction) Increase surface water drainage Re/detention of water in surrounding areas
Drought risk area	Depaving Greening Restore (decanalise/resurface) surface water Use re/detention elements Limit drainage
High infiltration potential	Prioritise depaving and greening in places with high imperviousness and low vegetation while having highly permeable soil and little relief Use re/detention elements (simultaneous with street reconstruction)

Table 4: Overview neighbourhood interventions

The areas that have too much pavement with not enough green are mostly highly dense urban areas (city centre, Strijp-S, winkelcentrum Woensel, Woensel-zuid) or industrial estates (Flight Forum, Bedrijventerrein Acht, de Hurk, Kanaalzone, DAF). Priority is given to green and depave these areas where they overlap with the high effectiveness of the infiltration potential.

Figure 18 on the next page shows the combination of these interventions.

7.2.4. Density

Analysis showed the Ontwikkelperspectief Centrum 2040 to be not sufficient in terms of consideration of the water system.

The largest problem of the vision is the densification in the flood risk areas. By limiting extra densification in areas which are already prone to high groundwater levels, the disruption of flow in the system is kept to a minimum. Additionally, less proposed buildings in these areas will mean that there will be less groundwater nuisance experienced in the long term.

Having the Ontwikkelperspectief as the leading document for densification does counteract the vision of Stedelijk Gebied Eindhoven (SGE). There, they propose multiple, decentralised densification locations. These are central locations along high quality public transport corridors. This helps in alleviating the pressure of KnoopXL as leading location.

Densification does not have to be limited in drought risk areas. If the proposed development goes hand in hand with the overall shift towards an infiltration-based system and there is enough open ground to ensure a sufficient soil moisture content, there is no large caveat.

Figure 17 shows the densification vision of Ontwikkelperspectief Centrum 2040, and below it the proposal of this project.

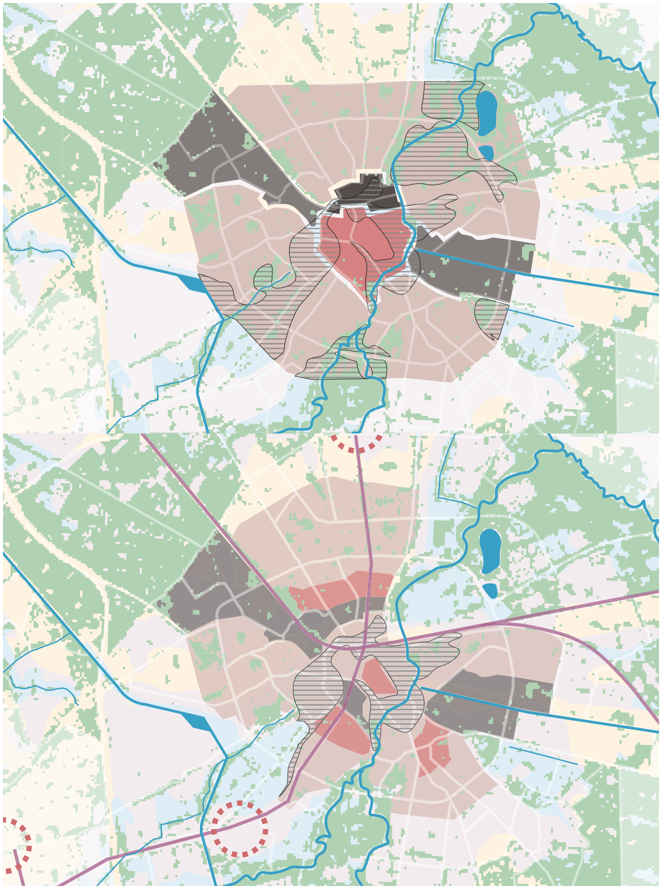


Figure 17: Strategy densification: current vision and water resilient proposal, scale 1:100.000

Proposed densities [135], [147]

- FSI 5,04
- FSI 2,92
- FSI 1,70
- FSI 1,34
- Densification in floodrisk area
- Other densification nodes
- High quality public tranport corridor

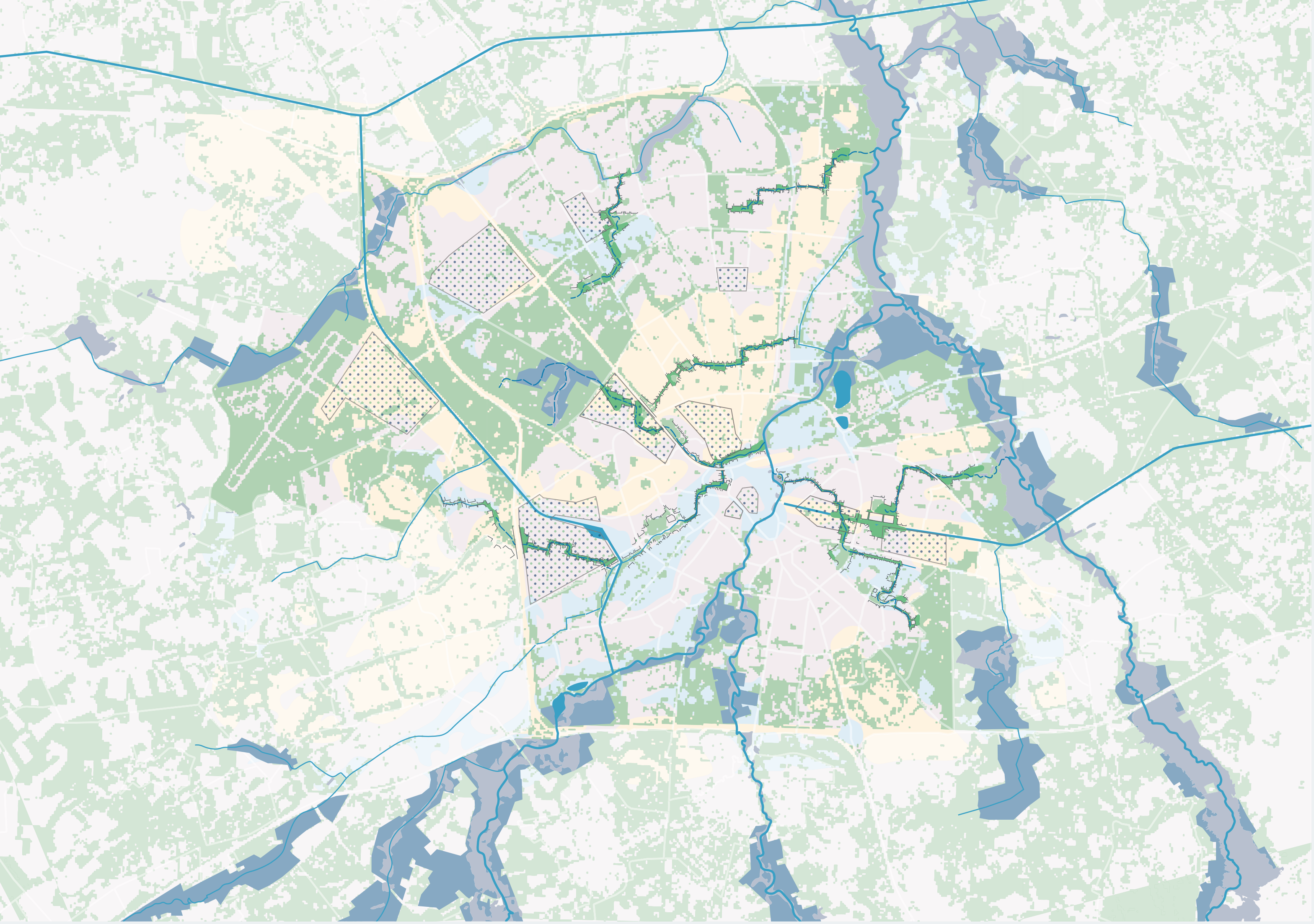


Figure 18: Implementations city strategy, scale 1:100.000

Groundwater [135]

- ALG > 3m (drought risk)
- AHG < 0,9m (flood risk)

Surface water [130]

- Surface water
- Seasonal retention

Vegetation [140]

- Within municipality (NDVI>0,35)
- Outside municipality (NDVI>0,35)

Implementations [135]-[140], [148]

- Regional: Expansion seasonal retention
- District: Resurfaced stream
- District: Green-blue network through resurfaced streams
- Neighbourhood: Priority greening and depaving; overlap in infiltration potential priority and low vegetation + high imperviousness

The current vision relies too much on wanting to build in the floodrisk areas in the centre and Fellenoord. By shifting the density more towards the periphery of the city centre, this is avoided. This proposal also fits in with the other city strategy components that have been mentioned in this chapter.

The type of densification differs per neighbourhood. Different severities of intervention can result in different amounts of added floorspace. Ranging from private do-it-yourself skyborn or ground-based extensions of their homes to transformation of existing building stock to complete redevelopment of certain building blocks to increase FSI [149]. The degree of density needed gives differentiation in densification strategy. Using the current FSI per building block, the deficit of FSI (FSId) can be calculated [150]. Applying this method to the new densification proposal, it gives detailed insight in the distribution of needed floorspace per neighbourhood, as shown by figure 19.

The current densities substracted from the density proposal, clearly show the need for different approaches per neighbourhood. For instance, the city centre does not need added floorspace, while Limbeek-Zuid and Kanaalzone are important densification zones.

This densification proposal is in combination with the seasonal retention outside cities, the green-blue network of resurfaced historic streams, extra surface water drainage and separation of sewage in groundwater nuisance areas, focus on depaving and greening in the most effective areas and using street reconstruction to efficiently start implementing water resilience measures, a more water-considerate approach to densifying a city.

The following chapter will zoom in on a neighbourhood to show the implications on a smaller scale.

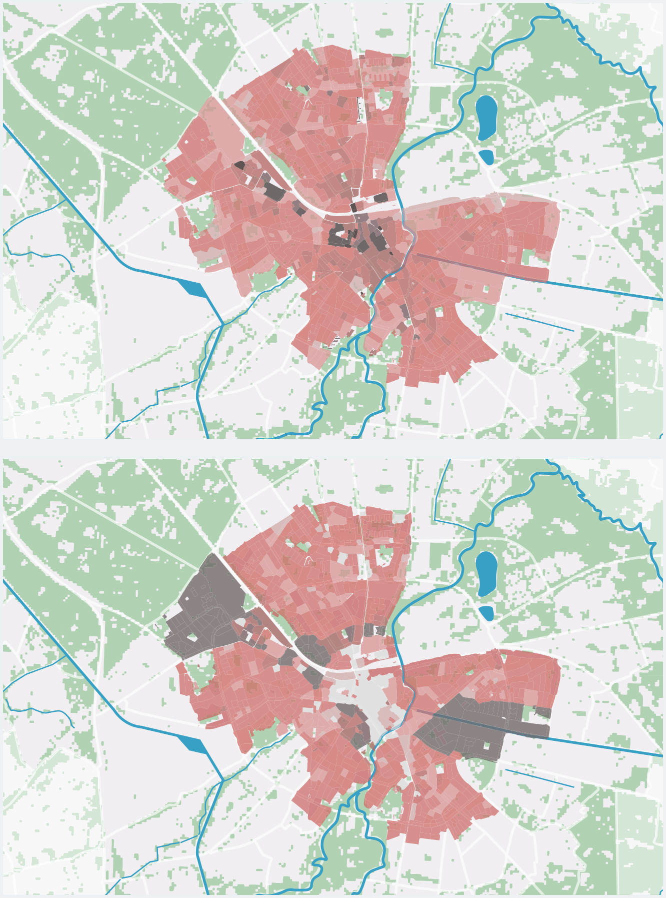
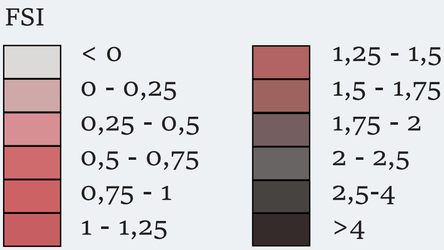


Figure 19: Current FSI and FSI deficit (FSId) per building block, scale 1:100.000, based on figure 17, [150]



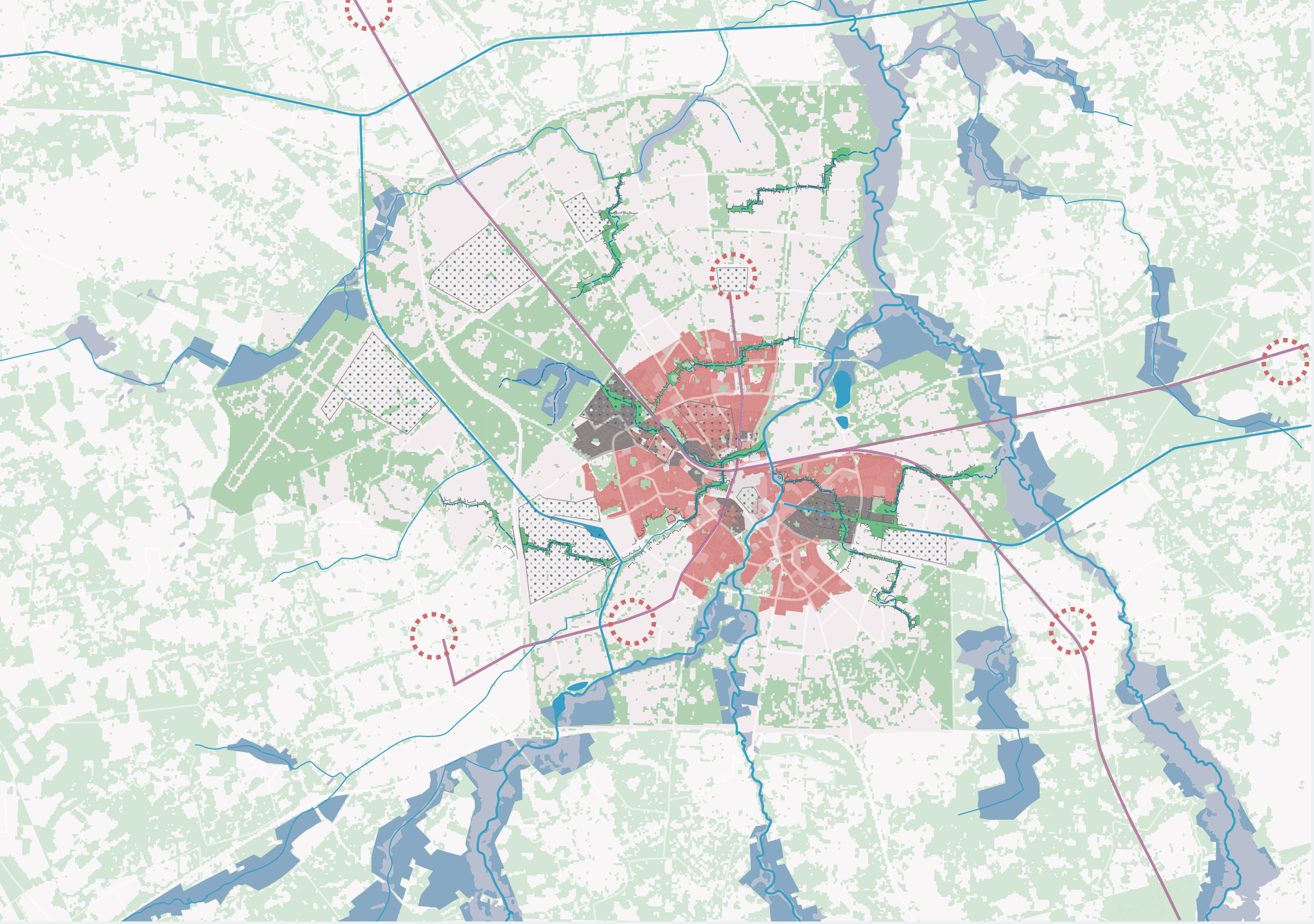


Figure 20: Complete city strategy, scale 1:100.000

Groundwater [135]

ALG > 3m (drought risk)

AHG < 0,9m (flood risk)

Surface water [130]

Surface water

Seasonal retention

Vegetation [140]

Within municipality

Outside municipality

Implementations [135]-[140], [148]

Expansion seasonal retention

Resurfaced stream

Priority greening and depaving

Green-blue network through resurfaced streams

FSI deficit [142],[150]

No densification (FSId < 0)

Low densification (FSId 0-1)

Medium densification (FSId 1-2)

High densification (FSId > 2)

Densification in Floodrisk area

Other densification nodes

High quality public tranport corridor

Neighbourhood scale design
Limbeek-Zuid & Fellenoord

8.1. Analysis

This chapter zooms in on two adjacent neighbourhoods with different contexts from a land use, accessibility and water perspective. Both Limbeek-Zuid and Fellenoord fulfil a central role in the city strategy. Fellenoord is envisioned in current policy documents to be the centre of the densification project KnoopXL. This makes sense through the lens of land use and accessibility, but less when considering water. The city strategy has therefore placed this centre of density more outwards, towards the banks of the stream valleys. Limbeek-Zuid is pivotal in this alternative vision of the densification in Eindhoven.

8.1.1. Introduction

Currently, Limbeek-Zuid is a low-density neighbourhood comprised mostly of terraced housing owned by social housing corporations. Although located in the very centre of the city, it is unlively. The typical Dutch 1980s 'bloemkoolwijk' layout together with the almost non-existent amount of amenities means that there is no reason to visit [151]. Figure 21 shows the backdrop of the neighbourhood, with mid- to high-rises surrounding the neighbourhood. A reminder of its central location. The street section is dominated by car parking on both sides of the street and fenced backyards with sheds terminate in uninspiring brick courtyards.

Fellenoord is the neighbourhood north of the train and bus stations. It serves a primary purpose of transportation. The few buildings stand isolated and anonymous in the tangled mess of all infrastructure, see figure 22. While being located centrally, there is little quality in the public space. The current proposal for the redevelopment of Fellenoord describes it as not the best first impression for visitors that enter the city by public transport [146].

Both neighbourhoods have potential for improvement. In the coming chapter an analysis of the area is conducted, after which a design proposal is made through a design strategy for the district Woensel-Zuid.

Figure 21: Limbeek-Zuid, Annie Romein-Verschoorstraat

Figure 22: Fellenoord, taken from Bogert

8.1.2. Analysis Limbeek-Zuid & Fellenoord

The analysis for these neighbourhoods is split in three components. Firstly, the historical context discussed. Secondly, the green-blue structure. Thirdly, the accessibility and land use are covered.

Figure 23: Historic context analysis, scale 1:10.000

Heritage

- Monument
- Historic radial
- Historic urbanistic structure
- Protected townscape

Building age

- < 1850
- 1850 - 1900
- 1900 - 1940
- 1940 - 1960
- 1960 - 1980
- 1980 - 2000
- 2000 - 2023

Water

- Surface water
- Historic surface water (1850 - 1900 - 1950 - 1975 - 2000)

The analysis for these neighbourhoods is split in three components. First, the historical context discussed. Second, the green-blue structure. Third, the accessibility and land use are covered.

History and heritage

Eindhoven has developed over the centuries as the merging of multiple villages. Eindhoven itself was the central village, with radials connecting to the others. These are still defining the structure of the city. The Kruisstraat and Lijmbeekstraat are noticeably older than the infill developments in between them [152]. They used to connect to the city centre, however, they do now terminate in Fellenoord. Enhancing the connection could be beneficial for the quality of the space.

Using historic maps, the location of water is superimposed on the city [127]. This shows the ongoing shift in the exact locations of streams. When resurfacing the Gender and Lijmbeek, they do not have to conform to an exact course. Rather, a different course can be chosen based on the context.

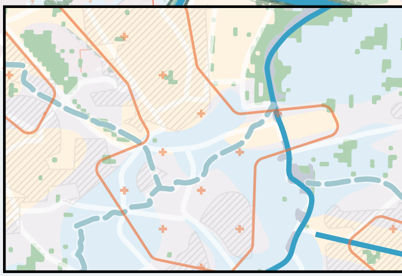
Blue and green networks

Based on the slopes of the streets, most stormwater would not run off towards the Dommel. This creates nuisance during peak precipitation events, as climate models predict [133]. The compartmentalisation shows accumulation areas at the Boschdijk, Anthony van Leeuwenhoeklaanpark and Neckerspoel. Piercing the compartments could form a more resilient, coherent whole. Woensel-Zuid is mostly located in a drought risk area. Together with imperviousness and a lack of green, it is needed to depave and green. As the city strategy showed, the resurfacing of streams can help with this, however, small scale interventions within the neighbourhoods can also help to create a water resilient future.

Land use and mobility

The bus and train stations need to expand to accommodate the projected growth of the city. Currently, proposals are made to better connect them together by placing the bus station underneath the train plaforms [153]. This clears space on the surface level for densification and water resilience measures. Nevertheless, this solution would not be ideal as the large subsurface structure and entrance tunnels would block the south to north flow of groundwater [154]. A different solution would be preferred.

Fellenoord is dominated by wide car infrastructure. The city of Eindhoven wants to move away from the car dependency in their system, especially within the ring road [155]. The roads will become unnecessarily wide when they do not have to endure through traffic anymore. A downgrade will create more space in the city. This space could be used for infill development, water resilience measures or a combination thereof. The office blocks and wide infrastructure also block the mixed-use radial of the Kruisstraat from connecting to the city centre. Introducing a better mix of functions in Fellenoord would decrease the barrier of the train tracks.



Close-up of city analysis

Figure 24: Blue & green analysis, scale 1:10.000

Surface water

- Surface water
- Historic surface water
- Runoff compartments
- Runoff direction
- Accumulation location

Groundwater

- ALG > 3m (drought risk)
- AHG < 0,9m (flood risk)

Greenery

- Public green
- Trees
- Natuurnetwerk Brabant
- Vegetation * perviousness < 0,15

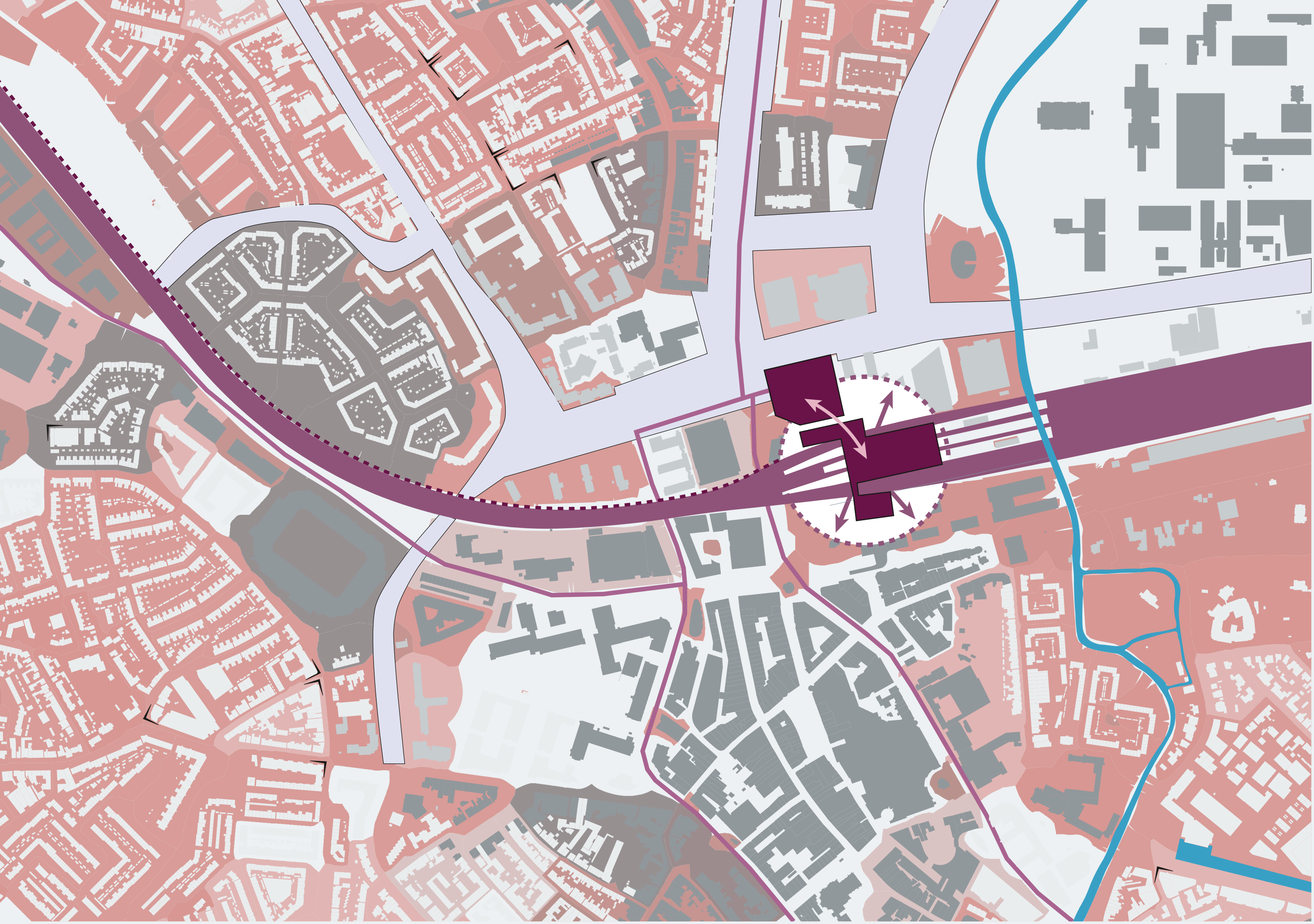


Figure 25: Density & mobility analysis, scale 1:10.000

Surface water
Higher density street corners

Land use type

Mostly residential
Mostly offices
Mostly mixed use

FSI deficit per building block

No deficit
0 - 0,25
0,25 - 0,5
0,5 - 0,75
0,75 - 1
1 - 1,25
1,25 - 1,5
1,5 - 1,75
1,75 - 2
> 2

Mobility

Width infrastructure
BRT
Train tracks
Bus & Train stations
Proposed expansion

8.2. Strategy

As mentioned in chapter 7.2.4, different FSI deficits cause the need for different densification methods. This is applied in figure 28. Parts of the city with a large deficit and a low quality of current buildings have to undergo major redevelopment, such as in Limbeek-Zuid. A slightly smaller deficit results in the focus on partial redevelopment and infill opportunities, for example in Hemelrijken, Kruisstraat-Zuid and Woenselse Watermolen. Fellenoord has only a little FSI deficit, so there the focus should be on transformation of the current building stock and infill development. Based on the context, the downgrade of wide car infrastructure, recreation of the Kruisstraat radial and opportunities for creating a public space at the north side of the station are also interesting as development guidelines.

Separation of public transport, car traffic and slow traffic networks forms a safer and more relaxed traverse of the city. Although traffic of cars is restricted, the cycling network emphasizes the connection of north and south through the continuation of mixed land use along the Kruisstraat.

The resurfacing of the Lijmbeek introduces, besides the water resilience benefits, the human connection with the water. It should be used as the centerpiece of the high density neighbourhood, creating a varied string of high quality public spaces, gradually transitioning in the resurfaced Gender. Here, the residential surroundings transform into a city park. Introducing the much needed green space in the city centre, while also piercing the runoff compartments and ensuring the alleviation of stormwater accumulation in Limbeek and Neckerspoel. The downgrade of infrastructure creates the opportunity for green corridors to penetrate into the impervious neighbourhoods, emulating the natural water system based on capillaries and arteries, shown in figure 26 and 27.

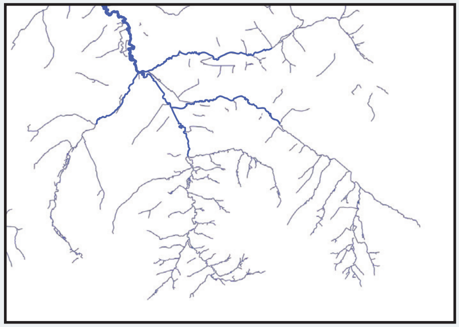


Figure 26: Capillary - artery structure of natural catchments, Geul valley, scale 1:250.000

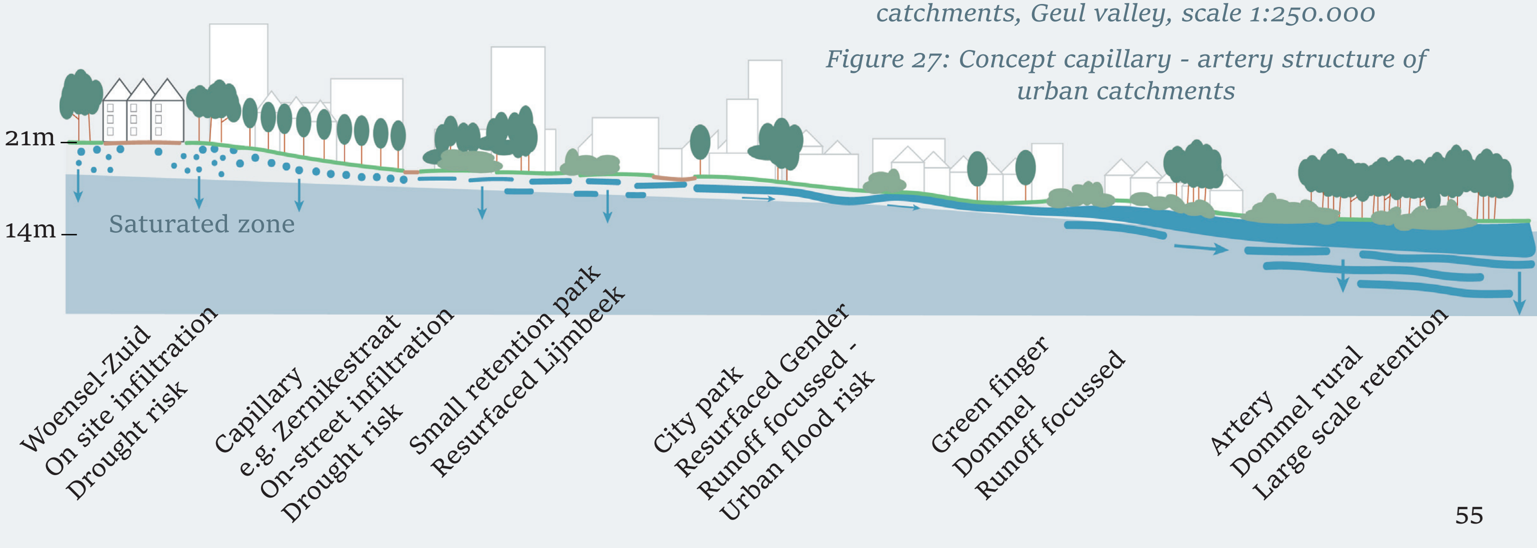


Figure 27: Concept capillary - artery structure of urban catchments

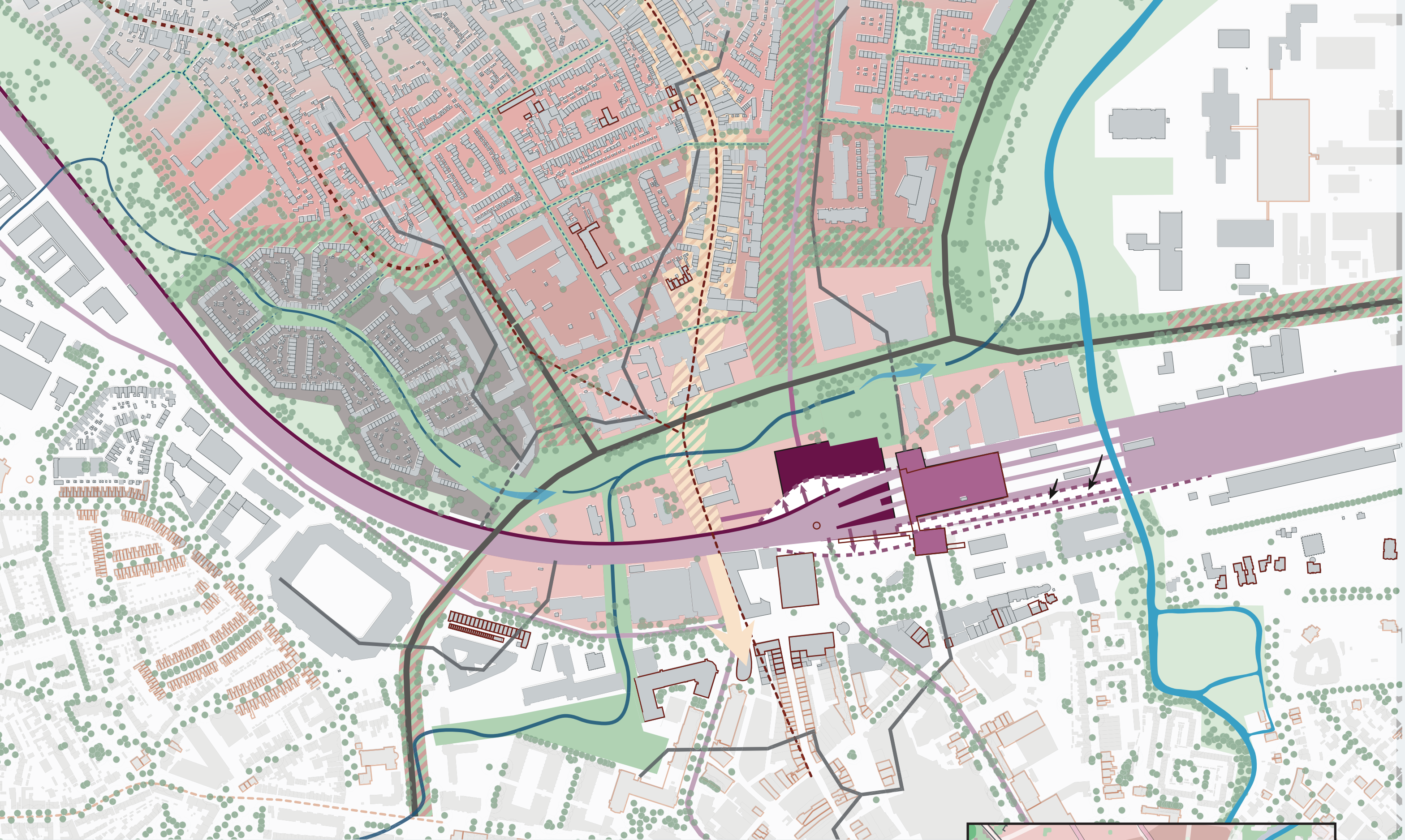


Figure 28: Fellenoord and Limbeek-Zuid strategy, scale 1:10.000

Densification

- Major redevelopment
- Partial redevelopment
- Infill & extension
- Transformation existing stock
- Downgrade infrastructure; infill and greening
- Expansion public transport stations

Surface water

- Surface water
- Resurfaced historic stream
- Runoff compartments
- Compartment pierced
- Street level green blue infrastructure drought risk

Heritage

- Monument
- Historic radial
- Historic urbanistic structure

Close-up of city strategy

Greenery

- Pre-existing public green
- Trees
- Downgrade infrastructure

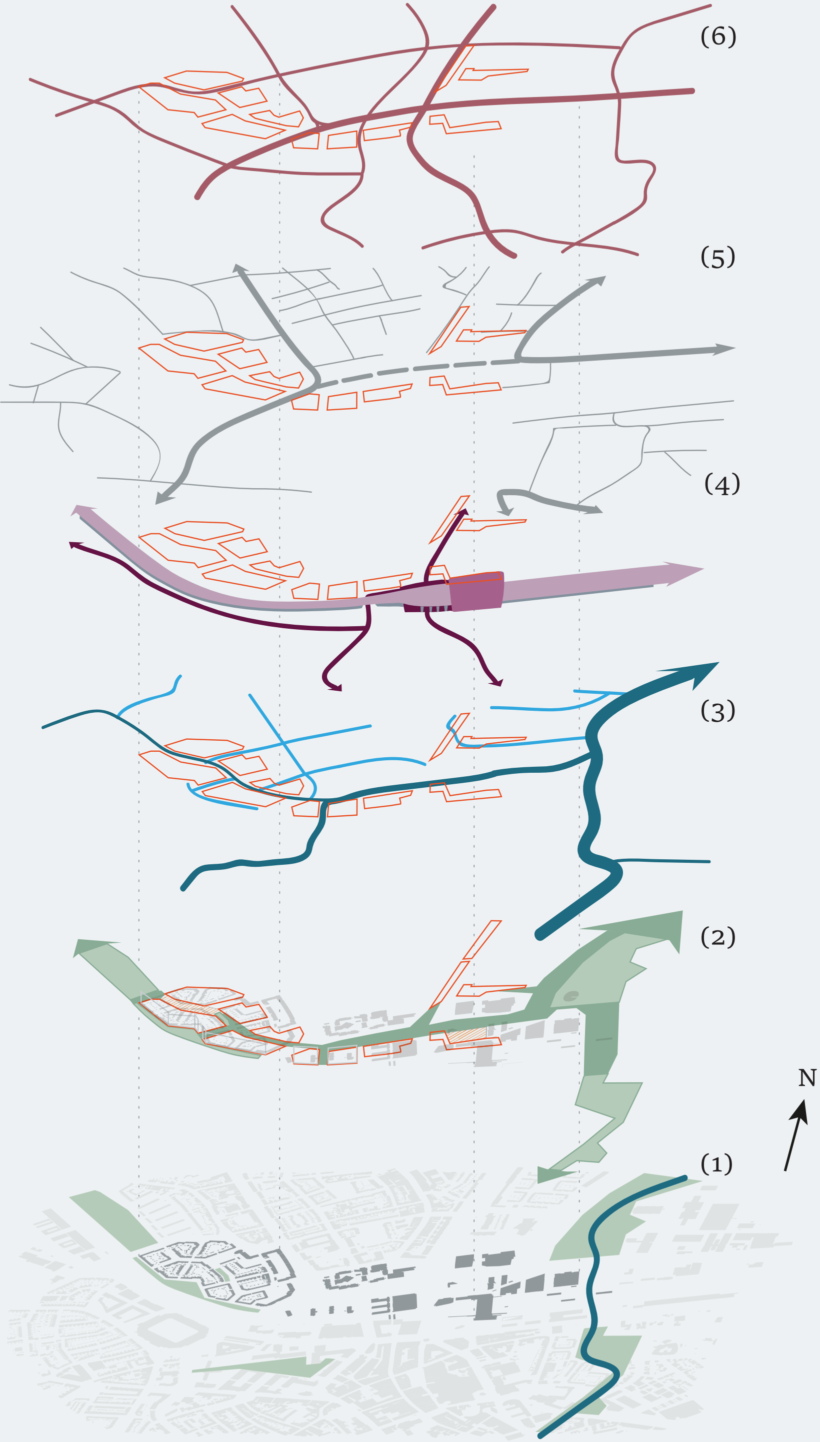


Figure 29: exploded strategy diagram (1) current situation; (2) green network and densification plots; (3) resurfaced streams and capillaries; (4) public transport infrastructure; (5) car infrastructure; (6) cycling infrastructure

Figure 29 shows the steps taken in creating the design. Starting at the bottom ascending through the exploded view: (1) The current buildings in Fellenoord and Limbeek-Zuid, the parks and the Dommel are highlighted. (2) The leading principle of the city strategy on district level is to connect the green fingers of Eindhoven to make a green-blue network. Also, the densification locations are identified. The densification and green-blue network should be balanced carefully, as to create water resilience and not overshadow one another. (3) The resurfaced streams of the Lijmbeek and Gender flow through the newly created green connections, forming attractive parks or creating quality real estate at the densification plots. (4) The public transport system is expanded. A larger train station and a larger and relocated bus station form the central node in the transportation network of Eindhoven. By sliding the bus station partially underneath the western emplacement of the elevated train station, the two have an easier to navigate connection, and consequently space becomes vacant on the north side of the public transportation node. Here, a square adjacent to the resurfaced Gender does create a public space that can serve as the entrance to the city as well as improving the transportation system. (5) As chapter 8.1.2 indicated, future through-traffic of cars within the ring will be heavily restricted towards 2050. The John F. Kennedylaan and Professor Dorgelolaan form connected access radials in the eastern part, as well as Boschdijk and Vonderweg in the western part. Removing through traffic removes a large quantity of cars.

The amount of lanes is therefore halved. Both directions can fit in the space which previously accommodated one direction of traffic. The allows the space of the other lane and median to become space for greening or densification. For now, the Fellenoord can serve as a connector in this design. However, later it may become obsolete in the mobility strategy of the municipality. Leaving it in also keeps the possibility open of connection of different access radials. For instance, instead of removing the Fellenoord, the tunnels underneath the railroad could be closed for car traffic. (6) Part of the restricting of car traffic is to encourage a modal shift towards public transportation and cycling. The cycling network north-south and east-west axes intersect in the Fellenoord neighbourhood as cyclists are mostly directed around the city centre. With population growth and the predicted modal shift in mind, the cycling network is reinforced. Also, the experience of cycling is enhanced. Preferably, at-level crossings are removed, traffic lights are kept to a minimum and priority is given for cyclists. The downgrade in car traffic lanes of the Fellenoord street establishes opportunities for the east-west cycling axis to be in the park of the resurfaced Gender.

8.3. Design

8.3.1. Masterplan

Figure 31 shows the design in plan format. The relation between the building volumes and the water is emphasised by giving the streams a central role in the redevelopment of the neighbourhoods. The public spaces form a string of varied experience, based on the degree of urbanity. Figure 30 indicates these differences.

Starting in the west, the Lijmbeek flows from the Wielewaal, through Strijp-T&S, into the masterplan area. Here, the stream arrives in the neighbourhood park at the Anthony van Leeuwenhoeklaan. The focus should be on recreational and natural qualities.

Flowing further south-east, the urban influence gradually increases as the park funnels down into the width of the stream itself and surrounding buildings move closer to the water. Setbacks in the building blocks allow ample daylight into the street profile. This also ensures the feeling of enclosure without inducing claustrophobia.

Along the railway, a parking garage blocks sound and vibrations for the adjacent apartment blocks and allows the rest of Limbeek-Zuid to be a car-reduced neighbourhood. This concept is also applied within Strijp-S. Within Limbeek-Zuid, only slow traffic is allowed at the spaces along the stream to increase the experience. Motorised traffic is redirected through the insides of the blocks. There, the spaces are designed around the infiltration of water with a focus on rainwater gardens and retention ponds.

At the centre of Limbeek-Zuid, where the cycling path and the Lijmbeek diverge, the buildings leave a triangular space. A lowered square which can serve as overflow capacity during high water in the stream is the defining element of the public space. Along the edges of the square, amenities are placed in the plinth to serve the additional dwellings in the neighbourhood, as well as to create liveliness in the public space.

Flowing out of the neighbourhood, the stream profile opens up again with a parking garage-apartment blocks combination similar to the north side of the neighbourhood. Here, it can also provide car access for the football stadium across the rails. The opening of the stream profile serves as a transition towards the more open Fellenoord park where the Lijmbeek joins the Gender.

Currently, the main problem in the experience of the Fellenoord neighbourhood is the openness, largeness of surroundings and business of all the people using the space for transport. By shifting away from the large-scale motorised traffic dominated urban fabric and creating enclosure by planting vegetation and providing continuous building blocks with varied functions, the space will become more pleasant to visit and stay. Horizontal building blocks connect the office high rises to the street level. The downgrade of lanes of the Fellenoord street allow for a linear park to be fitted. Height differences between the lower altitude of Neckerspoel and the higher stream bank of Woensel-Zuid create opportunities for interesting park design. The differences in height differentiate between wetlands along the Gender and drier areas on the banks. Besides allowing the stream to adjust its width during wet periods and preventing flooding, this also provides the possibility to create a gradient in vegetation species as certain species thrive in wetter or drier environments. A 10 meter wide pedestrian promenade is the main piece of infrastructure of the park at the lower level, stretching from Limbeek-Zuid towards the public transport stations and university. On the southern side, a mix of functions lines the street, while on the northern side there are views of the park and stream. Narrower, semipaved recreational paths also navigate the park. In places where they traverse the wetlands, they turn into elevated 'vlonders'. The existing parking garages between the office towers are covered with green roofs, which can serve as a garden for both the offices and the residents of the added horizontal blocks.

Moving further downstream, the Gender arrives at the station square. Again, building blocks are used to provide enclosure of the space. This is done on three sides, with the north side left open to create a connection to the stream-park. Allowing the water and vegetation into the square cools it down on warm summer days. The pavement is extended across the stream, supplying interesting bridges and plenty of edges to sit on. Additionally, normal seating furniture is placed underneath the tree canopy which covers most of the square.

Even further eastwards, the park narrows as it flows under the elevated infrastructure bundle. Here, a cycling and pedestrian path connecting the stations and university join the stream to avoid crossing at-level. The park opens up again to join the Dommel in the park which is widened due to the narrowing of the John F. Kennedylaan. The Dommel flows further north into one of the green fingers which form the base of the green-blue network of Eindhoven.

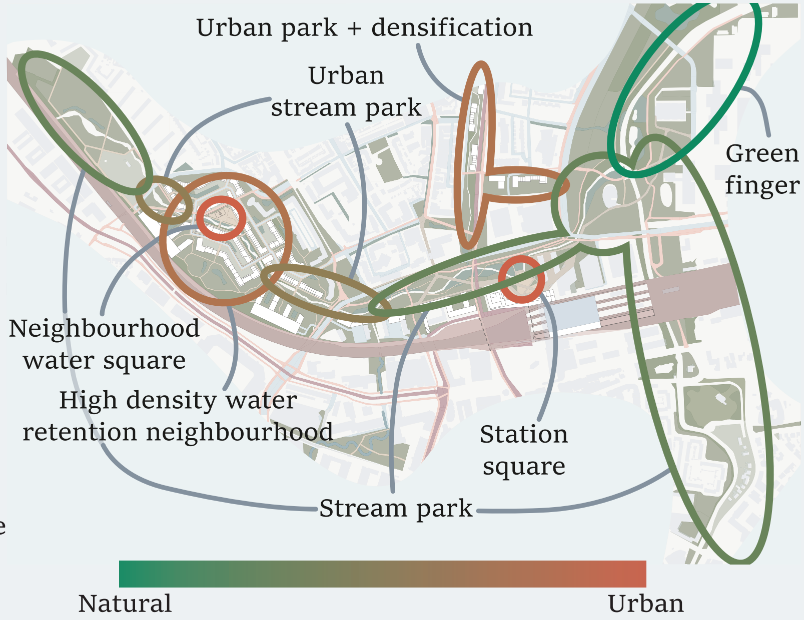
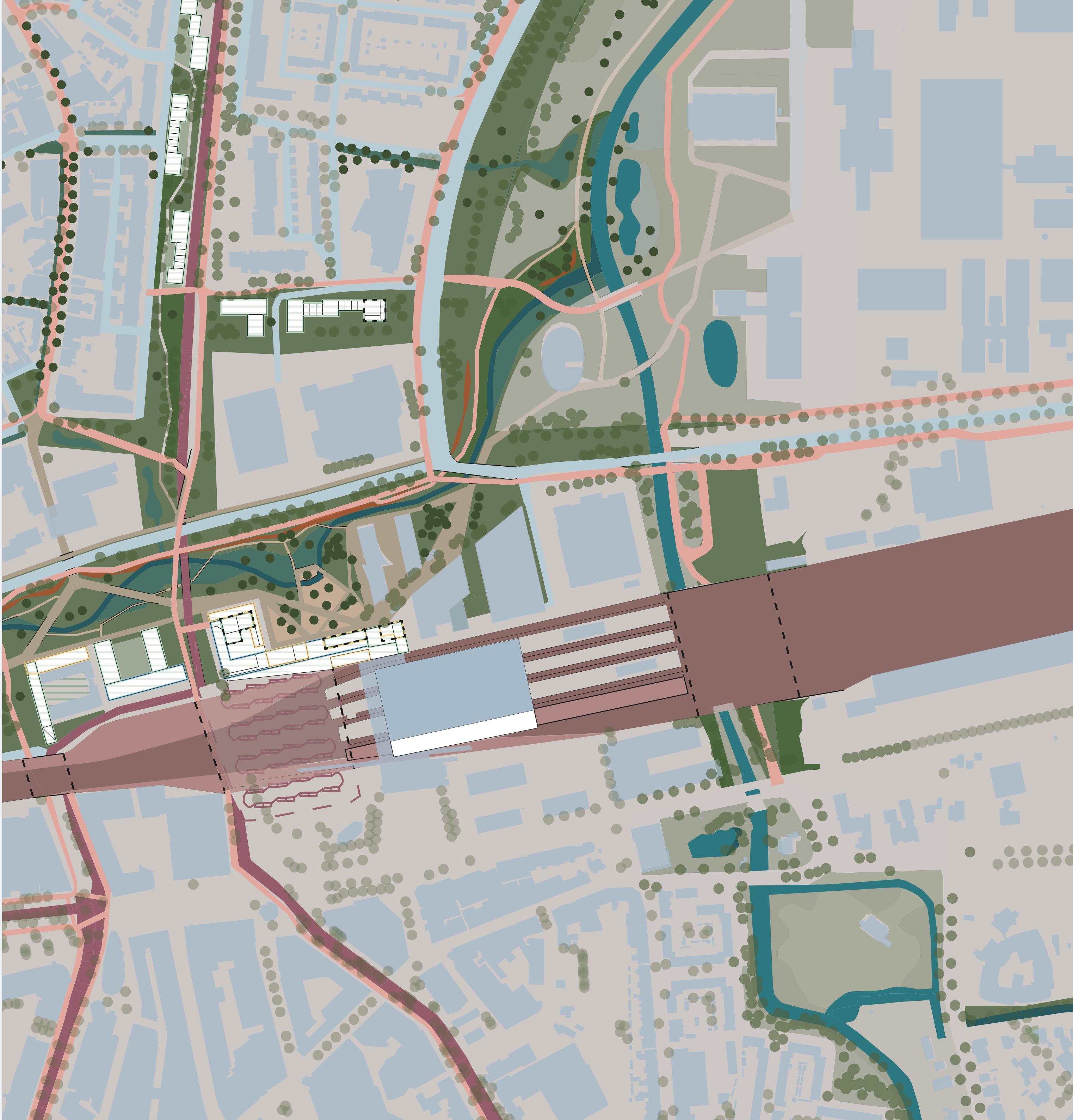


Figure 30: Indication natural-urban varieties in public spaces, scale 1:20.000

Figure 31: Masterplan Limbeek-Zuid & Fellenoord, scale 1:50.000



8.3.2. Water system

Figure 32 shows the water system and the steps taken to improve it through this design, based on the strategy of figure 27. As the city and neighbourhood strategies prescribe, the water system and densification should be structured around urban flood and drought risk areas.

Woensel-Zuid falls into the drought risk category. Here, the focus should be on the on-location re/detention of precipitation for infiltration purposes to increase soil moisture and groundwater levels. The residual portion which exceeds the capacity of the infiltration implementations, overflows into a set of runoff measures forming a capillary or it runs off into the sewage system. Capillaries can be as simple as semi-continuous depaved areas, as narrow as a metre in the street section.

Limbeek-Zuid is not located in a risk area, however, it could serve as an infiltration buffer for the surrounding drought risk areas. Therefore, it is redesigned with the water system as a basis. Many surfaces are depaved. Capillaries connect to rain water gardens and retention ponds. Overflow gets redirected to the Lijmbeek or separated stormwater sewage. The Lijmbeek itself is lined with rainwater gardens, further detaining water before infiltrating or flowing into the stream.

Fellenoord is located in a flood risk area, the focus should be on run off and prevention of flooding. The profile of the Gender is widened, to prepare for high water in wet periods. Throughout the new and existing developments, vegetation on roofs can be used to intercept and detain water.

Figure 32: Water system concept, looking eastwards

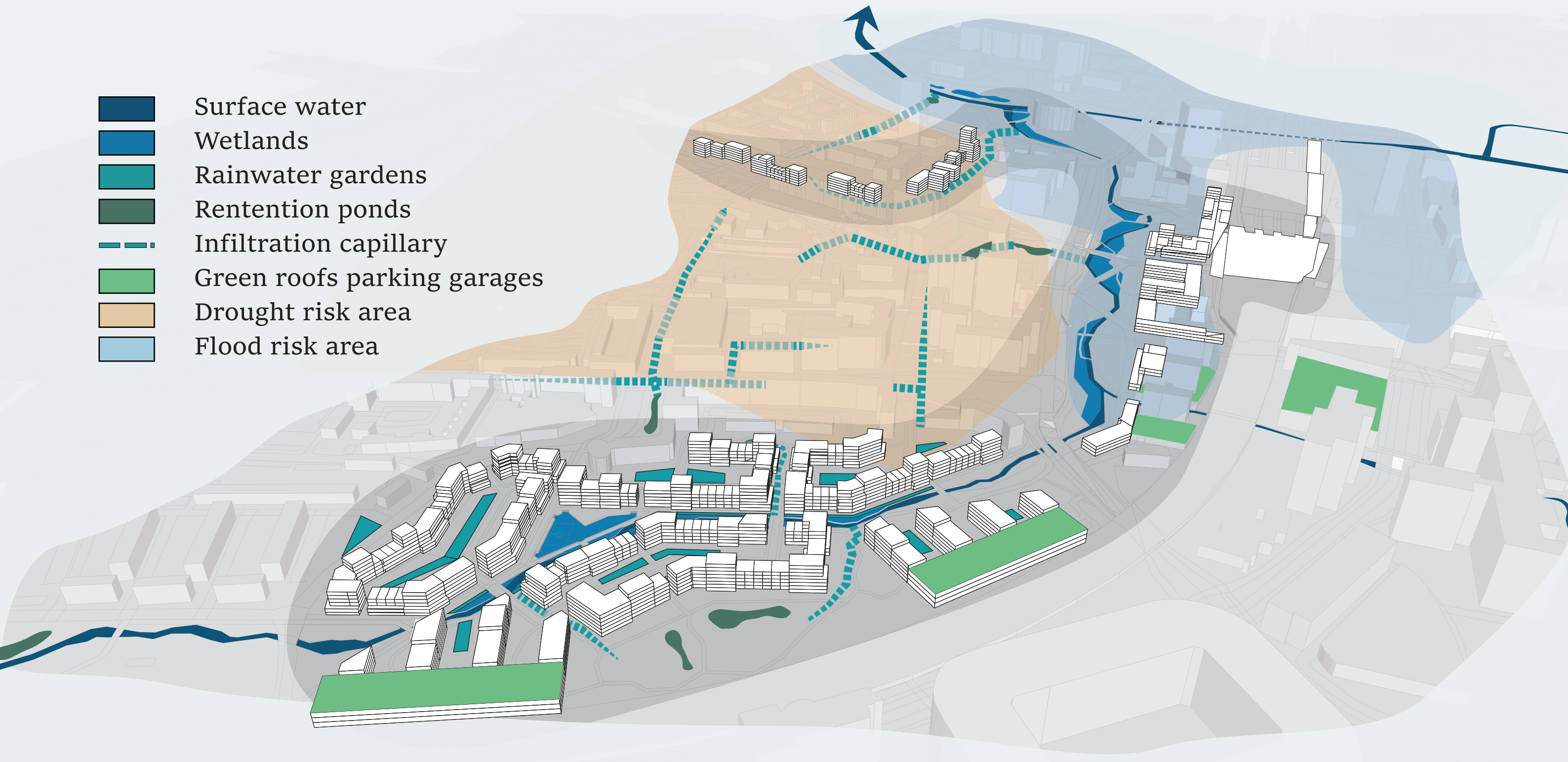
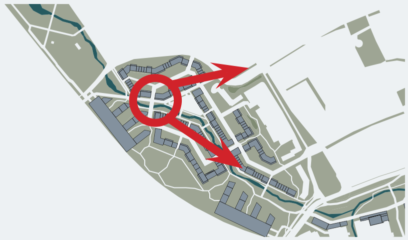


Figure 33: Impression Lijmbeek, towards neighbourhood water square



Limbeek-Zuid is redesigned with densification and water retention as leading design principles. Figure 33 gives an impression of the stream and water square from the street level. The separation from motorised traffic and the amount of vegetation both in the street and on roofs enhances the experience of living along the water. The setbacks provide openness in the street profile. The section of figure 34 shows the overview of the whole neighbourhood, with the elevation stepping down towards the stream.

Building heights are restricted to 4-7 floors in the neighbourhood, with exceptions at the north side of the water square and the railway sides of the south-western blocks, where apartments are 5-8 floors in height. This acts as the marker of the central location without shading the square for the former and a sound barrier from the trains for the latter.

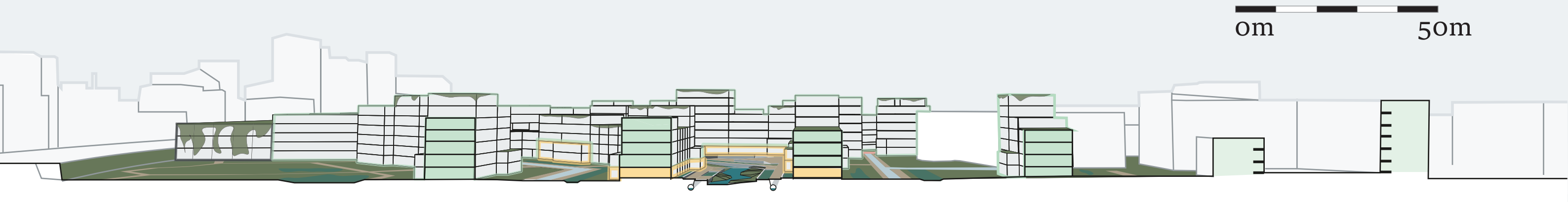


Figure 34: Section Limbeek-Zuid

- Commercial/other amenities
- Offices
- Residential
- Parking

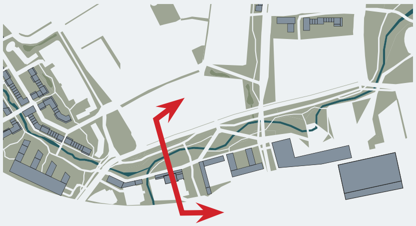
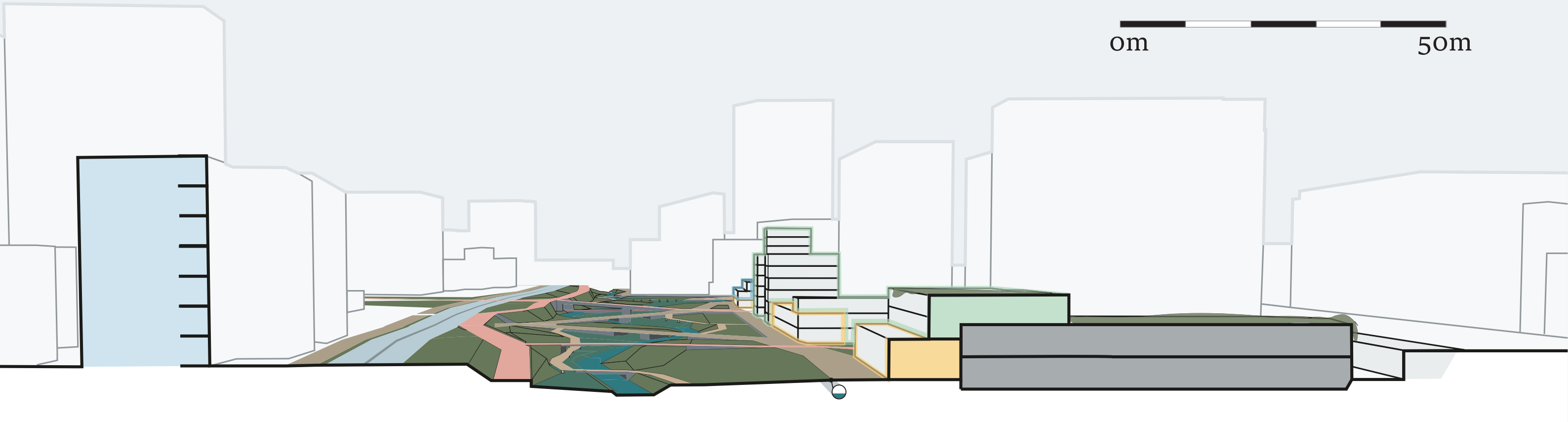
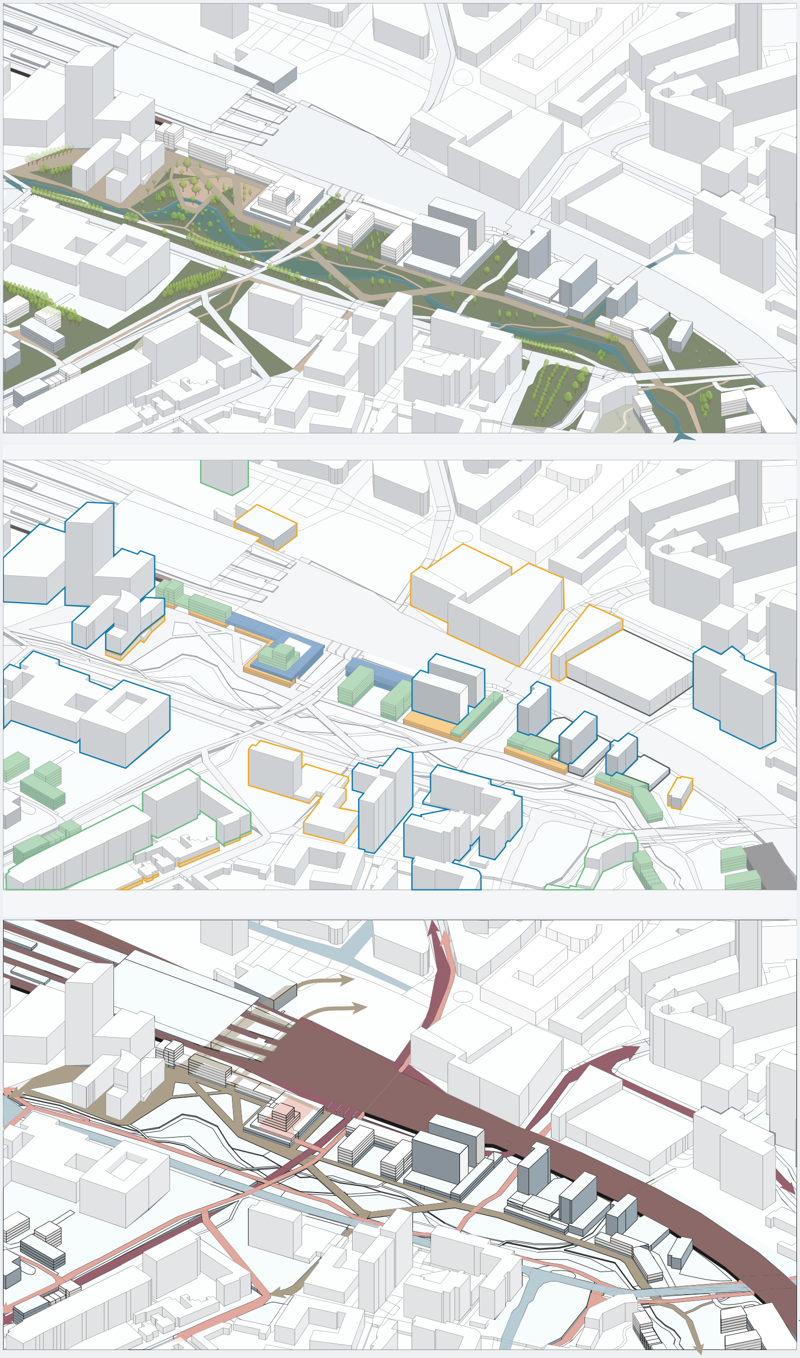


Figure 35: Section Fellenoord

As discussed in the masterplan, Fellenoord is redesigned having the water and park as the connection between land use and transportation. Figure 36 shows the interconnectedness of these three elements. Again, the sections shows the differences in elevation that create the variation in the park, shown in figure 35. The promenade connects the entire length of the park. Commercial plinths are added with residential spaces on higher floors. Together with the existing offices, this creates a lively mix of uses. Around the bus and train station, a larger block houses a multifloored bicycle garage. Perpendicular on the park, the north-south roads are restricted from private motorised traffic.





Park

Surface water
Wetlands
Vegetation
Promenade
Unpaved walkway

Land use

Newly added
Existing

Commercial/other amenities
Offices
Residential

Infrastructure

Train rails
Bus Rapid Transit
Car road
Cycling paths and parking
Pedestrian paths

Figure 36: isometric view of Fellenoord, showing the park, land use and infrastructure

8.4. Key performance indicators

To test the effectiveness of the proposed design, key performance indicators are used. These quantify important metrics which can be used as a type of assessment. Given the results of the literature, the design is based around increasing vegetation, resurfacing streams and increasing floor space. These three are calculated for the old situation and the situation in the proposed design. Table 5 shows the improvement in table format.

Starting at Limbeek-Zuid, street level vegetation has more than doubled. For the old situation, the public green has been added with 25% of the private gardens. The assumption of a quarter of vegetation per garden on average has been estimated from satellite imagery. While the GSI is kept stable, the floorspace has increased by 56%. This is done by having the added apartment blocks have more floors than the current building stock. Another part of the design is the use of green roofs for retention purposes. If half the roofs of all added buildings and the entire roofs of parking garages are covered with vegetation, another 9% can be added to the total vegetation area of the neighbourhood.

The design provides similar conditions in Fellenoord. Vegetation has increased by 55% through the introduction of the park along the Gender. GSI even decreased by 17 as the Beursgebouw and part of the towers and the Lardinoisstraat have to make way for the expansion of the train station. FSI is still increased as the removal of the Beursgebouw, being a 1-floored building with massive ground area, majorly influences the ratio. Around the station square and around the Bunkertoren new buildings with a higher amount of floors are added. Again, the same steps in calculating green roof space are used as in Limbeek-Zuid. This results in a potential 43% added to vegetated surface.

On the northern side of the railway, roughly a kilometre of both Lijmbeek and Gender are resurfaced. This length is used to enhance the water resilience while also providing value for the public space in both living environments as well as recreational parks.

Important to note is that the official delineations of the neighbourhoods are used. Some parts of park and added buildings along the Veldmaarschalk Montgomerylaan are not included in the calculations as Fellenoord only stretches until the Vincent van den Heuvellaan.

Limbeek-Zuid	Old	New	% increase/decrease
Vegetation	36616 m²	76848 m²	+ 109,9 %
GSI	0.20	0.20	+ 0,4 %
FSI	0.63	1.08	+ 71,4 %
Green roofs	0 m²	7117.5 m²	+
Fellenoord			
Vegetation	31996 m²	49473 m²	+ 54,6 %
GSI	0.23	0.19	- 17,3 %
FSI	0.61	0.94	+ 53,6 %
Green roofs	0 m²	21326 m²	+
North of railway			
Resurfaced Gender	0 m	974 m	+
Resurfaced Lijmbeek	0 m	1070 m	+

Table 5: Key performance indicators [150], [156]

Critical reflection

This research aims to get an understanding of the importance of the water system in relation to living environments, including the spatial trends which will affect the future water situation. By focussing on groundwater interactions and applying findings to Eindhoven, the goal was to make an alternative on current urban planning practices and to make the mostly invisible system of water in a city tangible.

While this thesis tried to be as thorough in delivering a utopia where the living environment and water system exist in symbiosis, a more realistic conclusion should be made. The approach taken in the research approximates the interactions and sketches a basic picture of the current problems and the steps to create a stable future through urban water resilience measures.

On the one hand, the fluxes in the water cycle are reduced to a few indicators which are weighed equally. This does not represent the real world as many more variables act upon the conditions in a city. Also, the degree of influence of the indicators is almost certainly differing, however, this is not possible to quantify exactly for every location.

On the other hand, living environments should be created with the notion in mind that focussing excessively on only one concept will not result in the best options. For spaces to adequately function, more research should be done on a wide array of fields, e.g. social aspects such as demographics and well-being, and economic aspects such as market demand or accessibility/land use valuations.

A city scale strategy applied the findings of the literature. Through the application of water resilient urban planning measures, the neighbourhoods of Fellenoord and Limbeek-Zuid are transformed to accommodate urban densification and a healthy water system.

Other aspects of the constraints outside the scope are consciously not discussed. Water quality, soil contaminations and aquifer thermal energy storage systems are inevitable to affect context when discussing urban water quantity. Including these would form the risk of making this research too broad and extensive, and consequently not in-depth enough.

The resulting proposal for a design is therefore based on the process of constantly balancing between the tunnel vision of applying the concepts found in literature and the consideration of the feasibility of the end product. As the literature showed, densification and the natural water system do oppose each other if ignored. This research and the following design show the compromise that is needed for both to coexist and even cooperate to create natural and urban quality.

Literature & policy reviews showed the threats of urban densification and climate change, together with the possibilities for water resilience within cities. A spatial analysis was conducted and a city scale strategy applied the findings of the literature. Through the application of water resilient urban planning measures, the neighbourhoods of Fellenoord and Limbeek-Zuid are transformed to accommodate urban densification and a healthy water system.

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Appendices

Appendix A

1 [43]	Investigating the influence of future landuse and climate change on hydrological regime of a humid tropical river basin
2 [44]	Application of the gleization soil layer to assess centurial drops in shallow groundwater levels across the southeastern coast of China
3 [45]	Impacts of land use land cover change and climate change on river hydro-morphology- a review of research studies in tropical regions
4 [46]	Mitigation of Urban Flooding by using Green Infrastructure in Surat, India
5 [47]	Research on Evaluation Method for Urban Water Circulation Health and Related Applications: A Case Study of Zhengzhou City, Henan Province
6 [48]	Quantifying the uncertainty in future groundwater recharge simulations from regional climate models
7 [49]	Groundwater level estimation in northern region of Bangladesh using hybrid locally weighted linear regression and Gaussian process regression modelling
8 [50]	GIS-based analytical modeling on evaluating impacts of urbanization in Amman water resources, Jordan
9 [51]	Impact of Climate Change on Water Crisis in Gujarat (India)
10 [52]	Assessment of Groundwater Vulnerability to Climate Change of Jalgaon District (M.S.), India, Using GIS Techniques
11 [53]	Retrofit Upgrade of Stormwater Controls with Real-Time Mechanism for Smart and Sustainable Urban Water Resources Management
12 [54]	Monitoring of land subsidence due to excessive groundwater extraction using small baseline subset technique in Konya, Turkey
13 [55]	Article: a new approach in determining the decadal common trends in the groundwater table of the watershed of lake “neusiedlersee”
14 [56]	Estimating groundwater resource and understanding recharge processes in the rapidly urbanizing Dhaka City, Bangladesh
15[57]	Review: The influence of global change on Europe’s water cycle and groundwater recharge
16 [58]	Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India
17 [59]	Ensemble modelling framework for groundwater level prediction in urban areas of India
18 [60]	Climate change scenarios and its effect on groundwater level in the Hiranyakeshi watershed
19 [61]	Simple Methodology for Estimating the Groundwater Recharge Potential of Rural Ponds and Lakes Using Remote Sensing and GIS Techniques: a Spatiotemporal Case Study of Roorkee Tehsil, India
20 [62]	Evaluation of groundwater sustainability in the arid Hexi Corridor of Northwestern China, using GRACE, GLDAS and measured groundwater data products
21 [63]	Simulating land cover change impacts on groundwater recharge under selected climate projections, Maui, Hawai
22 [64]	Climate change projections in the Ghis-Nekkor region of Morocco and potential impact on groundwater recharge

23 [65]	Examining climate change impact on the variability of ground water level: A case study of Ahmednagar district, India
24 [66]	Impact of urbanization on climate change and geographical analysis of physical land use land cover variation using RS-GIS
25 [67]	Water Resources Assessment of Basins of India Using Space Inputs
26 [68]	Investigating effects of climate change, urbanization, and sea level changes on groundwater resources in a coastal aquifer: an integrated assessment
27 [69]	Impact of anticipated climate change on direct groundwater recharge in a humid tropical basin based on a simple conceptual model
28 [70]	Modelling the historical water cycle of the Copenhagen area 1850-2003

Appendix B

	research type	region	country	climate type	data period	method(s) used	variables used
43	empirical case study	Western Ghats	India	Am (tropic monsoon)	1980-2016	Hydrological model (SWAT) and LULC over time (TerrSET Land Change)	Topography data (altitude, slope, flow direction, accumulation); Soil type; LULC; Meteorological data (precipitation, temperature, windspeed, solar radiation); Gauge discharge; Reservoir water level
44	empirical case study	Southeastern coastal China	China	Cwa/Cfa (subtropic humid)	2010-2012	regression analysis	soil data (location, soil type, soil layering topographic features, land use type, chemical properties); groundwater level; altitude; economic density
45	meta analysis	tropic regions	multiple	Af/Am/Aw (tropic)	2010-2021	overview of literary sources	LULC; climate type; streamflow; surface runoff; evapotranspiration; groundwater level; water yield
46	empirical case study	Surat	India	Aw (tropic savannah)	2006	analysis of one flooding event	buried water infrastructure; reservoir level; LULC; imperviousness; salinisation

definition	source	design recommendations
CartoDEM digital elevation model, 30m grid; 1:500.000 map; Maximum likelihood classifciaton; Accuracy of 0.25x0.25 degrees till 2.5x2.5 degrees; Daily readings; Daily readings	National Remote Sensing Centre; National Bureau of Soil Survey and Land Use Planning; Sattellite data(LandSat LIS-III); National meteorological institute (IMD); Global cirulation models; Water authority (CWC)	Cropland and urban land uses are expected to increase, soil stabilisation, preventing erosion and maintaining soil nutrients to avoid desertification and soil degradation; Prevent flash floods and increased runoff by increasing vegatative cover; Protect current vegetation; Balance water requirement in wet and dry seasons
-; -; 30m raster; in gdp/km2	China Science Press (soil series of china); China Science Press (soil series of china); Digital Elevation Model; region statistics books	Groundwater pumping managment policies; Groundwater level change is caused by climate change>economic activity> land use>soil type
percentage change per catchment; koppen climate classification; percentage change from baseline; percentage change from baseline; percentage change from baseline; percentage change from baseline; percentage change from baseline	multiple sources	Reforestation; Land cover development management
lack of adequate drainage; no management of buffer capacity; -; urbanisation on floodplains river; proximity to sea	SMC; -; -; SMC;	slow down stormwater; spread stormwater out; let stormwater infiltrate; design bioswales; construct green roofs; apply permeable pavement

47	empirical case study	Zhengzhou, Henan	China	Cwa (subtropic humid)	2010-2020	three scale AHP and EFAST algorithms to set criteria to use in water-cycle health assessment models (TOPSIS)	water demand; green coverage rate of built district; grondwater flux; storage capacity of rivers and lakes; density of buried water infrastructure; water resources amount; annual water storage change of reservoirs; mean annual precipitation; proportion of groundwater supply; water consumption; reuse of production water
48	empirical case study	-	Qatar	BWh (hot desert)	-	climate forecasting based on regional climate models to use in groundwater recharge modelling (WetSpass)	air temperature; precipitation; wind speed; evapotranspiration
49	empirical case study	Northwestern Bangladesh	Bangladesh	Aw (tropic savannah)	1993-2017	modeling framework based on locally weighted linear regression (LWLR) and Gaussian process regressions (GPRs)	precipitation; air temperature; soil mosture; vegetation index; population growth rate
50	empirical case study	Amman governorate	Jordan	BSk/Csa (cold semi-arid/hot mediterranean)	2000-2019	remote sensing and GIS	altitude; temperature; precipitation; runoff; evaporation; infiltration values; LULC; drainage network density

-	national, regional and municipal statistical yearbooks	increase ecological protection of surface waters; reduce groundwater exploitation; balance water requirement in wet and dry seasons; improve natural disaster response capacity
Celsius; mm; m/s average; Penman-Monteith equation	regional climate models (CORDEX)	groundwater withdrawal should not exceed groundwater recharge; urban flood prevention, focus on recharge
monthly (mm); average temp (celsius); %; normalised difference; -	national meteorological institute (BWDB); food and agriculture organisation (FAO); national meteorological institute; Climate prediction centre (CPC); national bureau of statistics (BBS); national water authority	switch to surface water withdrawal; safe yield managment (monitor industry and agriculture withdrawals); artificial aquifer recharge; rainwater harvesting; wastewater reuse
raster; -; shapefile; estimated by runoff coefficient; estimated by blaney-criddle equation; estimated by water balance equation; sattellite images using ENVI 6; shapefile km river/km2 basin	NASA; water ministry; water ministry; -; -; -; Landsat 7; ArcGIS	landuse policy regulations controlling urban expansion preventing groundwater depletion and flash flooding; surface water restorations to decrease flooding and increase water resources; water harvesting during wetter seasons

51	empirical case study	Gujarat	India	BWh/BSh (hot desert/hot semi-arid)	1981-2010	statistical analysis to find Pearson product-moment correlation between precipitation and groundwater level over time	precipitation; groundwater level average; pre and post monsoon groundwater level
52	empirical case study	Jalgaon District, Maharashtra	India	BSh (hot semi-arid)	1991-2019	remote sensing and GIS, weighting parameters with Delphi technique	distance from residential area; distance from major roads; LULC; slope terrain; drainage density; precipitation; net groundwater recharge; average groundwater level
53	empirical case study	Chattanooga	United States of America	Cfa (humid subtropic)	-	Sustainable Watermanagement model (SWMM) integration with Realtime control (RTC)	Surface water storage capacity; capacity buried water infrastructure; soil type; infiltration; slope; precipitation
54	empirical case study	Konya	Turkey	BSk (cold semi-arid)	1990-2018	using interferometric synthetic aperture radar (InSAR) with other data to correlate land subsidience with decreasing groundwater level	LULC; vegatation index; groundwater level; land subsidience
55	empirical case study	Neusiedlersee	Austria, Hungary	Dfb (humid continental)	1997-2012	Dynamic factor analysis (DFA) applied to the spatial and temporal dataset to deduct determining parameters	groundwater level; precipitation; evapotranspiration

mm/year; m below groundlevel; m below groundlevel	national meteorological institute (IMD); regional water authority; regional water authority	groundwater withdrawal management; wastewater reuse
buffer analysis; tracing highways and buffer analysis; unsupervised classification; altitude map; altitude map and flow accumulation; raster calculated rainfall per month; groundwater suveys; groundwater surveys	Landsat 4,5,8; google Earth; Landsat 4,5,8; digital elevation model; digital elevation model; WorldClim sattellite images; Regional water surveys (GSDA Jalgaon); Regional water surveys (GSDA Jalgaon)	Using inverse distance weighted formula to estimate groundwater level between measure stations; introduce artificial recharge in vulnerable areas; rainwater harvesting (rooftop/reservoirs) for infiltration
in m3; diameter stormwater pipes; sandy loam soil; -; mm/day	field surveys; province GIS database (Tennessee); -; field surveys; -; regional meteorological institute	use mechanical stormwater controls in comination with modern green infrastructure as dry detention ponds to prevent Combined sewage overflows (CSOs); monitor performance of retention areas to aid modelling calibration; apply machine learning to predict and automate water management
CORINE land cover; normalised difference; measurements from 6 wells; altitude over time	sattellite imagery (Landsat 5,8); -; National water authority; Global navigation satellite system (GNSS)	planning groundwater withdrawals according to climatic conditions
data over 15 years in 101 wells; data of 38 meteorological stations, in mm/month; Penman equation of evapotranspiration	Regional hungarian water authority and national austrian water authority; local meteorological stations; local meteorological stations	to counter sinking groundwater levels external water sources can be introduced; industrial and agricultural processes using less water

56	empirical case study	Dhaka	Bangladesh	Aw (tropic savannah)	2000-2015	hydrological model (VIC) using remote sensing methods of spatio temporal information to reflect real time data	LULC; precipitation; temperature; groundwater level; withdrawal locations; aquifer capacity; soil type; altitude
57	literature review		multiple	multiple	-	Summary on existing literature about recharge in Europe	precipitation; evapotranpiration; vegetation; LULC; temperature; surface water; slope; soil moisture
58	empirical case study	Kancheepuram	India	BSh (hot semi-arid)	-	using weighted overlay analysis and analytical hierarchy process (AHP) and GIS to identify groundwater potential zones	geomorphology; drainage density; lineament density; slope; elevation; geology; LULC; soil type; precipitation
59	empirical case study	Bengaluru	India	Aw (tropic savannah)	2010-2017	machine learning ensemble modeling (SSA,MI, GA,ANN,SVM) approach to predict groundwater level	groundwater level; precipitation; average air temperature; population growth/rate of urbanisation
60	empirical case study	Hiranyakeshi watershed	India		-	Modflow integrated approach with climate scenarios	Altitude; groundwater level; lithology; soil type

5m raster; daily from 9 stations; daily from 9 stations; monthly statistics; monthly statistics; monthly statistics; -; 30m raster	national geo database (SOB); national meteorological institute; national meteorological institute; municipal water authority; municipal water authority; municipal water authority; World soil database	include lateral flow between aquifers to accurately predict groundwater; artificial recharge to counterbalance rapid urbanisation; switch withdrawal partly to surface waters
-; usually Penmann equation; based on climate and land use; vegetation deforestation increasing cropland and urbanisation influence interception, evapotranspiration, infiltration, withdrawals, etc.; affecting hydraulic conductivity and evapotranspiration rates; ground surface and precipitation interactions; indicator of recharge fluxes, drier soils implies less recharge	multiple sources	Set up water saving programmes; infiltrate stormwater instead of runoff in urban areas; protect vegetation to decrease tree mortality in heat waves/droughts; develop appropriate adaptation strategies per individual system
type of landscape; m/m2; fault lines in m/m2; %, digital elevation map; -; ease of percolation; -; annual	SOI Toposheet; CARTOSAT I-30; - ; CARTOSATI-30; CARTOSAT I-30; SOI Toposheet; NBSS; national meteorological insitute	prevent groundwater depletion by artificial groundwater recharge; areas with high groundwater potential could be new withdrawal locations
monthly data of 24 wells over 8 years; monthly rainfall over 8 years; average temperature over 8 years; yearly data converted to monthly growth	Provincial water authority; -; -; world population review	apply watermanagement wherecompetitive demands co-exist
to demarcate watersheds, 32m raster; -; measurements from 8 wells; hydraulic conductivity, specific yield, storage	Cartosat 1; Regional water authority (CGWB); -	rainwater harvesting during wetter months

61	empirical case study	Roorkee	India	Cwa (subtropic humid)	2002-2016	using GIS and a semi analytical groundwater recharge model (We-GREM)	LULC; altitude; watersheds; precipitation; evaporation; soil type
62	empirical case study	Hexi corridor, Gansu	China	BSk (cold semi-arid)	1981-2016	using a mixed method approach to compare to groundwater measurements and find groundwater vulnerable areas	groundwater storage; groundwater level; lithography; precipitation; air temperature; regional population; GDP; LULC; output value of agricultural activities
63	empirical case study	Maui	United States of America	multiple	1978-2007	participation and climate scenarios approach to deduct future land use, remote sensing and GIS to calibrate current data to groundwater recharge	LULC; precipitation; interception; irrigation; evapotranspiration; runoff; soil type; vegetation index; climate projections
64	empirical case study	Ghis Nekkor	Morocco	Csa/BWk (mediter-ranean/ cold desert)	1982-2012	Climate forecasting using CMIP5 and GCM's in a model using taylors diagram and linear regression	precipitation; temperature
65	empirical case study	Ahmed-nagar	India	BSh (hot semi-arid)	1996-2016	future scenario based modelling based on climate data and GIS	groundwater level; LULC; precipitation; air temperature; evapotranspiration; groundwater recharge

image based classification using eCognition 64; Digital Elevation Map; Digital elevation map; 1 weather station over 14 years; Mass transfer method, in m/day; -	Google Earth; CartoSat-1; CartoSat-1; National hydrology institute; regional civil engineering department	conservation of surface water bodies to prevent eutrophication; ponds with still standing water help recharge tremendously
Montly satellite statistics; monthly measurements from 196 wells; regional; yearly; yearly; yearly; -; -; -	GRACE, GLDAS (NASA); -; CCGM-CGMW; national scientific data center; national scientific data center; Regional bureau of statistics; Regional bureau of statistics; Regional bureau of statistics; -	surface and groundwater should be jointly managed over longer periods of time
existing maps	national geological survey; national geological survey; national geological survey; national geological survey; national geological survey; national geological survey; national geological survey; national geological survey; CMIP3,CMIP5	changes in land use change recharge, green restoration efforts to counteract urbanisation; integration of ground and surface water management to ensure sustainability; apply zoning regulations and withdraw water where it causes less stress on the system
monthly based on 4 stations; minimum and maximum temps	cordex africa project; cordex africa project	-
42 wells; -; daily; daily; daily; R = 1.35(P – 14)^0.5, where R = net recharge due to precipitation and P = precipitation (in inches)	regional water authority; Landsat ETM+Tropical rainfall measuring mission (TRMM); Modern-Era Retrospective analysis for Research and Applications (MERRA); Modern-Era Retrospective analysis for Research and Applications (MERRA); -	increase water us efficiency; change irrrigation/industry policies; reuse water; artificial recharge

66	empirical case study	Turineveli	India	BSh/Aw (hot semi-arid/ tropical savannah)	1971-2012	remote sensing and GIS to analyse runoff using regression analysis	precipitation; runoff; groundwater recharge; population growth; LULC
67	empirical case study	-	India	multiple	1984-2015	water resource availability modelling by using geospatial and climatic variables	LULC; soil type; altitude; precipitation; air temperature; river discharge; reservoir flux; groundwater flux; LULC; water consumption
68	empirical case study	Mazandaran	Iran	Csa (mediter-ranean)	2002-2017	integrated modeling approach linking SWAT MODFLOW SEAWAT to evaluate salination	precipitation, air temperature; LULC; altitude; soil type
69	empirical case study	Kerala	India	Am (tropic monsoon)	2000-2009	using a groundwater recharge model to estimate daily water table fluctuations	precipitation; termperature; coastal flooding; urbanisation; LULC; soil type; slope
70	empirical case study	Copenhagen	Denmark	Cfb (oceanic climate)	1850-2003	root-zone model, grid distribution flow and groundwater flow model to approach urban hydrology	soil type; LULC; temperature; precipitation; lithography; buried water infrastructure

monthly; using SCS curve method; using fluctuation and rise and fall methods; -; -	Regional meteorological institute; -; -; municipality; Landsat imagery	population growth is proportional to the urban land use growth, creating unsustainable runoff in larger areas
Advanced Wide Field Sensor (AWiFS); determining infiltration; delineating basin boundaries; gridded data over 30 years; mean annual temperature; annual at subbasin level; annual delta; sum of all data points in a subbasin; to estimate potential evapotranspiration monthly; -	Indian Remote sensing; National soil survey and land use planning (NBSS & LUP); Shuttle Radar Topographic Mission; IMD; IMD; -; national water authority; CGWB; -	rainwater harvesting during wetter months, limiting runoff to prevent floods and droughts; water managment based on the water basin conditions; evaluate priority between industrial agricultural and urban withdrawals
2 stations; 2 stations; -; 10m raster	National meteorological instute; National meteorological instute; National geology institute; United states geological survey; National geology institute	solutions targeting urbanisation are more effective than climate change solutions in decreasing groundwater depletion; groundwater depletion results in higher concentrations of salt, proper managment should be in place to prevent this
-	national meteorology institute; national meteorology institute; -; -; -	adaptation management strategies on a regional level, based on local context; design to cater climate scenario analyses that are complimented with lulc
125x125m grid size; historical maps; meteorological station; meteorological station; water pockets; -	geological institute; -; meteorological institute; meteorological institute; geological institute; regional water authority	rising groundwater levels cause subsurface flooding, drainage must be applied; artificial recharge of stormwater can prevent CSOs, only apply this in areas with low enough groundwater table

Appendix C

setup		overall direction	main water problems identified	identifying urban land use intensification as a water challenge	identifying climate change as a water challenge
Norwich					
national	Department of Communities and Local Government	sustainable development (economically, socially and environmentally)	providing water quality, recreational, water supply quantity, flood control	no, mostly about density as economic and efficient tool	'Plans should take a proactive approach to mitigating and adapting to climate change, taking into account the long-term implications for flood risk, coastal change, water supply, biodiversity and landscapes, and the risk of overheating from rising temperatures'
provincial	East of England / Norfolk County Council	economic growth and large scale infrastructure connections	water demand growth, need to create water resilience. Water should not become a supressor to economic growth.	no, does not even mention densification	'Focus on delivery of water-related climate change mitigation and adaptation strategies including net zero carbon ambition.'
water authority	Water Resources East	focus on sustainable water resources in an environmental and economic context	growing demand, changing climate, environmental impact, integrated stakeholders management, room for use of nature based solutions	no, only growing population seen as increase in water demand	Reducing due to climate change impacts, the need to increase drought resilience, and environmental constraints on water abstraction
regional (often coop-eration multiple munici-palities)	Greater Norwich Development Partnership	well balanced vision, but no in depth water addressed	flood risk (not only prevention, but also reducing the causes of flooding), water quality, water supply approach over the whole watershed	Focussing on economic efficiency, not discussing water implications	climate change resiliency hand in hand with growth, but mostly seen in mobility solutions

how is (ground) water addressed per category? Land use	Infrastructure	Topographical	Interesting policies	general conclusion
protecting green belts around cities, creating density around city centres & using brownfields	connect dense areas with better public transport	do a flooding risk assessment to find vulnerable locations and not developing there		only a general planning framework for local authorities to base it on, no specific national vision.
flood control	delegating responsibility to water supplier for water demand solutions	-	-	the main direction is towards economic development instead of water conscious city planning
reinforcing nature	reducing leakage and have seasonal capacity, reuse water, desalinisation	-	best document as far as England's policy goes	clear and sustainable plans
reinforcing and expanding green infrastructure/nature. Green infrastructure corridor network	-	-	-	seems like a checklist of national framework instead of locational approach

municipal	Norwich City Council	focus on making new developments sustainable, instead of also existing buildings	small scale green design to reduce surface runoff, groundwater protection,	no relation with water	focus on preventing flooding
water supplier	Anglian Water	sustainable vision, also main contributor to water authority	flood, drought, depletion	while east of england has the highest population growth, only water demand is mentioned as effect, no spatial	including the effects on the region.
other documents (regional surface water flooding document)		only flooding, but does capture effects of urbanisation	only flooding	the effects of the city are closely monitored	the modelling is based on more intense flooding events
Enschede					
national	Ministerie van Binnenlandse zaken en Koninkrijk-srelaties & Ministerie van Infrastructuur en waterstaat	Integral approach for management of living environment	One of the top priorities, need to rethink water management	Housing shortage should be decreased by nation-wide within city densification, the effects of water are not directly linked	'Veel nationale belangen en opgaven grijpen in of maken gebruik van de eigenschappen van het bodemwatersysteem en het daarin aanwezige natuurlijke kapitaal in de vorm van draagkracht, grondwater, bouwgrondstoffen en mijnbouwdelfstoffen. Het efficiënt, veilig en duurzaam gebruik van het bodemwatersysteem is noodzakelijk om alle nationale belangen in voldoende mate te kunnen bedienen en werkt in die nationale belangen ook door. Meer dan voorheen worden functies dáár neergelegd waar ze passen bij de natuurlijke eigenschappen en karakteristieken van het bodem-watersysteem.' page 124
provincial	Provincie Overijssel	regional subdivisions of problem analysis and solving	The different degrees of natural available water	Densification mostly as the chance for agriculture to manifest itself and worsening its impact on water	heat drought and flooding as increasing risks and the effects in a densifying scenario

green corridor network,	sustainable drainage	landscaping to ensure functioning vegetation		
urban effects on water cycle processes	identifying flooding vulnerable areas, creating			
acknowledging the impact of agriculture and urban land uses	protected groundwater essential for functioning, adequate infrastructure in place to provide society	rebuilding coastal fundaments, giving space to rivers, creating better dikes for vulnerable areaas	soil type as the determinant for regional differences (p. 138)	very relevant towards the findings of this article
multiple scenario's of regional function distributions	the understanding of need for adequate infra	different approaches between riversides and dry high parts	-	holistic approach acknowledging water situations

water authority	Waterschap Vechtstromen	sustainability focus. Working with nature to resolve demand problems	Flooding, heat stress, ecologic damage, droughts and dependencies between locations in the region	Increased runoff, canalisation of surface water and heat stress	One of the 3 main challenges, increased intensity precipitation, heat waves; land subsidence and periods of drought
municipal	Gemeente Enschede	very general	the need for green blue system as base layer, but especially in cities' surroundings instead of also within the city	densitication works as negative impact on a climate adaptive city	focus on green solutions of climate change instead of also blue
water supplier	Vitens	infrastructure perspective of northern Netherlands	higher demand, geologic and topographical contexts	only mentions higher demand of growing cities	'Klimaatverandering zorgt voor verandering in pieken en dalen in aan- en afvoer van hemelwater en oppervlaktewater in rivieren. Daarnaast kunnen stedelijke gebieden last krijgen van hittestress. Met klimaatadaptatie tracht men deze ontwikkelingen tegen te gaan, bijvoorbeeld door het aanleggen van waterberging, het vergroten van riolen en door het aanleggen van groen in steden. Deze klimaatadaptatiemaatregelen hebben impact op de ruimtelijke ordening van de ondergrond, met name in het stedelijke gebied.'
Eindhoven					
national	see Enschede/ national				
provincial	Provincie Noord-Brabant	Official strategy document old, more recent substrategies do include the relevance	connection retention and drought resilience	green-blue structure in cities and countryside as positive for recreation and nature, not specifically water management. Decrease UHI, health of city, space for recreation.	increase peak precipitation, in countryside water retention, in cities peak runoff reductions

'Het op grote schaal verplaatsen van functies zal niet direct haalbaar zijn in ons land en ons beheergebied. Waar we wel op in kunnen en moeten zetten, is aanpassen binnen de functie.'	shift in focus from drainage to accumulation, 'Het grootste en meest geschikte reservoir om water in te bergen is de bodem'	using elevation differences as base layer to planning approaches	reintroducing surface water in cities,	good balance of future vision between countryside and cities' impact on water system
			-	seems like they copy pasted a concept of Utrecht and had little inspiration
function follows water (abstract option)	complete strategy to provide every part of the region with adequate quality and quantity of water	having withdrawal locations at non-vulnerable, lower altitude locations. After which infrastructure pumps it to higher regions	-	
green blue structures and water retention sites mostly seen as an outside-of-city application	water infrastructure is delegated to the water authority	-		water seen as a countryside element, no connection with groundwater made // the new document is very progressive in the approach

water authority	Waterschap de Dommel	Recognises the importance of water resilience	agriculture, nature and urban connected through the water network. Functions should adapt to water instead of vice versa	infiltration in the place of precipitation: climate buffers within cities	Location specific adapation measures
regional (often cooperation multiple municipalities)	Brainport	Not a legislative entity, focus on fitting economic growth in sustainable development	transition to sustainable development in context of water	protection against heat islands, having water buffers, fight for space in a city	health and microclimate benefits are stated
municipal	Gemeente Eindhoven		water nuisance, overexploitation, sewage overflows	'In het centrum komen de drie landschapsparken samen en gaat verdichting hand in hand met vergroening. Het centrum en de wijken worden omringd en dooraderd door groen. Groen draagt bij aan een gezonde en duurzame leefomgeving. Het bevordert de biodiversiteit (fora en fauna), de klimaatrobuustheid en het versterkt het woon- en vestigingsklimaat van onze stad.'	'Een gezond en toekomstbestendig Eindhoven is een stad waarin inwoners veilig en gezond leven. Eindhoven heeft een bodem- en watersysteem dat bestand is tegen het veranderende klimaat. Zo verminderen we wateroverlast en droogte bij de toenemende weersextremen.'
other documents (municipality WKA)		practical applications of water resiliency concepts	flood, drought, new development sites, sewage capacity, heat stress	'Door hittestress en stijgende temperaturen staat het leefklimaat in de stad onder druk. Door het versterken van het bodem- en watersysteem spelen we in op de veranderende weersomstandigheden. Hiermee wordt de sponswerking van de bodem beter benut.'	'De aanleg van meer en grotere rioolbuizen is niet meer voldoende om het stedelijk watersysteem van Eindhoven robuust en klimaatbestendig te houden. Door de klimaatverandering neemt de kans op overlast en schade door hevige neerslag, hitte, droogte en overstromingen toe.'

public and private parties should adapt to water detention, incentives subsidy	renewing buried water infrastructure the opportunity for climate friendly street redesign, reuse of effluent, increase stormwater capacity for less CSOs, stream restoration projects, sluice gates regulating surface water		while within city management should be done by municipalities, strategies are provided
provide green blue structures in cities	water level management	resurfacing of streams	
new developments climate adaptive measures, green blue corridor structure, densification sites with extra care for health and climate adaptivity			

Hannover

national	Bundes-ministerium für Raum-ordnung	guidelines in a decentralised approach	flood conrol, water retention, decrease in precipitation will increase droughts	heat stress, need for open spaces and vegetation + reduce new land take	spatial analyses to find climate vulnerabilities
provincial	Nieder-sachsen	this scale level not used as independent planning level	does not state the underlying reasons for the preferential development areas	does not state the underlying reasons for the preferential development areas	the direct connection to water missing
water authority	-	this level is managed by the municipality			
regional (often cooperation multiple municipalities)	Region Hannover		mostly flood control and water demand	'In bebauten Gebieten wird das Regenwasser von Dächern, Straßen, Wegen und Plätzen zumeist über das Kanalnetz in Fließgewässer abgeleitet, häufig ohne Begrenzung der Abflussspitzen. Dadurch verändert sich die Abflusscharakteristik der Gewässer. Für eine nachhaltige Regenwasser- bewirtschaftung, auch wegen des Hochwasser-schutzes, sollen weitere negative Veränderungen verhindert und die Abflussspitzen gemindert werden. Soweit der Untergrund dies zulässt, sollte das Regenwasser möglichst getrennt vom Schmutzwasser und möglichst nahe am Entstehungsort versickert werden. Darüber hinaus können in anderen Gebieten Mulden-Rigolen-Systeme oder Regen.' page 214.	One of the main themes in the planning. 'Als Querschnittsaufgabe soll auch weiterhin der Schutz des Klimas, die Vorsorge bezüglich des Klimawandels und die Anpassung an die Folgen des Klimawandels bei allen Planungen und Maßnahmen zur Entwicklung der Region Hannover eine große Rolle spielen und berücksichtigt werden.'
municipal	Gemeinde Hannover	-			

minimise spatial conflict of use, but no further mention of combining it with (ground)water	mostly reuse and establishing regional water reservations	-	-	very clear but general approach, many parts still geared towards economy
special groundwater withdrawal and protection zones established, no further relation with the land uses	-	-		not relevant at all

other documents (municipality climate adaptation document)		many options provided for climate change	seasonal changes in precipitation, high water protection		'Auf unversiegelten, mit Vegetation bewachsenen Flächen wird das Niederschlagswasser zum größten Teil (zwischen)gespeichert. Ein Teil des Wassers versickert, ein Teil wird in der Vegetation zurückgehalten und verdunstet (Evaporation) oder wird nach Aufnahme durch die Pflanzen über die Blattoberflächen an die Atmosphäre abgegeben (Transpiration). Nur ein kleiner Anteil des Niederschlagswassers fließt zeitverzögert oberflächig ab. Auf versiegelten Flächen (Straßen, Dächer) wird der größte Teil des Regenwassers ohne Zeitverzögerung oberflächig abgeleitet und gelangt über die Kanalisation in den Vorfluter (Trennkanalisation) oder die Kläranlage (Mischwasserkanalisation). Nur ein kleiner Teil des Regenwassers kann verdunsten, eine Versickerung findet nicht statt.'
Münster					
national	See Hannover/ national				
provincial	Nordrhein-Westfalen	economic and raw material based. No in-depth strategy to implementation of water solutions	need for within city surface water, assign flood plains, protection of climate sensitive biotope control,	Newly (re) developed sites should have climate adapation measures in place, page 54-55	Starkniederschläge und längere Hitzeperioden, reduction of overall yearly precipitation
water authority	Wasserverband Westdeutsche Kanäle	this is only included as to show a coooperation in water policies, but is only infrastructure-based. Not relevant			

decanalisation of surface water, on site retention	reuse of rainwater, green roofs, etc. for retention		'Eine Analyse vorhandener und voraussichtlich neu entstehender „Hot Spots“ vorausgesetzt, kann die Anlage neuer Grünflächen notwendig sein, um einer Überhitzung der dicht bebauten Stadtflächen entgegen zu wirken.'	this is the only document on the subjects that goes in depth in Germany
minimise spatial conflict of use, but no further mention of combining it with (ground)water protection of withdrawal sites to ensure fully optimal drinkwater supply	mostly reuse and establishing regional water reservations	-	-	very clear but general approach, many parts still geared towards economy

regional (often cooperation multiple municipalities)	Münsterland	Protection of environmental sites, but no indepth on what strategies to use	rising water demand, flood control, drinkwater quality and ecologic protection	'Vorbeugender Hochwasserschutz beginnt schon mit dem Rückhalt des Niederschlagswassers in der Fläche. Durch die Rückhaltung werden die abzuleitenden Wassermengen deutlich reduziert, der Anstieg der Wasserpegel damit abgemindert und die Gewässer insbesondere in ihren Oberläufen entlastet.' - not specifically urban, but rainwater should be detained on location.	expansion nature protection, new development in less vulnerable areas, sustainable
municipal	Gemeinde Münster	guidelines per city district	flood control, retention sites, drinkwater protection, Naturraum & Stadtklima	no relation between innenentwicklung and wasserschutz	

'Die Überschwemmungsbereiche der Fließgewässer sind für den Abfluss und die Retention von Hochwasser zu erhalten und zu entwickeln.
Sie sind von entgegenstehenden Nutzungen, insbesondere von zusätzlichen Siedlungsflächen, freizuhalten.' page 89

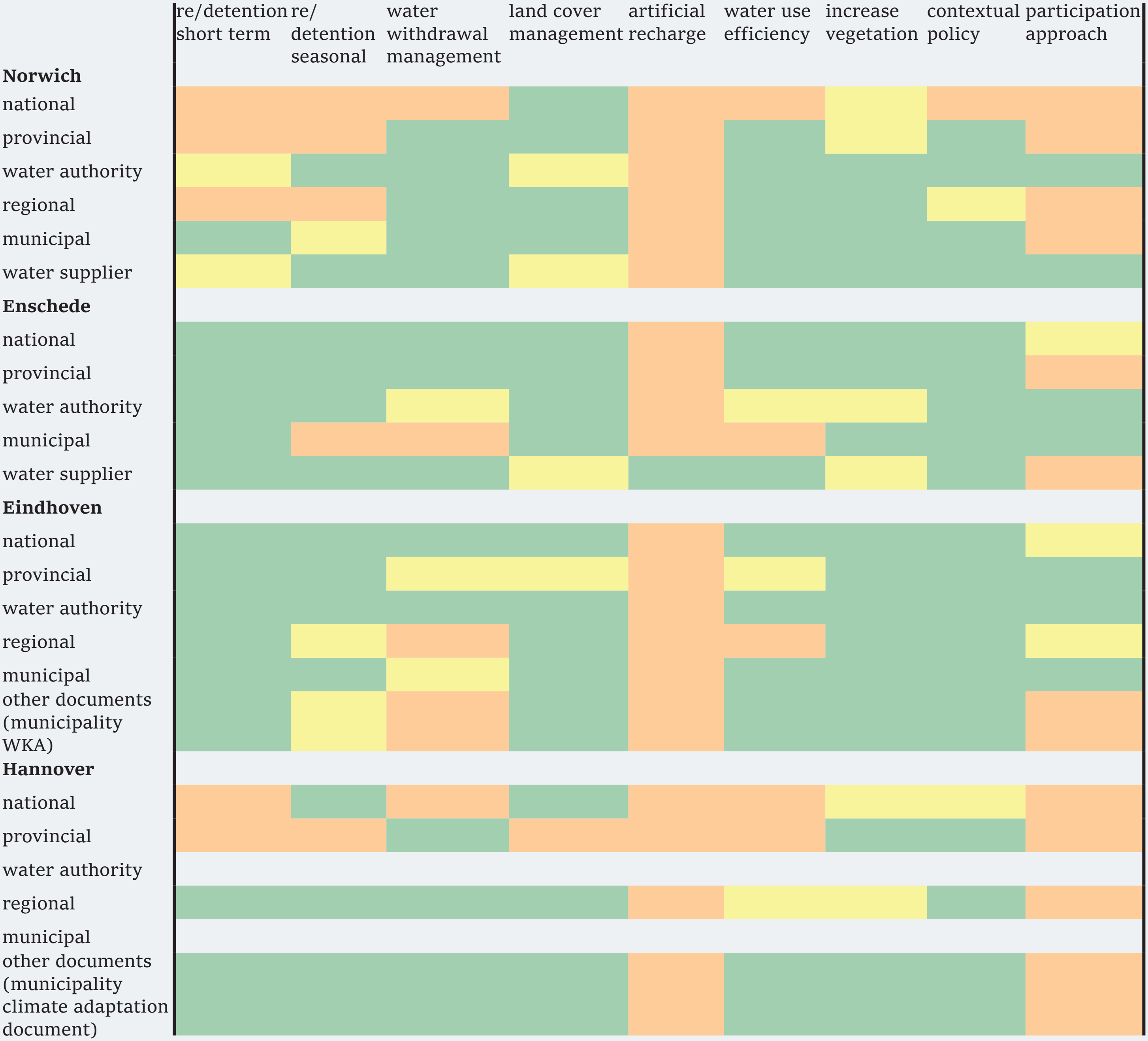
'Aufgrund dieser Belange sind die Bereiche der neu dargestellten Wohnbauflächen im Umweltplan als „Siedlungsflächen mit besonderen Anforderungen an den Wasserschutz“ gekennzeichnet. Diese besonderen Grundwasser- und Bodenfunktionen sollten bei der nachfolgenden Bebauungsplanung im Rahmen einer Umweltverträglichkeitsprüfung besonders berücksichtigt werden.'

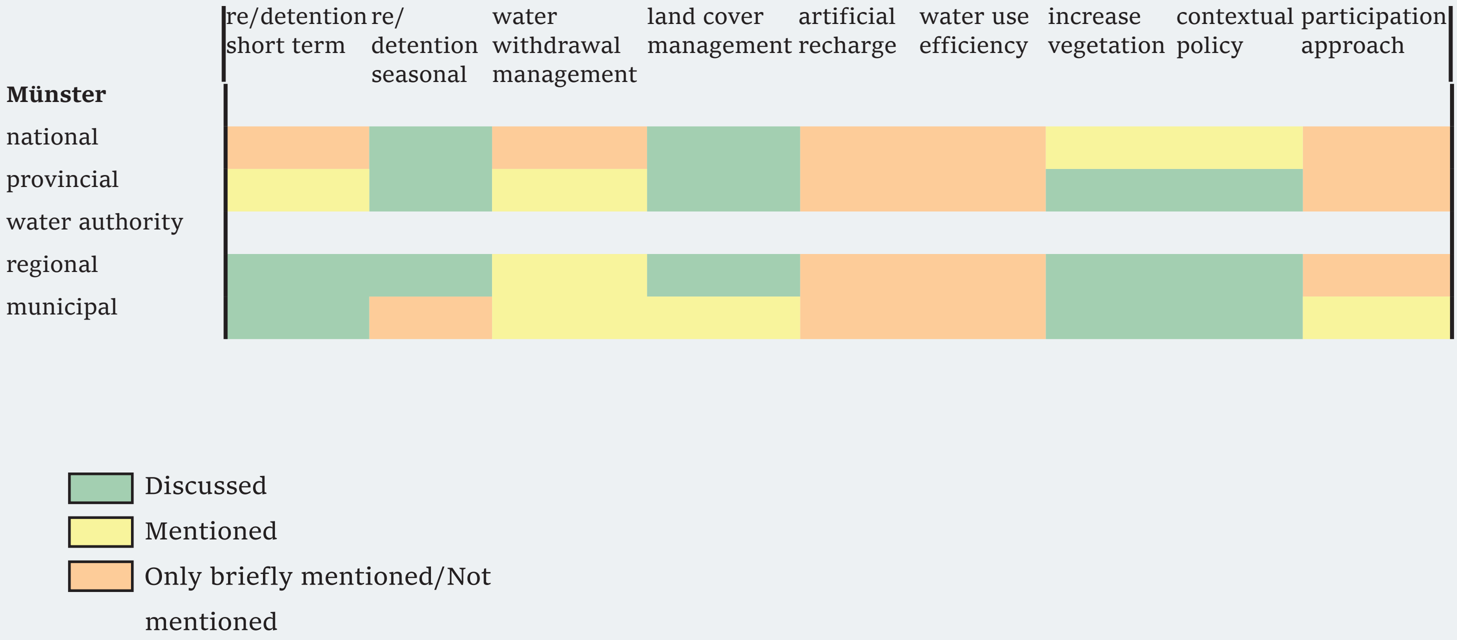
preservation of canals, mostly for shipping, but also for water management

explanation per city district, no overarching connections

Appendix D

Design recommendation classifications




re/detention short term
re/ detention seasonal
water withdrawal management
land cover management
artificial recharge
water use efficiency
increase vegetation
contextual policy
participation approach
Münster
national
provincial
water authority
regional
municipal
Discussed
Mentioned
Only briefly mentioned/Not mentioned