Common Ground:

Bridging Subsurface Information Models and Climate Adaptation Design

Double Degree Graduation Thesis (Geomatics and Urbanism)

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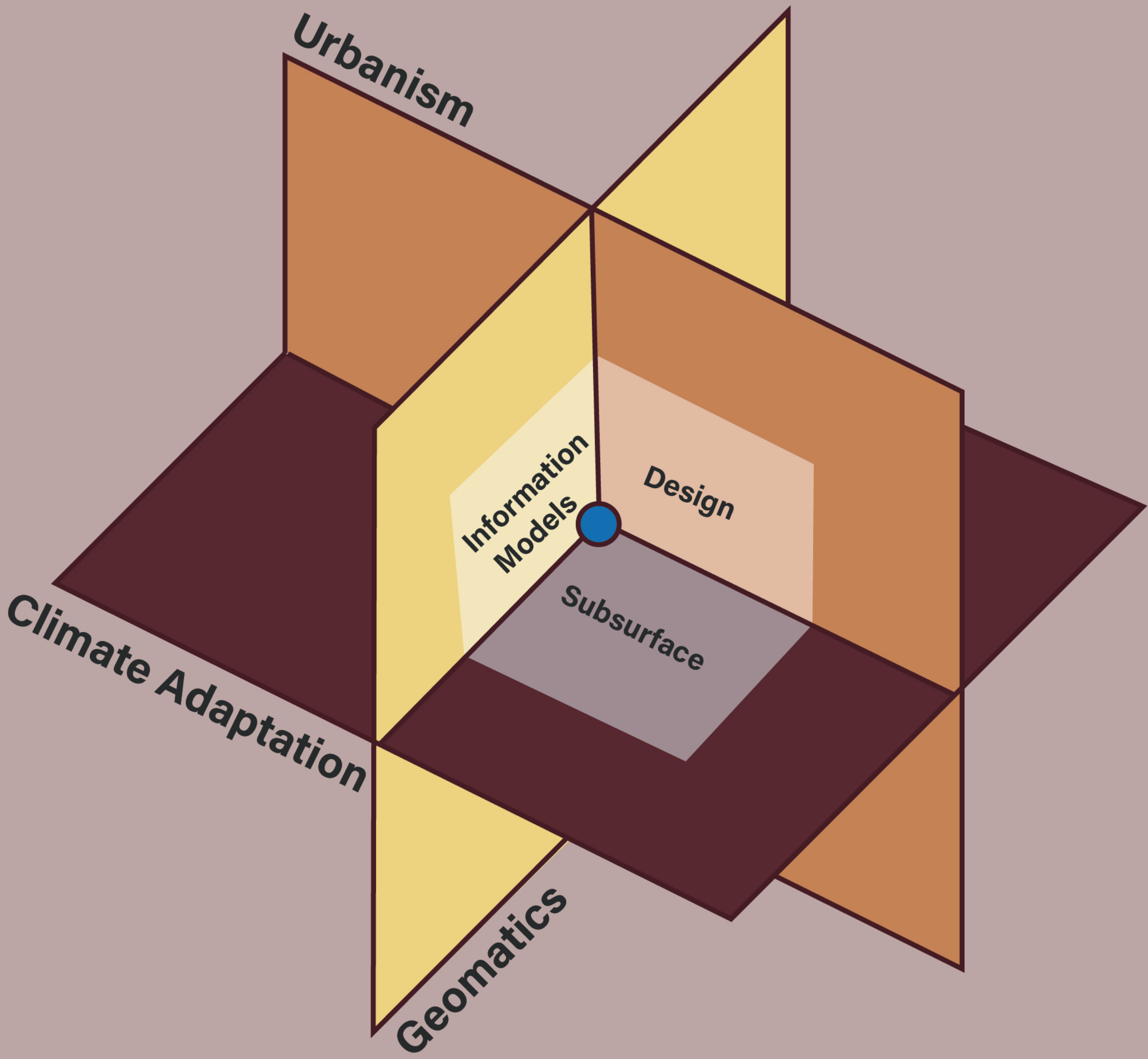
Mentors External: Rob van der Krogt (TNO), Wilfred Visser (TNO)



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Abstract

The Delta Porgramme states that the Netherlands must be climate-resilient and water-robust by 2050, posing a great challenge to spatial planning [1]. This imminent challenge of climate adaptation requires a common ground of interdisciplinary approach as monodisciplinary reductionist approaches are often not enough to deal with complex phenomena such as climate change [2].

In this context, combining information models can support well-informed design decisions, since many interventions related to climate adaptation, such as those related to water storage, soil infiltration and underground spatial management, require a deeper knowledge of subsurface characteristics and configurations.

However, this interdisciplinary approach still face many organizational, technological and institutional barriers, related to inherent characteristics of design and geoinformatics in combination with practical challenges related to standardization and interface of existing products. There has not been yet an integrated approach that relates subsurface information models and local climate adaptation design interventions in a single place even if literature and design examples suggest information needs.

This thesis aims to explores how subsurface information models, in particular 3D ones, can aid the cause of concrete well-informed urban climate adaptation design interventions, identifying the reasons for an under use of existing subsurface data models and assessing existing subsurface information models, both in 2D and 3D, to better understand what are the information requirements for climate adaptation design interventions in the Netherlands.

As climate adaptation can often be a broad concept, this research opted to focus on concrete examples of standards for climate adaptation in urban design, coming from the Leidraad 2.0, the Maatlat, and the Klimaateffectatlas. The interventions used for the design analysis are also standardized and refer to a document published by the Dutch government containing the twenty five most relevant climate adaptation design interventions in the Netherlands [3]. The study of these interventions, standards, and models, along with the study of their interdependence, indicate information needs for local climate adaptation design.

Therefore, this thesis provides both theoretical and practical foundations for better integrating subsurface data models into standardized urban design practices for climate adaptation. As a result of this research, a tangible tool named CLIMACAT is developed. CLIMACAT integrates pre-existing subsurface information models in accordance with FAIR data principles: ensuring findability, accessibility, interoperability, and reusability. Subsequently, both the tool and the established information models undergo testing via design proposals across four neighborhoods within the city of Utrecht.

Keywords: climate adaptation, urban design, subsurface, information model

Acknowledgments

A significant part of this research is based on what I believe to be the interdependency of geoinformatics and design. That is, the way in which we model and catalog real-world information influences the way in which we design, and vice versa. This fundamental hypothesis is what convinced me to pursue a double degree at TU Delft in both fields, and moreover, convinced me to pursue a double degree thesis which would merge them.

I would like to thank my supervisors for helping me to explore this hypothesis, guiding me, and pointing out areas that I was missing. I know how challenging this combination was, and I truly appreciate the patience and openness I received from all my mentors from the very beginning.

In particular, I am thankful to have acquired both urban design and information modeling knowledge in a very balanced way. To my mentors at TNO, thank you Rob and Wilfred for your knowledge about subsurface models and urban planning, and for always explaining what the models are and how to use them. And to my mentors at TU Delft, thank you Ulf, Peter, and Alex, for not only guiding me onto the right path supported by your expertise in the specific fields of climate adaptation design and standardized information models, but also for your help with the bureaucracy of a double degree thesis. I could not have done this without your help.

Thank you to my parents for all the support throughout these years. Thank you for sending me to a completely different continent at such a young age to fulfill my academic ambitions. Thank you for trusting me when I decided to pursue a double degree half way though my studies, even if you had no idea what Geomatics was. Thank you to the friends I made that made this decision easier (Go Alis, I am looking at you). And finally, thank you to Philip, who is my best friend every day.

Contents

1 Introduction

The Delta Program states that the Netherlands must be climate-resilient and water-robust by 2050, posing a great challenge to many different fields, including that of spatial planning [1]. This imminent task requires a collaborative, interdisciplinary approach. Relying solely on mono-disciplinary reductionist methods, as argued by Bhaskar, often proves insufficient when confronting complex phenomena because climate adaptation is a multifaceted issue that encompasses ecological, social, economic, and technological dimensions [2].

Climate adaptation is thus directly and indirectly related to many different topics. One of them is subsurface information. In 2022, the cabinet selected 'water and soil guiding' as a fundamental principle for spatial planning in the Netherlands. And, while the principle may appear clear-cut initially, translating it into practical solutions proves to be a complex task [4]. To mention a few examples, some design requirements for subsidence do not apply to higher sandy soils and water infiltration rate and capacity are directly related to the soil permeability, indicated by soil types and groundwater level, of the different surface layers. In addition, the lack of knowledge on subsurface information can lead to undesired consequences, such as groundwater being contaminated by sewage due to lack of knowledge on groundwater levels, parks with high maintenance costs due to the planting of species that are not suitable for a certain soil type, or a building that sinks irregularly because part of it is in a different, more soft, soil type.

There are also financial reasons to justify using subsurface information when designing. For example, Dirksland, located in the South Holland municipality of Goeree-Overflakkee, was a residential area under construction with a total of twenty-seven houses that were demolished in 2014. The reason for this was the use of too short foundation piles, causing the houses to sink and creating cracks in the walls. The contractor attempted to repair the foundation to prevent demolition but without success. This resulted in significantly high costs [5]. By better assessing the soil conditions in advance, the demolition could have been avoided, and additional costs could have been saved.

In this context, data models can support well-informed design decisions, since many interventions related to flood and drought, such as water storage, soil infiltration and underground spatial management, require a deeper knowledge of soil characteristics and configurations. These characteristics have been traditionally represented in 2D. However being some of these subsurface properties 3D objects in real life, such as cables, pipes and the different soil type layers, 3D representations are potentially beneficial, not only to illustrate the final design, but during the integral design process [6].

Currently, the Netherlands benefits from multiple 3D data models with subsurface information of the whole country. However, interviews with professionals in relevant fields show that there are still barriers to the integration of existing data models into climate adaptation design. Literature suggests that these barriers are often related to the differences between the way designers and geodata engineers carry out their activities and approach problems in combination with a historical introduction of Geographic information systems (GIS) into urban design. Other barriers are more technological and data-related, such as the fact that cities went from data-poor to data-rich and advances in GIS technologies that were developed separately from planning and are still underused in climate adaptation design due to the lack of knowledge of designers of what is available and how to use it.

In addition, there are barriers related to standardization, both in the geoinformatics and the urban design realms. Through data standardization these models could be integrated in design, planning, and overall land administration to solve multiple urban challenges, including climate adaptation. In a similar way, through design standardization, climate adaption becomes concrete through well-defined interventions, leading to realistic road maps for cities goals related to climate, such as the one defined by the Delta Programme.

As highlighted by the Delta Program, to achieve concrete results it is important to reach an agreement on what climate adaptation means in practical terms, through standardization [7]. For this reason, this research opted to focus on concrete examples of standards for climate adaptation in urban design, coming from the Leidraad 2.0, the Maatlat, and the Klimaateffectatlas, and the relationship of these with existing Dutch subsurface data models, namely the Key Registry for the Subsurface, and other subsurface data models from the province and the municipality of Utrecht.

For the same reason the thesis opted to focus on information models instead of data models in specific. While data models are used in actual implementations, information models are more abstract and focus on the meaning (semantics), attributes and relationships between managed objects.

Thus this thesis explores how standardized information models can aid the cause of climate design adaptation in the Netherlands, in particular through the creation of an information model and a digital tool (CLIMACAT) that combines different information needed for climate adaptation design. For this purpose, the created model should relate subsurface properties, existing 3D or 2D information models, and design interventions, to indicate where the relationships and dependencies between information and practice is stronger, and thus where climate adaptation is most likely to benefit from existing data models. The goal is to create a common ground, where designers can find necessary information, and data providers can fulfill information needs, for climate adaptation design. This is done, in this thesis, by identifying, relating, and combining different information.

Design proposals were made for four different 500 by 500 meter areas in Utrecht, namely Kop Voordorp, Lunetten Zuid, Kanaleneiland Noord, and Voordorp. Each area will cover one of the four landscapes in Utrecht and will take into consideration their main climate challenges. To focus purely on the relationship between subsurface and climate adaptation, the four chosen areas have similar density, urban morphology and social aspects. For each area, a more specific area of intervention was identified, such as one public space. Once the smaller area is defined, standardized design interventions are selected and their information needs are tested, remaining sensitive to the social, ecological and subsurface aspects of the area, studied using existing subsurface models and the created tool. The design proposals showcase how this integrated approach could be and explore the added value for climate adaptation when using information models.

1.1. Research Question

This thesis aims to answer the following question:

How can 3D subsurface information models support standardized local climate adaptation design?

The goal is to create a common ground for subsurface information, in particular in 3D, and climate adaptation design interaction. Climate adaptation is highly dependent on 3D subsurface characteristics and while this information is available at a national level in the Netherlands, it is still underused. This thesis aims to highlight the relationship between different design interventions and subsurface properties that can be found on existing 3D and 2D data models while exploring what are the data requirements for different design interventions. By assessing existing models and design requirements, it reaches a better understanding of the potential need or benefit for using 3D models to represent different subsurface properties. It also explores what are climate adaptation design requirements and how precise do information in the data models must be. By exploring these topics, the research is able to fulfill its main ambition: understand how to make structured subsurface information beneficial for concrete climate adaptation design. The result is an information model and a tool that combines different information in a single place and makes the relationships and dependencies clear. To answer this main research question, the thesis explores different subquestions such as:

1. In which ways is climate adaptation depends or relates to subsurface characteristics?
2. What are the existing barriers or challenges for effective utilization of 3D subsurface information models in Dutch climate adaptation strategies?
3. What specific design interventions are commonly employed in Dutch climate adaptation? How do they relate to the subsurface?
4. What is the data resolution or scale needed for different climate adaptation interventions? How precise do models have to be to suffice design needs?
5. How comprehensive and accurate are the current national-level 3D subsurface data models in the Netherlands, particularly concerning their relevance to climate adaptation needs? Can we improve existing models?
6. What is this added value of integrating information models to climate adaptation design? Can this added value be quantified?

7. What methodologies can be established for the integration of subsurface information models into urban design?

1.2. Methodology

This thesis explores the relationships between subsurface characteristics that can be found in existing data models and the requirements of standardized local climate adaptation design. The main focus of this study is to understand what is needed in terms of scale and data resolution for standardized local climate adaptation design to benefit from subsurface information models. Is the information models that currently exist in the Netherlands enough? If not, what is needed in terms of data resolutions and scale to support local climate adaptation interventions? The answers to theses questions can be found when studying the explicit and implicit requirements stated in standardization design documents for climate adaptation such as the Leidraad 2.0. How are certain interventions represented and how do they relate to the subsurface indicate which resolution is needed.

The Urbanism research setup thus includes understanding what are the requirements for standardized climate adaptation design, through the study of existing standardization guidelines and other relevant literature, such as product manuals. It also tests the requirements for different interventions in practice, by proposing spatial interventions in four different neighborhoods in Utrecht, which also showcase a design methodology supported by information models.

The Geomatics setup includes understanding what is needed, in technical terms, to meet the requirements identified by the Urbanism side of this thesis. If for design it is a matter of which information is needed and in what scale, for Geomatics these are related to data resolution and information models, often represented in Unified Modeling Language (UML) diagrams. The Geomatics aspect of this research relates the requirements of standardized local interventions with existing data models, and compares which information are fulfilled and which ones are not, highlighting what are the weakness and strengths of existing models. It, moreover, indicates what are the benefits for representing certain subsurface properties in 3D for design purposes and overall what is needed for a model or a product with subsurface information that is tailored for climate adaptation design.

1.2.1. Methodology Urbanism

In short, *the Urbanism aspect of this thesis is in determining what is the necessary information for standardized local climate adaptation design.* As a methodology, that means firstly gathering the requirements from guidelines, such as the Leidraad 2.0, but also from practical design examples where this information needs can be identified. The methodology aims to give a well informed answer to questions such as: Which information is needed for local climate adaptation design? What is the added value for using this information?

When it comes to requirements, it is important to understand how the defined requirements relate to the different layers of subsurface. Some interventions are mainly related to the immediate subsurface layer while others may be related to deeper layers. In this sense, data resolution in 3D becomes interesting, it is not a matter of producing different 2D maps of different specific depths in the subsurface, but an integrated 3D model. One of the answer the research aims to answer is what information should these models include to support local climate adaptation design.

The setup thus includes studying what are the requirements but also by testing them through design interventions. These interventions will be all chosen from well documented measures found in a document published by the Dutch government containing the twenty five most used climate adaptation design interventions in the Netherlands [3]. Thus, the interventions will not be freely designed but will be chosen from existing guidelines. The choice between the different interventions will be made based on standards and themes relevant to the area, for example if an area is more or less prone to draught, heat stress, drought or other climate themes, and to the subsurface condition, for example soil type and ground water level. In this context, there are three identified ways in which local climate adaptation design relates to subsurface property, namely:

- *The subsurface dictates what a designer can and cannot do.* For example some soil types, such as peat or clay, cannot support much weight and thus heavily built interventions cannot be done in areas where this soil type is present at certain layers.
- *Ground water level dictates to which extend can you infiltrate.* Even if soil conditions are favorable for water absorption, the ground water level can interfere in the amount of water that can be stored.
- *Interventions are more or less suitable for different soil types.* In this case, soil types do not dictate what can be done but are, to some degree, more or less suitable to different interventions. For example, sandy soils are known to absorb more water and faster than other soil types. Thus open soil interventions related to rainwater retention do not depend on, but would benefit, from such soil type.

In addition, ecological and social aspects will be taken into consideration when choosing the interventions: a natural playground is arguably suitable for a neighborhood with many children while a green garden with tress is a justifiable design choice for a neighborhood that lacks greenery.

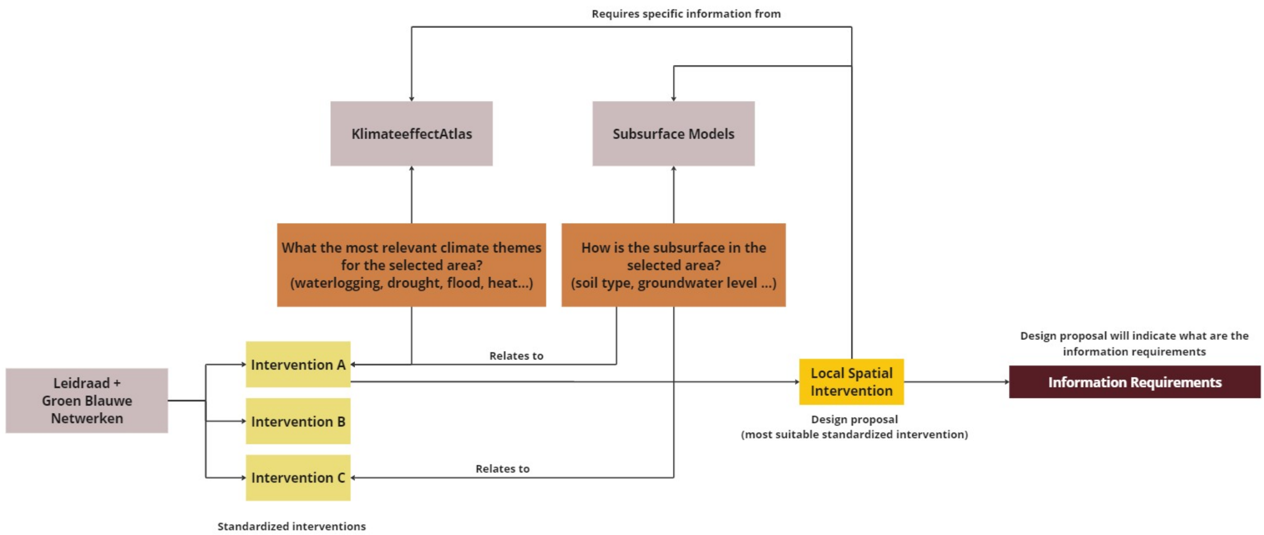


Figure 1.1: Methodology Urbanism

Spatial Interventions: Locations

Once a review of existing standardized climate adaptation interventions is made and their requirements are well studied, spatial interventions are proposed in the city of Utrecht, a city with four different well-divided subsurface and landscape types. To showcase how information models can support climate adaptation design and explore how, in practice, different interventions have different requirements, four areas of 500 by 500 metres in Utrecht were defined with the help of designer from the city's municipality. These areas are in the neighborhoods of Kop Voordorp, Lunetten Zuid, Kanaleneiland Noord, and Voordorp.

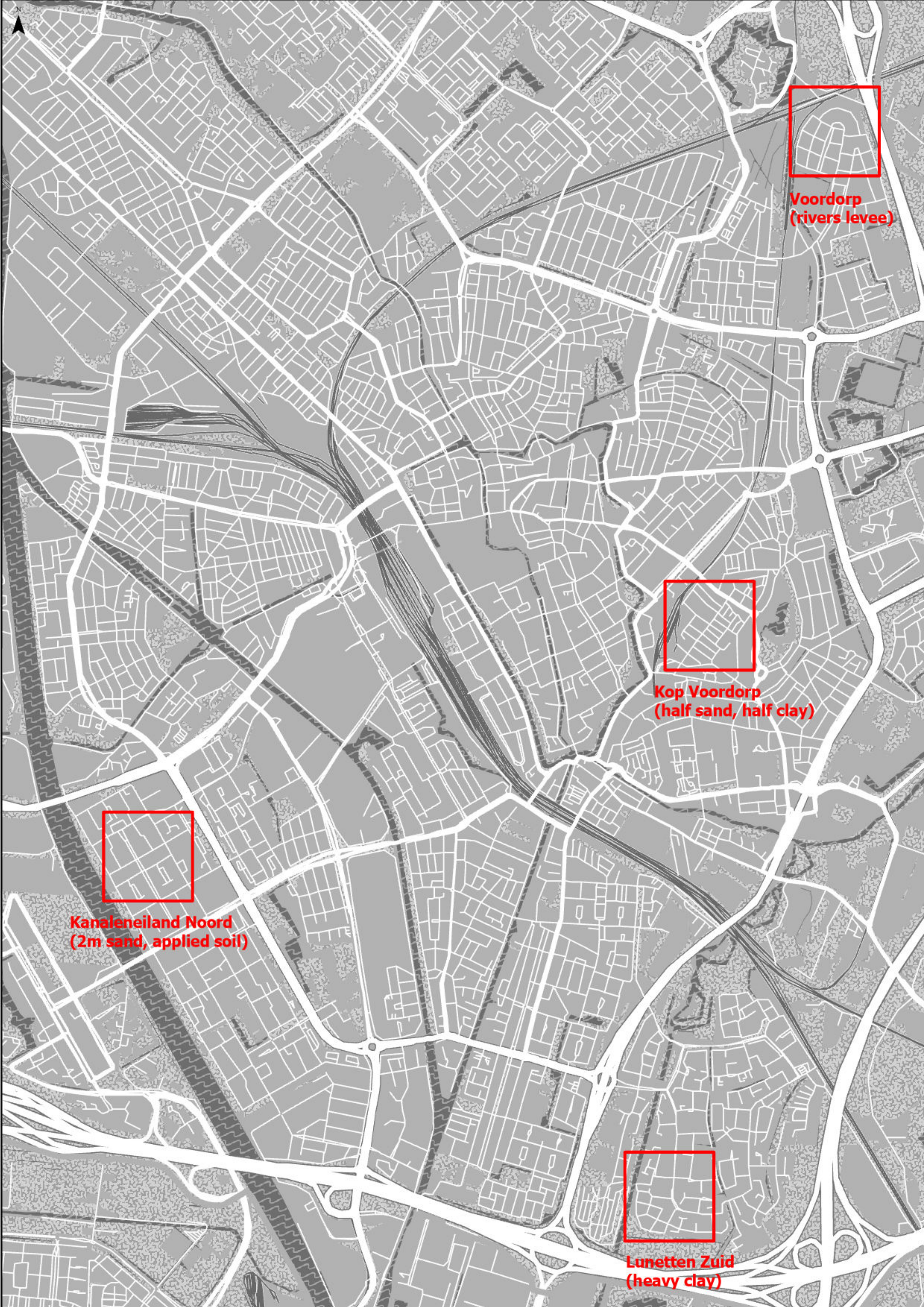
Each area represents one of the four subsurface types in Utrecht and have similar urban functions (mainly residential), allowing the focus to be mainly in the subsurface characteristics while exploring interventions in four very different subsurface conditions. For each squared area, a smaller area of interest was identified. For example, a public space or a paved area that would benefit from open soil.

Figure 1.2: The four soil types in Utrecht

The goals for the spatial interventions is to adapt a selected area inside of a 500 by 500 squared zone in one of the four selected neighborhoods in Utrecht. To test climate adaptability, climate scenarios were used, such as storm and air temperature simulations. Moreover, by doing that, an approach for local climate adaptation design including information models is showcased and the data requirements for different interventions are tested in practical design exercises.

The knowledge of the author in urban design allows the choice of interventions to be sensitive to a broader context of urban qualitative aspects. Attention is paid when choosing an intervention on how it related to its context such as which urban activities already exist on public spaces in the area, and what are demographic and social aspects of the population. In addition, if more than one intervention is selected, attention was paid on how they relate to each other, and choices were made between a chain design effect or punctual interventions.

Even though the main focus of the spatial intervention is to better understand the information requirements for local climate adaptation, other challenges could potentially also be answered by the design, and the interventions remained sensitive to urban transformations, such as densification or requalification, that happened or could happen in the neighborhood. In these cases, climate adaptation remains the focus, but it is included or related to other transformations.


Voordorp
(rivers levee)
Kop Voordorp
(half sand, half clay)
Kanaleneiland Noord
(2m sand, applied soil)
Lunetten Zuid
(heavy clay)

Location 1: Kop Voordorp (half sand, half clay)

The area is located between two main parks, the Wilhemina Park and the Sonnenborgh Park. The East part of the 500 by 500 metres squared area selected by the municipality of Utrecht, a part of the Het Spoorweg Museum is included. This is a museum on railways and is located inside of a railway station from the 19th century.

The area thus contains many interesting cultural and ecological elements, however the public spaces inside of the residential area that is studied do not seem to indicate the presence of these activities. For example, the main public areas right in front of the museum are used as a parking lot and an open space, with permeable pavement but no other seemingly activity. In addition, the greenery inside of the squared area comes mainly from to private gardens, with few exceptions. This can also be seen in the map created using the BARCODE division of urban functions created by the municipality of Utrecht. The red in the map indicates unpaved ground, making it more clear how the greenery is concentrated on private properties.

Therefore the aim of the design for this area is to better connect the two main parks and the museum while adding climate adaptation elements and social and urban qualities to the existing main public space in front of the museum.

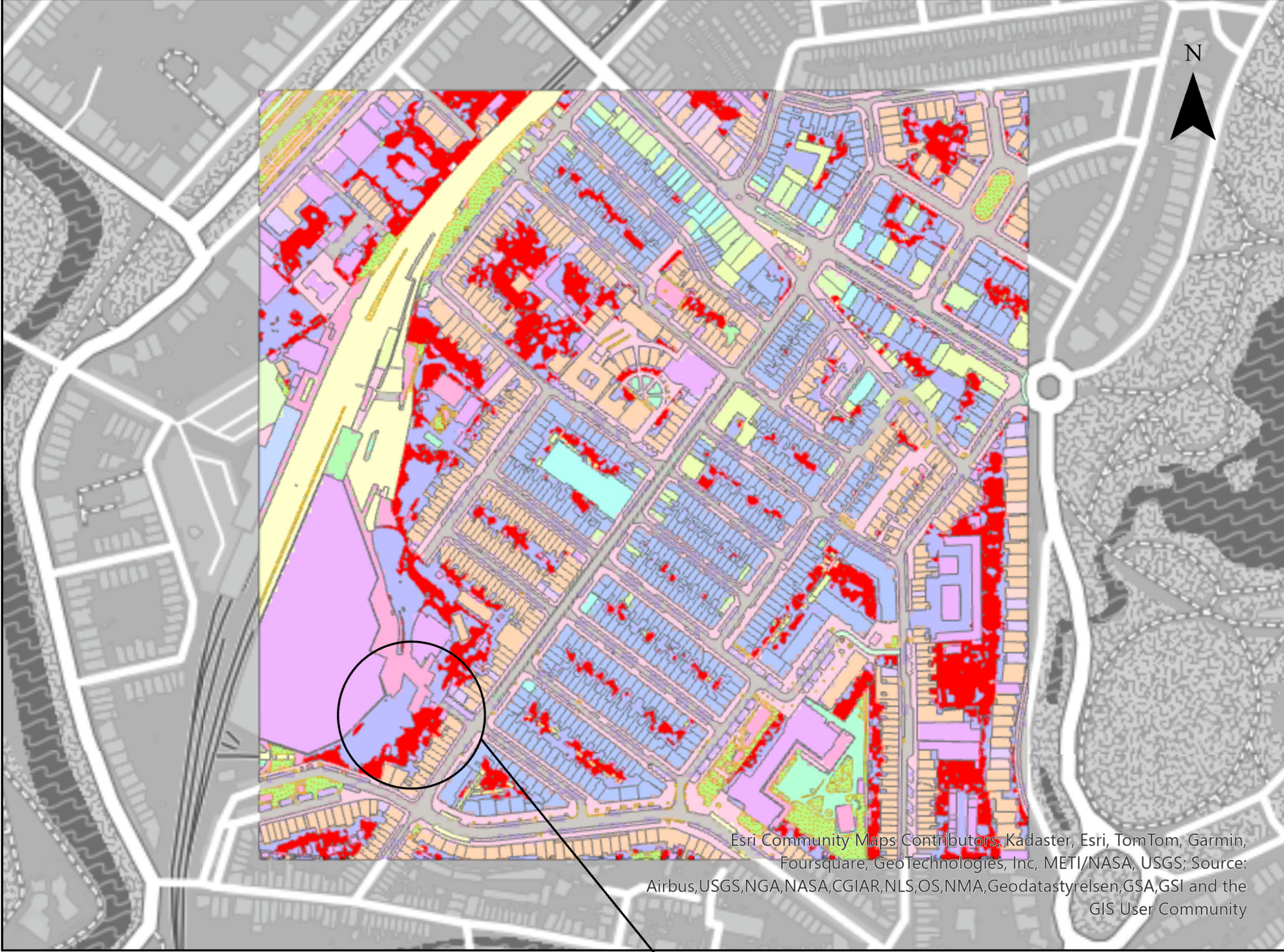
Location 2: Lunetten Zuid (heavy clay)

The squared area in the neighborhood of Lunetten Zuid is protected from the highway through a green buffer. The buffer is a substantial green area and includes several parks connected by a corridor around the neighborhood. However, differently from Kop Voordorp (area 1), the main parks can be connected by a green corridor that horizontally connects the two extremes of the green buffer.

This connection is sparse bigger areas of greenery that intersects Simplonbaan street. However, these areas could be qualitatively improved, highlighting the connective effect of this corridor. The spatial intervention will thus focus on this strip, and, in particular, on the intersection point between the corridor and Simplobaan street.

The design will also take into consideration the fact that the subsurface is mainly made of heavy clay. Thus, interventions will be thought to be aligned with this type of soil, a soil with poor drainage, which can leads to waterlogging and flooding during heavy rainfalls, such as the storm event simulated for this desing exploration. Heavy clay is also known for its tendence to retain heat, thus natural or artificial shades, and avoiding reflective materials, are key in this design. Since there is already a great concentration of public greenery, the native vegetation will be kept whenever possible.

Location 1: Kop Voordorp (half sand, half clay)



Scale: 1:6000

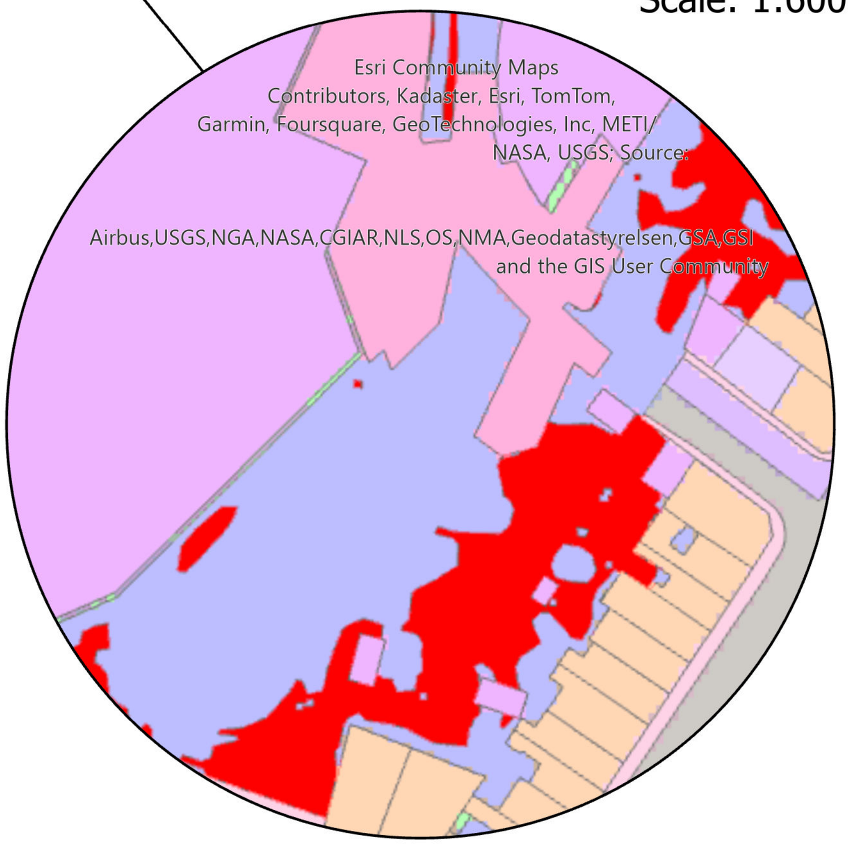
Location 1: Kop Voordorp (half sand, half clay)

Legend

Barcodekaart

Barcode

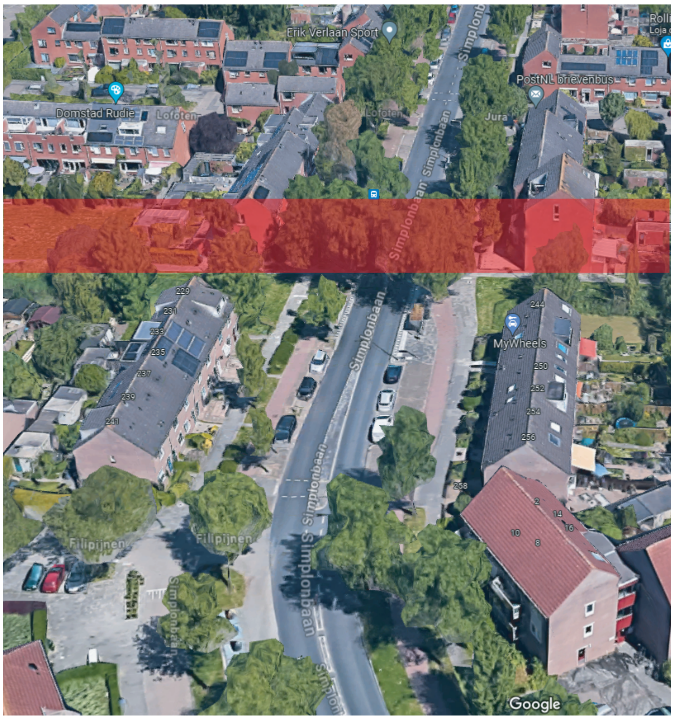
- auto
- bebouwd
- bebouwd - fsi/ functie onbekend
- erf - onverhard
- erf - verhard
- fiets
- groen
- mxi 0 - 0.25 - fsi 0-1
- mxi 0 - 0.25 - fsi 1-2
- mxi 0-0.25 - fsi >3
- mxi 0.25 - 0.5 - fsi 0-1
- mxi 0.25 - 0.5 - fsi 1-2
- mxi 0.5 - 0.75 - fsi 0-1
- mxi 0.5 - 0.75 - fsi 1-2
- mxi 0.75-1.0 - fsi 0-1
- mxi 0.75-1.0 - fsi 1-2
- ov
- overig bebouwd
- overig infrastructuur
- overig onverhard
- overig verhard
- parkeren eigendom openbaar
- parkeren privaat eigendom
- voetganger
- <all other values>



Museum public area

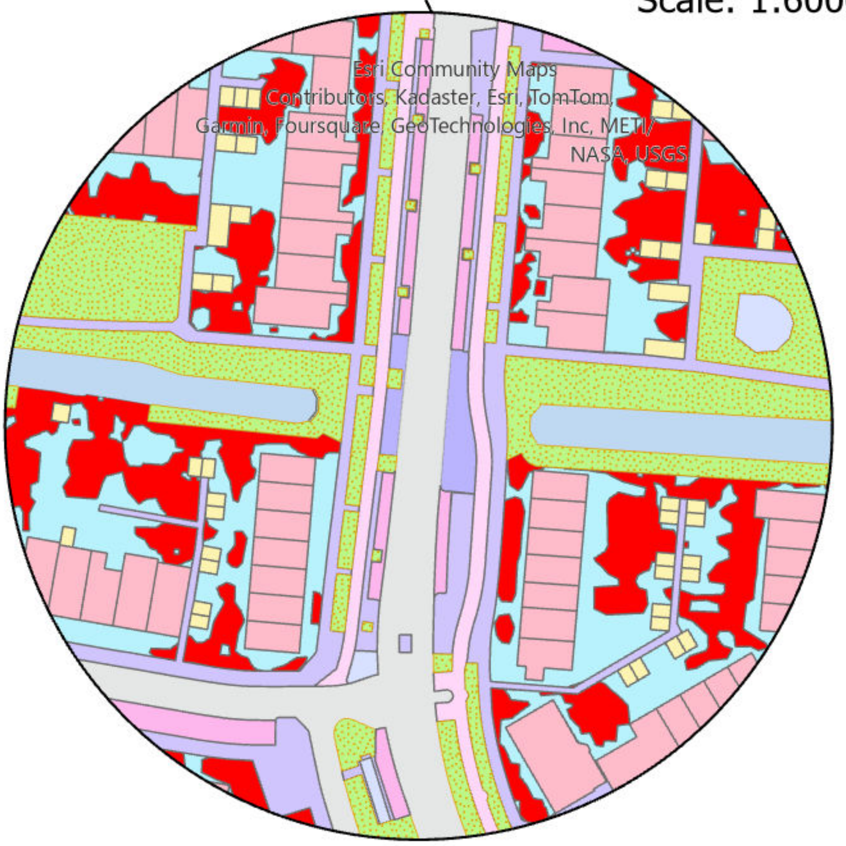
Scale: 1:1000

Location 2: Lunetten Zuid (heavy clay)



Scale: 1:6000

Location 2: Lunetten Zuid (heavy clay)



Intersection Simplonbaan

Scale: 1:2000

Location 3: Kanaleneiland Noord (2m sand, applied soil)

Kanaleneiland Noord has its main greenery facing the main canal. The green spaces are not only grass but often included urban activities, such as green playgrounds and dog parks.

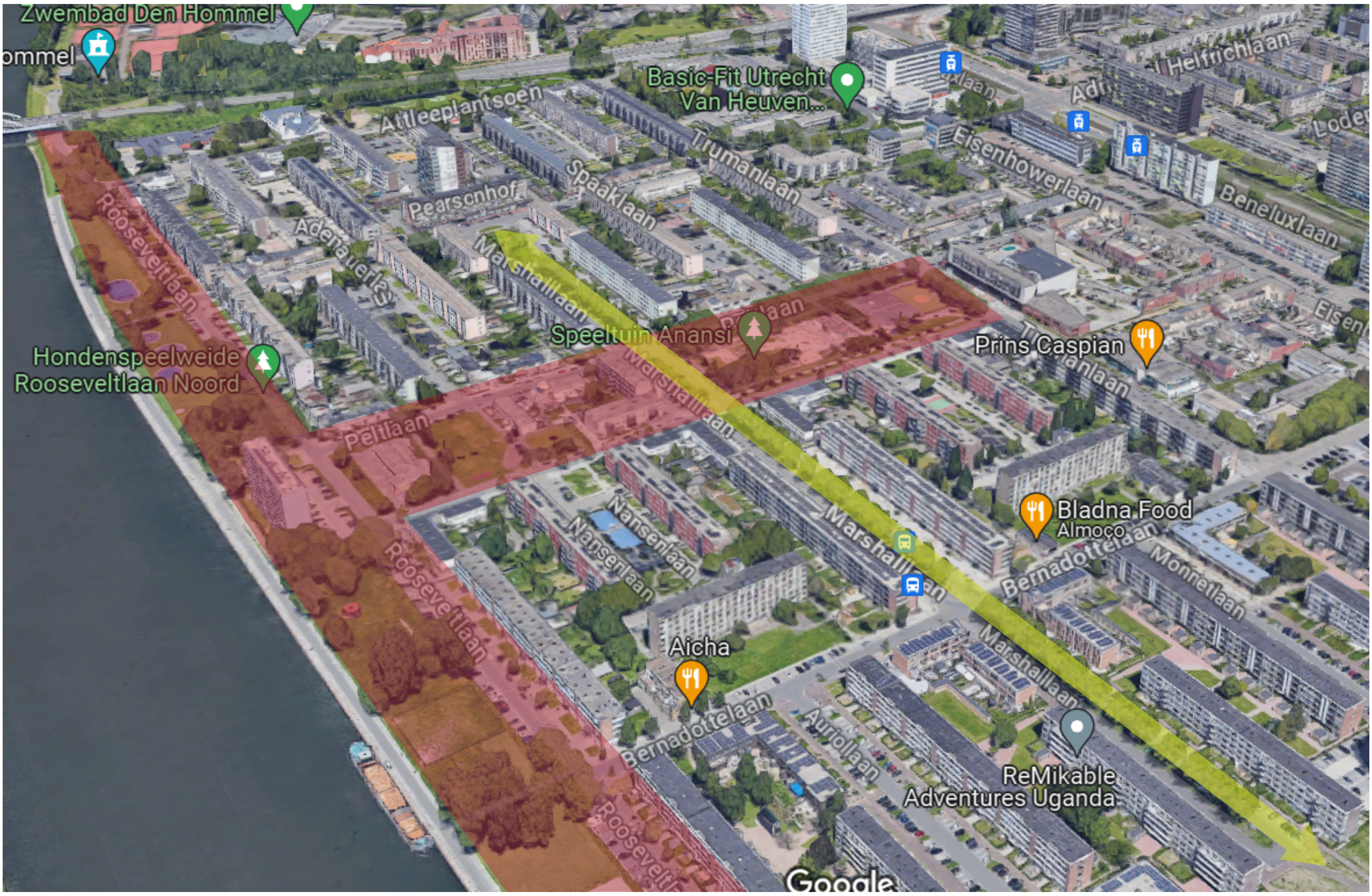
The greenery facing the canal is directly connected to green areas that lead to the Speeltuin Anansi, a relatively big playground that includes greenery, play areas and sport fields. The playground faces a school, connecting the school to the parks facing the canal.

Marshallaan is a street with a high presence of trees that crosses the Speeltuin Anansi, connecting north and south part of Kanaleneiland Noord to these main green spaces. The spatial design will thus focuses on this street, identifying places that would benefit from being unpaved, or adding different qualities to already existing green spaces. For example, there are a few public rain gardens and green squares that currently only have a couple of trees and grass. A potential design intervention would add different qualities to this space, while maintaining or improving its adaptability to climate change.

Location 4: Voordorp (rivers levee)

Most of the greenery in Voordorp comes from private gardens. In a map indicating the unpaved areas (in red) it is possible to identify that most of them are inside of private properties. With exception of the Chico Mendesstraat, a street with trees and a canal, most of the public spaces lack greenery and unpaved surfaces. Playgrounds and sport fields, for example, are most of the times fully paved. One such example is the playground in front of a school, circled in the map. This area has the potential to be one of the few public spaces, a green square, or an unpaved public area, but currently it is occupied by one playground and one sport field, both fully paved. Unpaving the surface is an intersting climate adaptation intervention in this area, that has on its surface level sandy soil, which can absorb rainwater faster than other soil types. The spatial intervention will thus focus on this area in front of the school.

Location 3: Kanaleneiland-Noord (2m sand, applied soil)



Scale: 1:6000

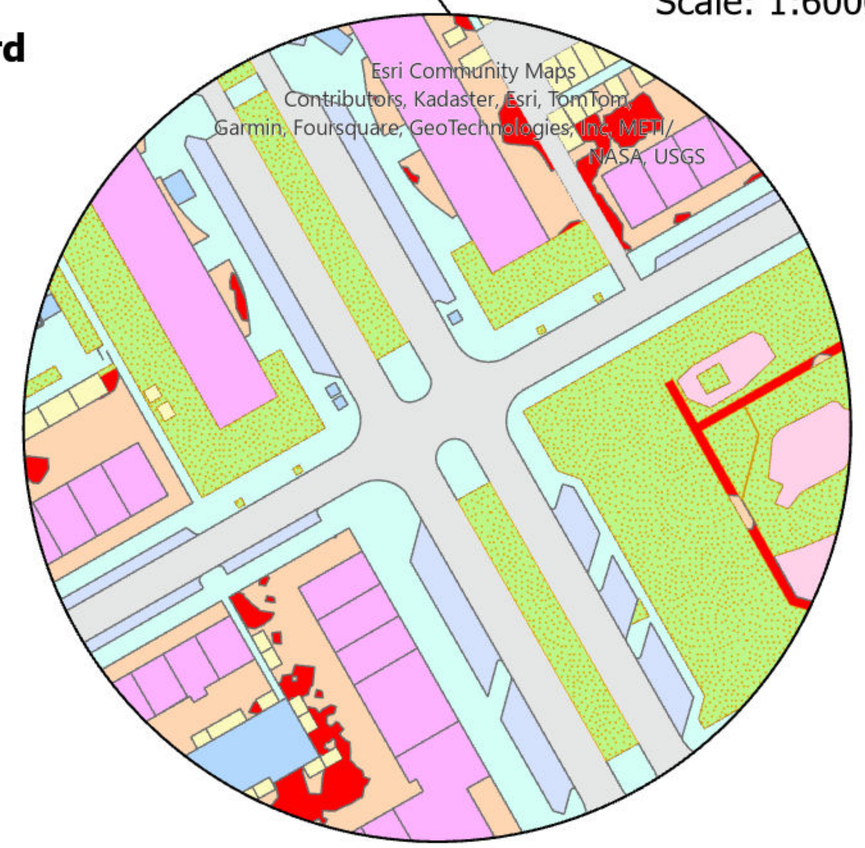
Location 3: Kanaleneiland Noord (2m sand, applied soil)

Legend

Area 3

Barcode

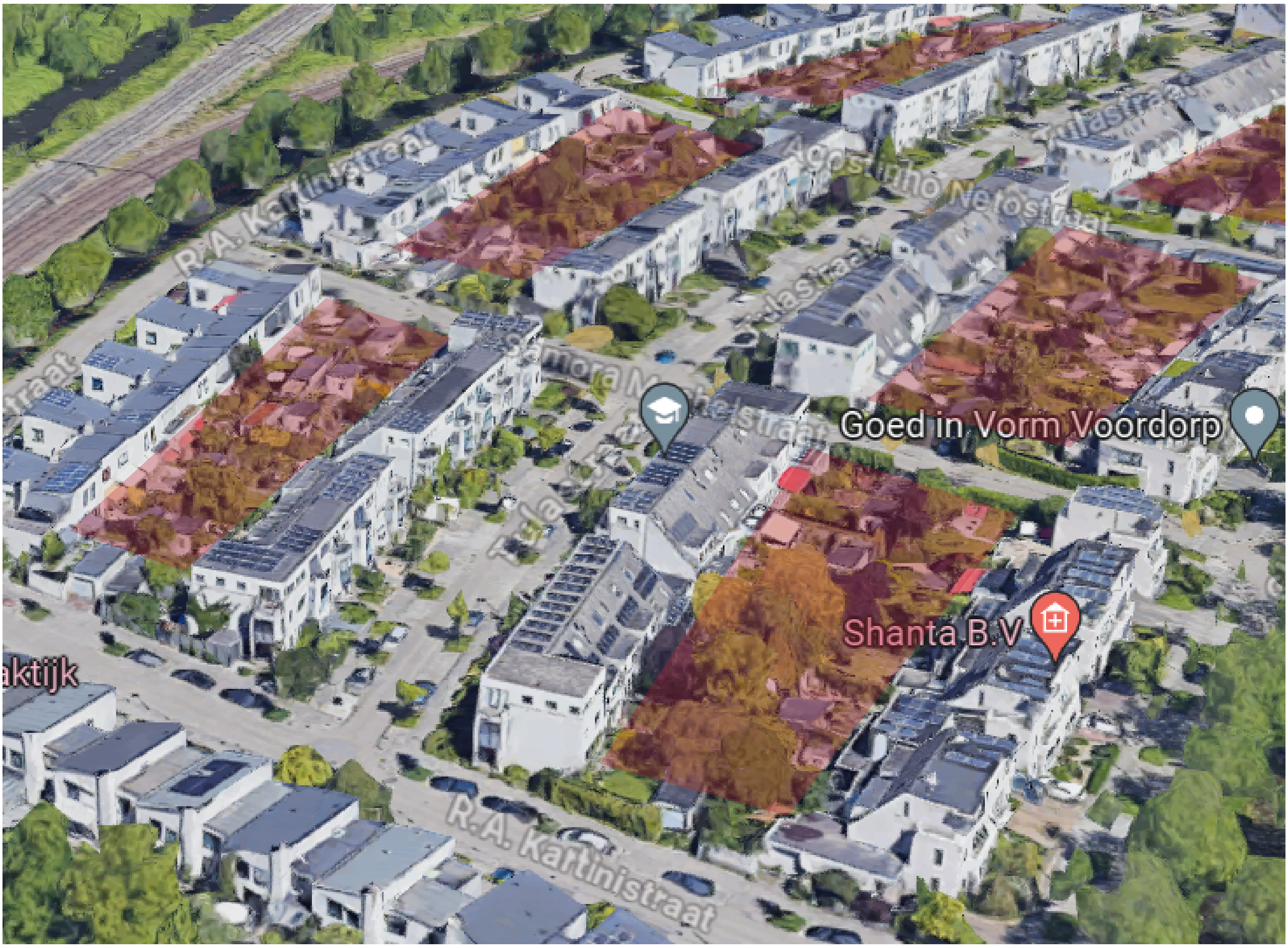
- auto
- bebouwd
- erf - onverhard
- erf - verhard
- fiets
- groen
- mxi 0 - 0.25 - fsi 0-1
- mxi 0 - 0.25 - fsi 1-2
- mxi 0.5 - 0.75 - fsi 0-1
- mxi 0.5 - 0.75 - fsi 1-2
- mxi 0.75-1.0 - fsi 0-1
- mxi 0.75-1.0 - fsi 1-2
- mxi 0.75-1.0 - fsi >3
- ov
- overig infrastructuur
- overig onverhard
- overig verhard
- parkeren eigendom openbaar
- sportveld
- voetganger
- water
- <all other values>

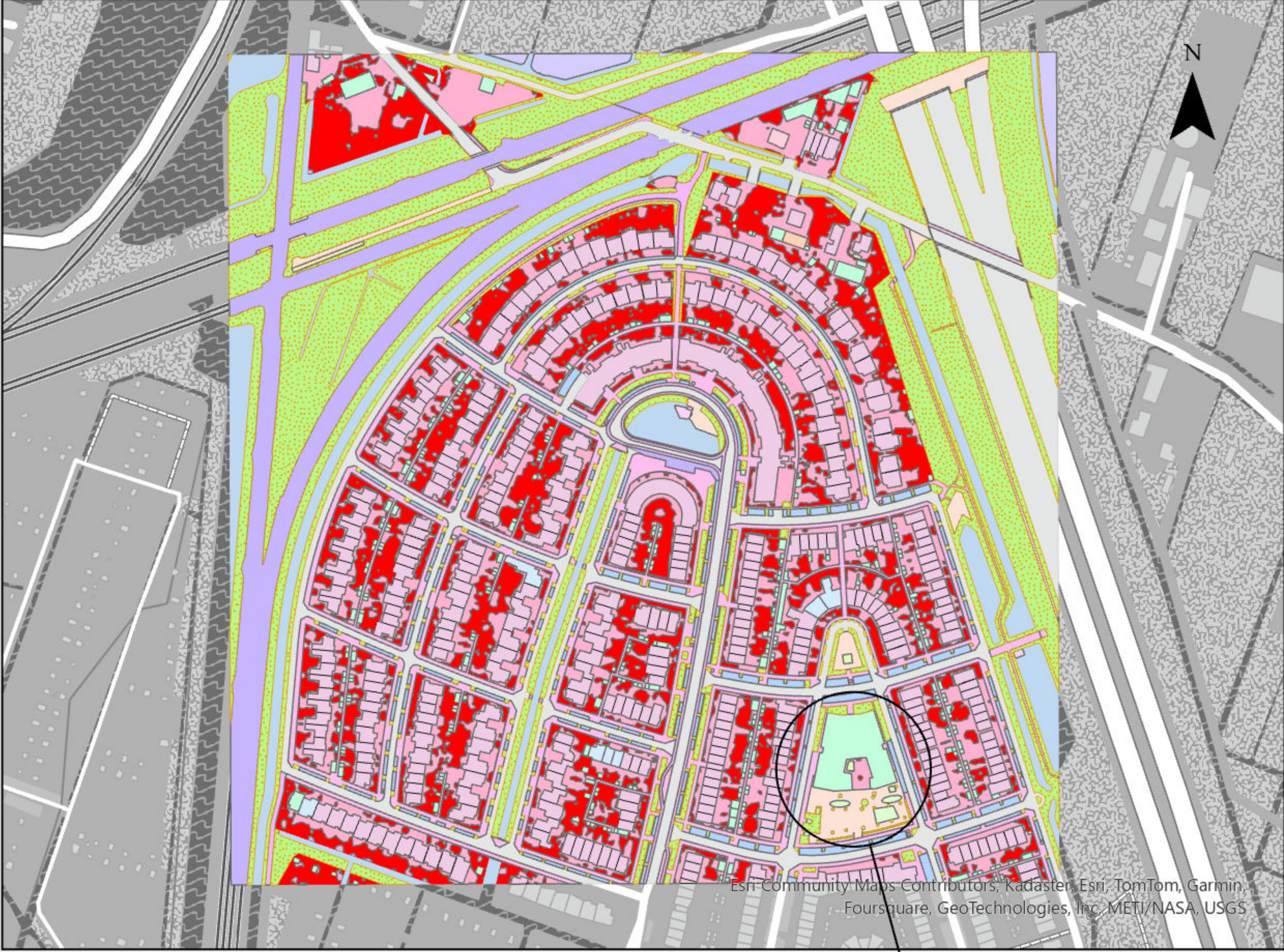


Intersection Simplonbaan

Scale: 1:2000

Location 4: Voordorp (rivers leeves)





Scale: 1:6000

Location 4: Voordorp (rivers levee)

Legend

Barcodekaart

Barcode

- agrarisch
- auto
- bebouwd
- erf - onverhard
- erf - verhard
- fiets
- groen
- mxi 0 - 0.25 - fsi 0-1
- mxi 0.25 - 0.5 - fsi 0-1
- mxi 0.5 - 0.75 - fsi 0-1
- mxi 0.75-1.0 - fsi 0-1
- ov
- overig infrastructuur
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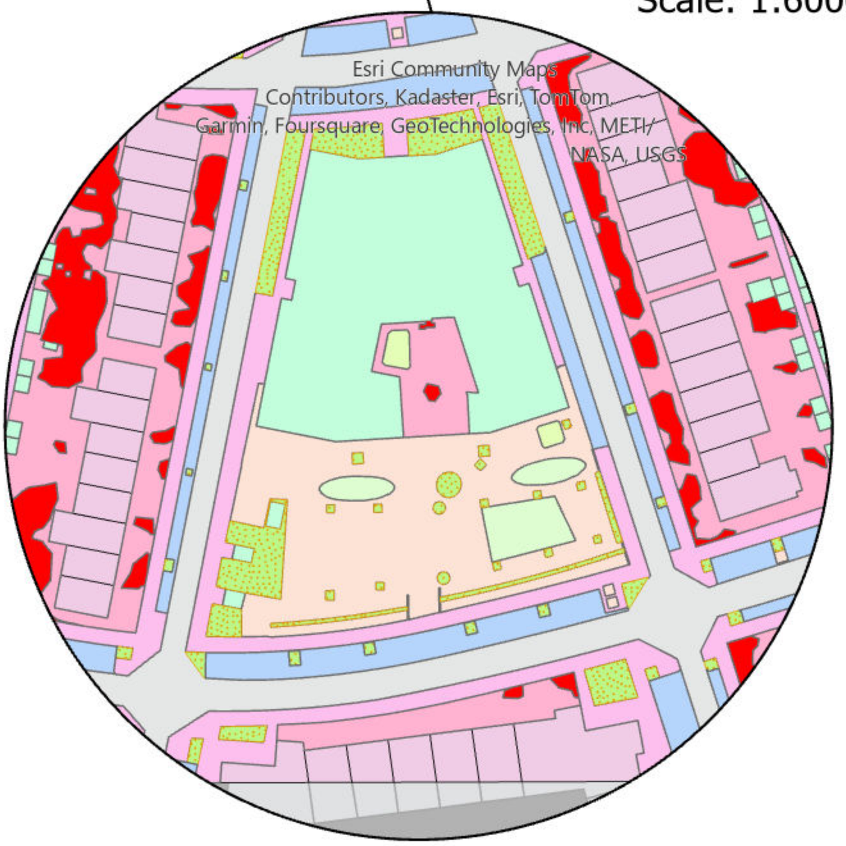
- parkeren privaat eigendom
- sportveld
- voetganger
- water
- <all other values>



Playground in front of school

Scale: 1:2000

Spatial Interventions: Storm Events

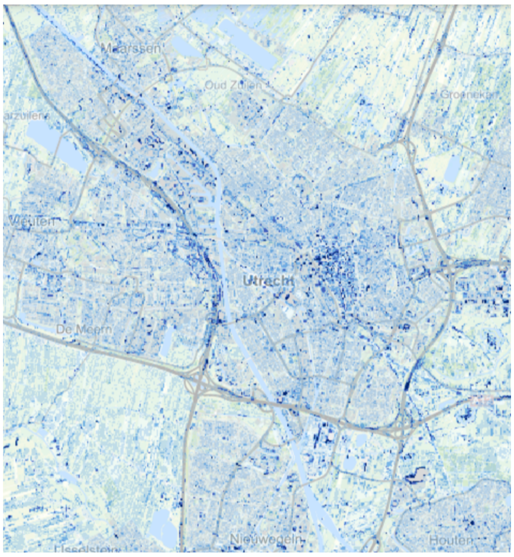
One of the conclusions of literature review is that themes and challenges of climate adaptation relate to the subsurface differently. Some aspects of climate adaptation seem to benefit more from information models support. For example, themes related to water absorption, such as waterlogging and flood, have more interventions with subsurface dependencies than heat, for example, that can include interventions such as blinds in buildings or artificial shadowing spots that have no interaction with the subsurface. This became even more clear after demonstrating graphically the relationships between standardized climate adaptation interventions and subsurface properties through the creation of an Unified Modeling Language (UML) diagram.

Since water absorption is particularly relevant when assessing the needs for information models that could support local climate adaptation design, it was decided to utilize a storm event scenarios while designing, having the Leidraad and Klimateeffectatlas as references.

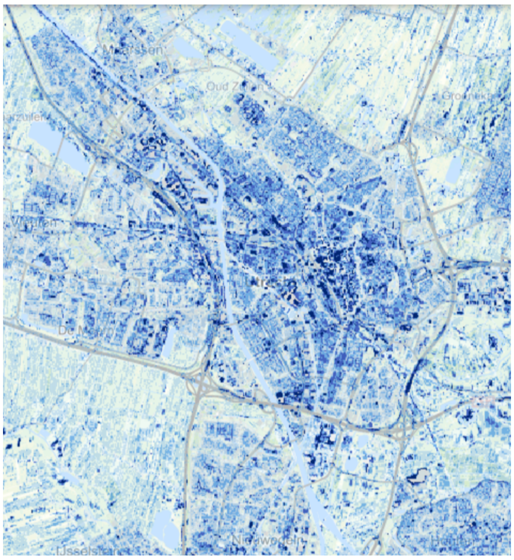
The Leidraad shows the expected recurrence times for precipitation events for the current climate and the climate in 2050 with a format for standardization [8]. In addition, Utrecht has three regulations regarding waterlogging that were used to define the storm scenarios. These are:

- *N1: In the planning area, no water damage occurs during a shower that can occur once every 100 years. Vital and vulnerable functions, for example electricity supplies and nursing homes, remain available in the event of a shower that can occur once every 250 years.* In 2018, this was 70 mm for once every 100 years and 90 mm for once every 250 years [8].
- *N2: A large part of the precipitation (50 mm) on private land is infiltrated, retained and/or stored in facilities on private property or in designated additional facilities in the planning area or within the water system boundaries.* Deriving from a shower of 70 mm in an hour for the once every 100 years scenario, that would mean the storage of 50 mm is required. In order to relieve the urban water system, the storage must be gradually drained away in a period from at least 24 hours after the shower (about 2 mm per hour). The storage room must be available again after 60 hours after the shower to absorb a second shower. The emptying times do not apply to controlled water storage systems that use weather forecasts, for example. However, it must be demonstrated that the controlled storage can be used effectively to collect the 50 mm of precipitation
- *N3: The development will be water-neutral and will not lead to additional water supply/drainage. Rainwater is retained and reused as much as possible in the planning area.* Thus, preference should be given to interventions that facilitate the retention and reuse of rainwater

Having the once every 100 years scenario of 70 mm and the laws related to rainwater retention/reuse for the city of Utrecht, two scenarios were defined. For flooding in built-up areas, the short local heavy showers of one hour are often decisive [8], thus in one of the scenarios the 70 mm are reached in one hour, and rain continues with the same intensity for another hour. In a different scenario, a more long term storm scenario was used, and the 70 mm is reached after two hours. Thus the two storm events used for the purpose of the spatial interventions consist of: a shower of 140 mm in two hours (or 70 mm/hour) or a shower of 70 mm in two hours. The consequences in terms of flooding for these two scenarios are available as maps through the Klimateeffectatlas [9], as is shown in the figures bellow. The source for these maps are Deltares and the Flood Risk Directive (ROR) from 2018.



(a) Storm event 70 mm in two hours



(b) Storm event 140 mm in two hours

Figure 1.3: Storm Events

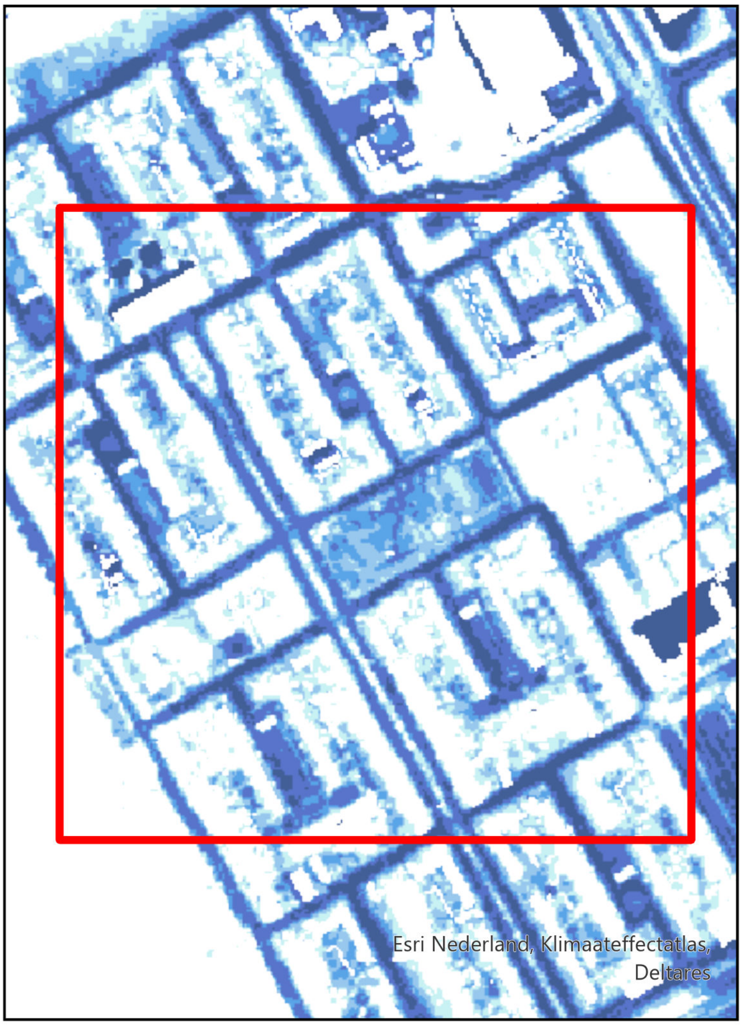
Spatial Interventions: Climate Themes

While storm events will be used to simulate climate scenarios where waterlogging and flood are the main climate challenge, other climate themes will also be included when relevant. This is because some themes are more relevant than others for different areas. Some areas might be more prone to heat stress or to flooding than the others, for example. Drought scenarios were also simulated, however, in the areas defined by the municipality of Utrecht, drought related to groundwater levels do not seem to be as relevant. This can be seem in a map on the next pages. Similar studies and maps regarding different climate themes will be done for each area, using the maps from the Klimateeffectatlas or from the geoportals of the province and the municipality of Utrecht. For heat stress, a map regarding air temperature on a heat wave from the municipality of Utrecht was used, while for biodiversity, the paved/unpaved map provided by the BARCODE (municipality of Utrecht) and a biodiversity map provided by the province of Utrech was used. For flood simulations, a map provided by the Klimateeffectatlas was used.

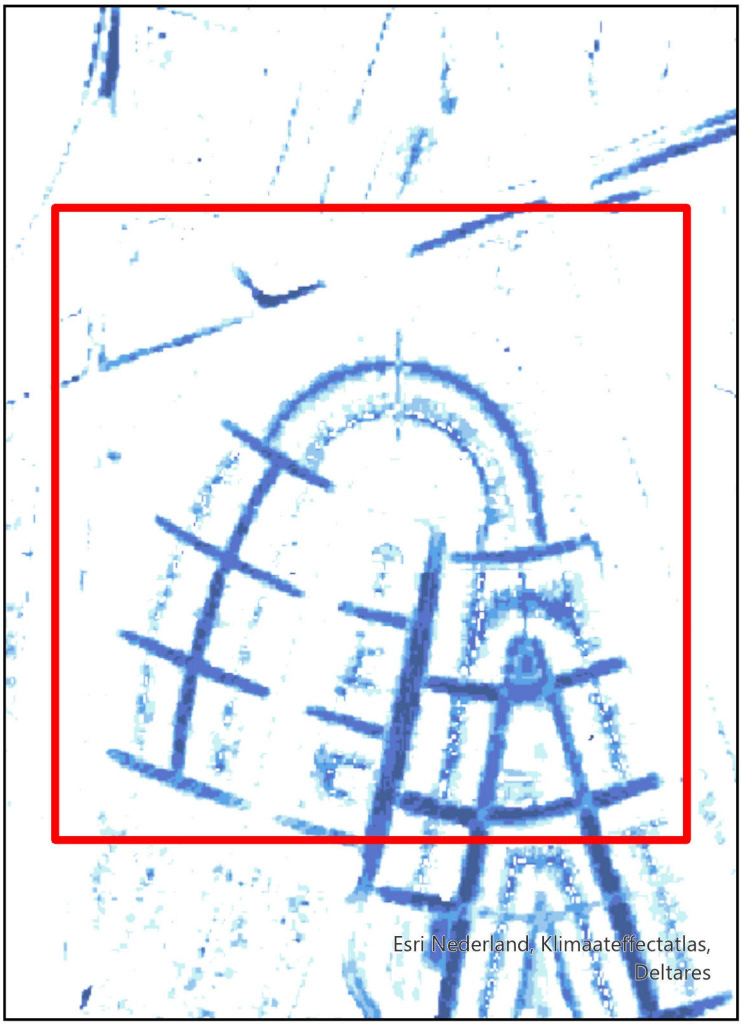
Storm Event 1/1000 years (140 mm/2 hours) - Scale: 1:6.000

Location 1: Kop Voordorp

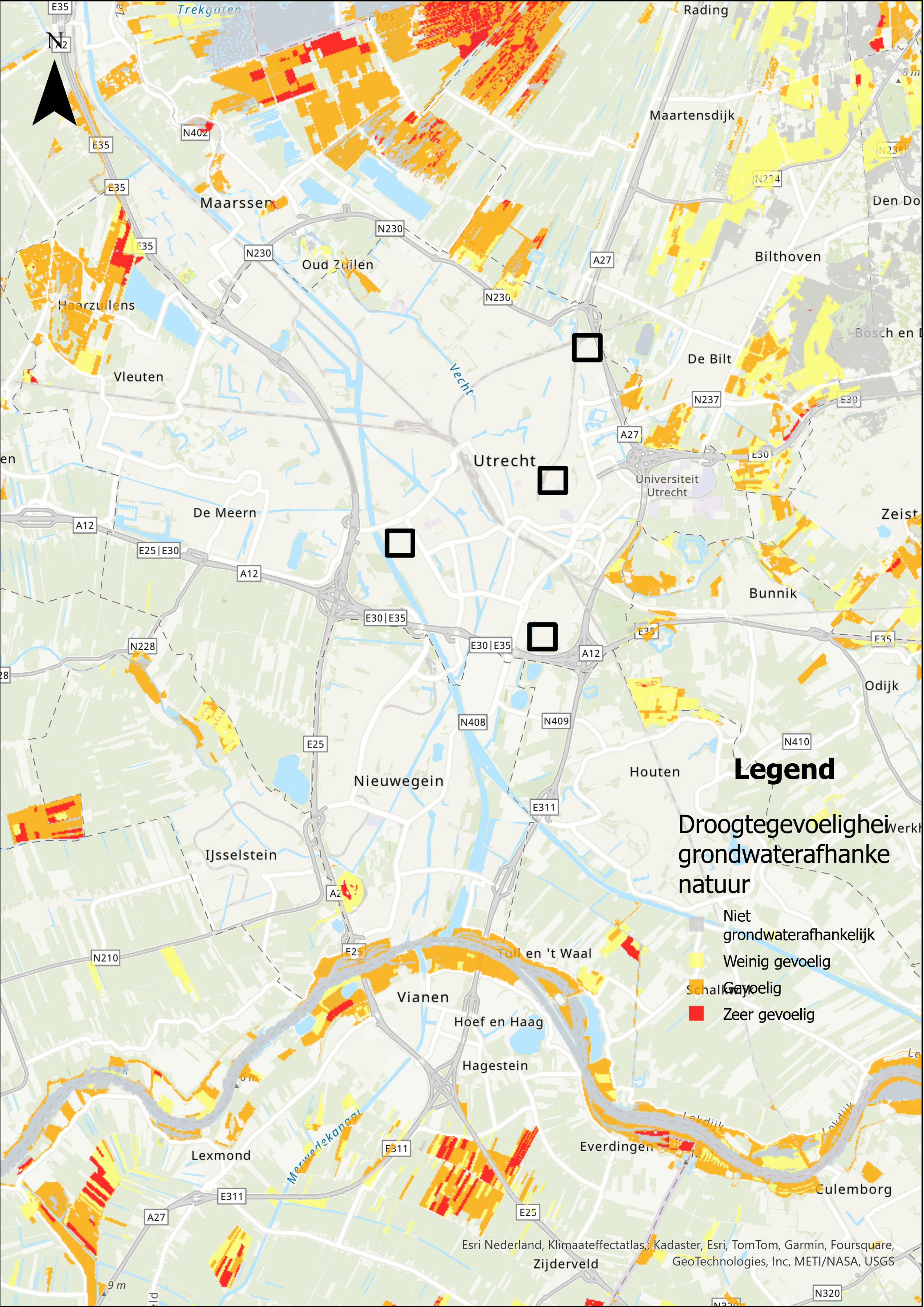
Location 2: Lunetten Zuid



Location 3: Kanaleneiland Noord



Location 4: Voordorp


N
Legend
Droogtegevoeligheid grondwaterafhankelijke natuur
Niet grondwaterafhankelijk
Weinig gevoelig
Gevoelig
Zeer gevoelig
Esri Nederland, Klimaateffectatlas, Kadaster, Esri, TomTom, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS
Rading
Maartensdijk
Maarssen
Oud Zuilen
Haarzuilens
Vleuten
Bilthoven
De Bilt
Utrecht
Universiteit Utrecht
De Meern
Zeist
Bunnik
Odijk
Houten
Nieuwegein
IJsselstein
Vianen
Tull en 't Waal
Hoef en Haag
Hagestein
Lexmond
Everdingen
Culemborg
Zijderveld
Vecht
Merwedekanaal
Trekgaten

1.2.2. Methodology Geomatics

In short, *the Geomatics aspect of this thesis is related to the technical aspect of information requirements models must fulfill to support local climate adaptation interventions.* After assessing what is available in terms of information and data models on a national, provincial, and municipal level regarding the subsurface for the city of Utrecht, the research assesses if the identified requirements are already sufficed by these models. And if they are not, guidelines are drawn on what is needed, from a technical point of view, to meet the desired information requirements. The methodology includes understanding what is necessary, in geodata terms, for an information model to be able to support local climate adaptation, as standardized by the Leidraad 2.0. guideline. The methodology consists of identifying areas of strength and weakness in the existing models for this purpose, serving as a guide for further implementations. For example, if a higher data resolution is needed to represent soil types, methods will be identified to solve this issue. One possible solution is the combination of data from other sources. For example, for top layers, other sources of data could come from the results of a cone penetration test (CPT), a method used to determine the geotechnical engineering properties of soils and delineating soil stratigraphy.

The research setup for the Geomatics side side thus consists of assessing what is available in terms of geodata vs. what is needed, identifying how to improve existing information and data models for the purpose of local climate adaptation design.

Moreover, standards are used as a quantitative measure. In the Netherlands, local climate adaptation interventions are already standardized, and their different data requirements can be drawn from existing literature, guidelines and manuals. This thesis aims to identify areas for improvement in existing information models to support these standards, filling information gaps when identified. The research thus showcase the importance of standards, in both climate adaptation design, and moreover urban design and land administration.

Standards also play an important role when it comes to disseminating knowledge regarding spatial plans.The Land Administration Domain Model (LADM) Part 5 (ISO 19152), which regards the standardization of information regarding spatial plans, defines a general schema for sharing spatial plan information in the context of the land administration. The class attributes defined by LADM Part 5 were used and slightly adapted to the context of local climate adaptation design.

In addition, the author knowledge in GIS allows the use of ArcGIS ESRI products to create information tools, such as story maps.

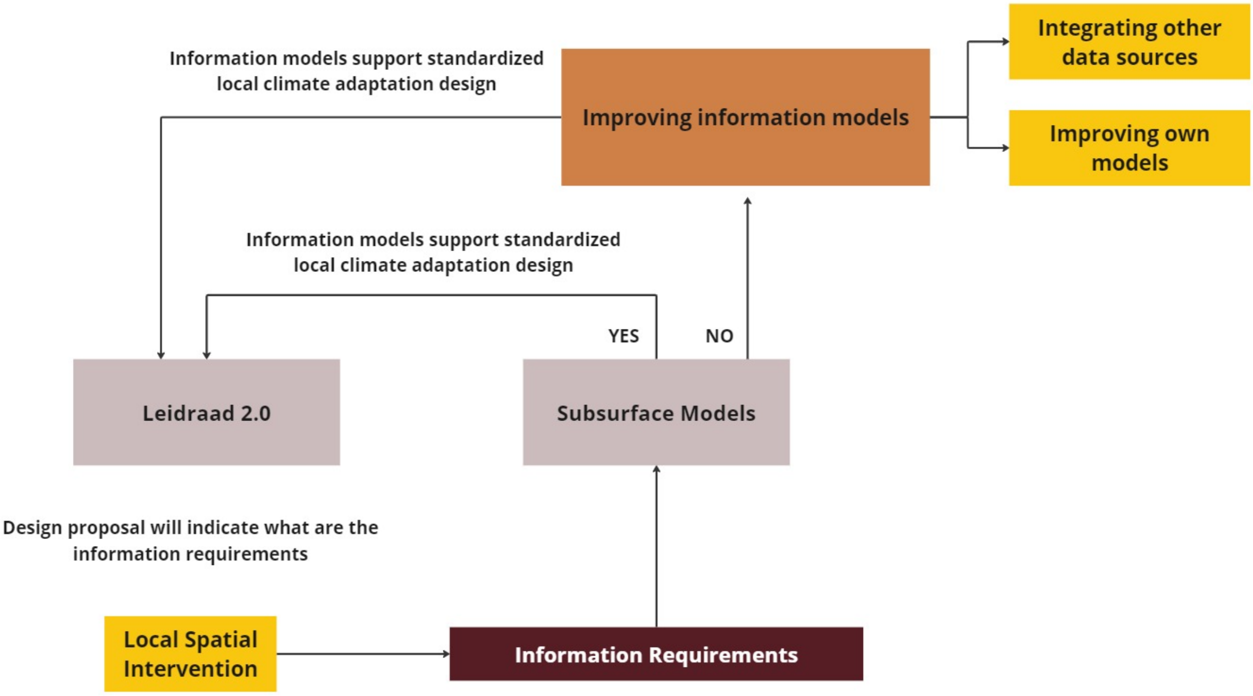


Figure 1.4: Methodology Geomatics

1.3. Thesis Structure

The main question that this research aims to answer is *How can 3D data subsurface information models support standardized local climate adaptation design?*. A general answer for this question would be: *through a common ground where local climate adaptation information requirements are met in a combined information model.*

Thus this thesis is divided into three different parts, aiming to better identified why, what and how to reach this common ground. Part I presents a literature review on **why** a common ground is needed. This first part introduces the reader to the topics of 3D subsurface models and climate adaptation design, advocating that the connection between the two, fuelled by the pressing concern of climate change in the Netherlands, can be a common ground for interdisciplinary collaboration. It includes an overview of what literature defines as the three main challenges regarding an interdisciplinary approach to climate adaptation design and 3D subsurface information model integration. These three barriers are: institutional, technological and semantic. These barriers are then compared to interviews made with urban designers and planners, identifying what are the challenges of a GIS approach to local climate adaptation design. This part also includes an overview on how climate adaptation relates to subsurface information, presenting dependencies found in existing standardized guidelines and examples of situations where the lack of this information had negative consequences.

In this part, the following subquestions are answered:

- How does climate adaptation relate to subsurface?
- What are the existing challenges for effective utilization of 3D subsurface information models in Dutch climate adaptation strategies?

Part II defines **what** is this common ground.This part presents standardized climate adaptation urban interventions, for example, a water square or rainwater pond, and how they relate to 2d or 3D subsurface data models in the Netherlands. This association is made by studying the requirements for different design interventions, such as the soil type and groundwater level, and identifying where this information can be found. To visually represent these relationships schematically, Unified Modelling Language (UML) diagrams are used.

In this part, the following subquestions are answered:

- What specific design interventions are commonly employed in Dutch climate adaptation? How do they relate to the subsurface?
- How comprehensive and accurate are the current national-level 3D subsurface data models in the Netherlands? Can we improve them?

Finally, Part III discusses **how** to reach this common ground. In this part of the thesis, the identified relationships between specific climate adaptation design interventions and existing information models are tested in practice. A virtual catalog is created with the purpose of combining existing models to the identified information needs for each one of the studied design interventions. In addition, the usability of this tool and the practical test includes a design exploration in four different existing neighbourhoods in Utrecht. The design is made using the created virtual catalog, the existing subsurface information models, and local and national guidelines. The design goal is to make these neighbourhoods adapted to the climate challenges and scenarios, by applying local standardized interventions based on the subsurface information found in the existing 3D and 2D information models.

By creating spatial interventions, the requirements identified in Part II are tested for different interventions. If Part II tests from a theoretical point of view what is the information needed for local climate adaptation to benefit from information models, Part III showcases how this would work in practice and test if the theoretical benefits exist in a practical exercise.

The design is then evaluated to confirm or refute the hypothesis of information models aiding the cause of climate adaptation in the Netherlands. In this part of the research, the models are tested for urban design and potential improvements may be drawn from this design exploration.

Utrecht is divided into four different main landscapes and soil types, which allows for the integration of subsurface models and climate adaptation design in four different scenarios. The four areas are defined by a 500 by 500 metres square where attention was paid to the similarity of other factors that could influence the design results, such as urban density, morphology and land use. In this way, the focus of the design exploration and the data models assessment is exclusively on the subsurface characteristics. The areas are located in Kop Voordorp, Lunetten Zuid, Kanaleneiland Noord, and Voordorp.

In this part, the following subquestions are answered:

- What is the data resolution or scale needed for different climate adaptation interventions? How precise do models have to be to suffice design needs?
- What is this added value of integrating information models to climate adaptation design? Can this added value be quantified?

- What methodologies be established for the integration of subsurface information models into urban design?

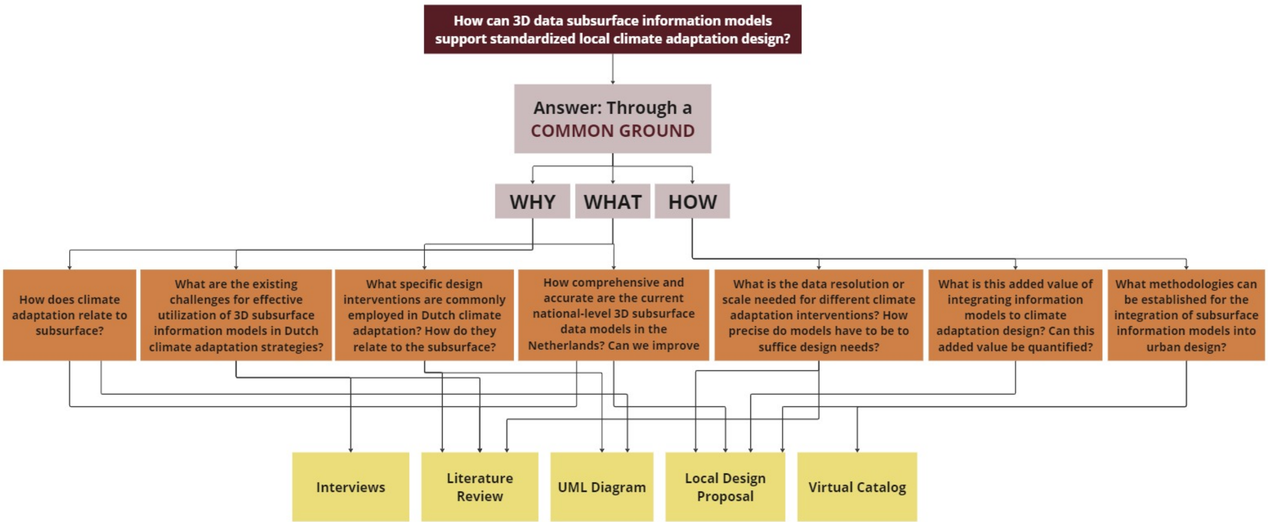


Figure 1.5: Thesis Structure

1.4. Tools and Datasets

The 3D Key Registry for the Subsurface

The thesis uses subsurface information from the Basisregistratie Ondergrond (BRO), also known as the Key Registry for the Subsurface. [10] The Key Registry for the Subsurface (BRO) is integrated into the network of key registers, which consolidates fundamental data about the Netherlands, encompassing topography, addresses, buildings, individuals, and vehicle registrations. The BRO contributes to this array of information by including data and details about the subsurface. [11] TNO is responsible for developing and managing the subsurface aspect of the Key Register.

Previously, individuals utilizing subsurface data and BRO models had to download and modify them independently to integrate them into geographic software. In collaboration with the Ministry of the Interior and Kingdom Relations, TNO, ESRI, and the Land Registry developed BRO 3D web services to simplify this process. By presenting data and models as accessible 3D web services through an API interface, they can be directly utilized in various standard 3D viewers (such as ArcGIS and CesiumJS version 1.99) and game engines (like Unity and Unreal via SDKs). Open OGC standards are employed for this purpose. [12] The web service also provides a user-friendly web interface which does not require any previous knowledge of GIS software. Through the website, users can add and remove different layers from ESRI Living Atlas in addition to 3D BRO data layers.

The four available 3D BRO data models will be used for this research. These consist of data models regarding soil, groundwater, and geotechnical characteristics of the subsurface on a national level. These models will be assessed based on their usability for urban design purposes.

Leidraad 2.0

The Leidraad 2.0 document, Dutch for Guideline 2.0, aims to provide concrete local guidelines to concepts that are often broad in design such as ’subsidence-resistant’ and ’nature-inclusive’. The document describes the application of agreements and requirements regarding climate adaptation in building and design solutions as defined in 2022 and is intended to be used by public and private project developers. The core of the Leidraad 2.0 is the process description of climate-adaptive area development. [13] These local standards are available for a selected number of regions, namely Amsterdam Metropolitan Area, Utrecht and South Holland. This document will be consulted to ensure that the design interventions are aligned with the local standards for the province of Utrecht.

Maatlat

In addition to local guidelines, designers must adhere to the national Maatlat, a concise seven-page document attached to a letter sent to the House of Representatives by several ministries regarding a ’National ruler for a green, climate-adaptive built environment’ [14]. The Maatlat outlines objectives and performance standards for issues such as flooding, drought, heat, biodiversity, subsidence, and waterlogging, but does not specify particular measures. This results in guidelines that are more generic compared to those at the local level, as they serve as the basis for local governments to develop their own tailored directives to meet the specific climate needs of their regions [15] This document will be consulted to ensure that the national guidelines are followed.

Klimateffectatlas

For an overview of what are climate-related challenges and how they are associated with subsurface information, the Klimaeffectatlas will be used. This uses the same climate themes categories as the Delta Plan. It consists of a four-theme structure: flooding, waterlogging, drought, and heat. In addition to providing a basic impression of how the changing climate may affect the Netherlands, now and in the future, the Atlas also contains context maps, such as storm events maps and maps indicating potential opportunities, which will be taken into consideration for each area.

The Klimateffectatlas is also responsible for providing the Average Highest Groundwater Level map which was used for every design area to better understand the infiltration capacities and opportunities. [16]

Utrecht BARCODE

The Utrecht BARCODE, created by the city planning department, is an integral component of the Ruimtelijke Strategie Utrecht (RSU) 2040. This tool effectively articulates and quantifies the spatial requirements of an expanding city, aligning with the 10-minute city concept to foster sustainable, equitable, and healthy urban development. The BARCODE aims for a precise and quantitative communication, while practitioners appreciate its straightforward visualization of the demands of future urban development.

The BARCODE information regarding the four selected project areas was made available by the Municipality of Utrecht for this thesis. The Municipality also helped to define the most relevant areas, using their experience with the different neighbourhoods and landscapes. This allows an overview of the programs and land use of the 500 by 500 metres area, allowing the focus of the design to be on the relationship between subsurface and climate adaptation.

Utrecht Geoportals

Other than the BARCODE provided by the municipality, the project uses different datasets regarding climate which comes from the province [17] and the municipality of Utrecht [18]. In particular the geoportal from the municipality was used multiple times regarding heat stress, through a map that indicate the air temperature during a heatwave [18]. The information regarding the suitability of the soil for consutruction (geomechanics) was based on a map from the geoportal Atlas by the province of Utrecht. [19] The underground congestion was studied using another geoportal coming from the municipality of Utrecht and open to public, namely the Utrecht 3D [20].

Part I

Why is a Common Ground Needed?

This first part of the thesis delves into the necessity of establishing a common ground, highlighting the link between subsurface information and climate adaptation design, particularly within the context of climate change challenges in the Netherlands. It offers an exploration of pertinent literature, describing dependencies outlined in design guidelines and instances where the absence of such information led to adverse outcomes.

In addition, this first part identifies three primary hurdles to the interdisciplinary integration of information models and climate adaptation urban design, namely institutional, technological, and semantic barriers. Furthermore, it juxtaposes these barriers with insights gathered from interviews with urban designers and planners, shedding light on the challenges encountered when employing GIS approaches to local climate adaptation design.

Therefore, in Part I, the following subquestions are answered:

- How does climate adaptation relate to subsurface?
- What are the existing challenges for effective utilization of 3D subsurface information models in Dutch climate adaptation strategies?

2

Climate Adaptation and the Subsurface

2.1. Nature-based Climate Adaptation and the Subsurface

The Klimateeffectatlas states that sustainable climate adaptation must take into consideration natural aspects of an area. In practice, this refers to design choices that are sensitive to natural characteristics, allowing the adaptation solutions to grow along with the changing climate. These are also called nature-based solutions [21].

Nature-based climate adaptation solutions are often dependent on water and subsurface information. For example, one way to create relieve for the main drainage system during severe rainfall is through natural local water storage. This solution benefits from low lying grassland parcels bordering the main drainage system. Thus, information regarding the main water systems, the height, and the agricultural crop type is needed. An opportunity map for this solution exists for the Ronstadt combining different data sources, TOP10NL to check which watercourses are part of the main drainage system, the Basic Registration of Crop Plots (BRP 2020) for the selection of only grassland plots that, making sure to select only those which lie within 50 metres of this main drainage system and lie lower than their immediate surroundings. For the heights, the General Elevation Map of the Netherlands (AHN3) was used [21]. The same map could be created in Utrecht, using the same sources.

Other solutions are directly related to the soil type, and therefore this specific information is interesting to be present in a subsurface model. For example, peat soil consists of organic matter and stores a lot carbon dioxide (CO_2). When this type of soil loses moisture, it rapidly decomposes, releasing CO_2 and causing soil subsidence. Keeping the soil moist helps this process, with an even more effective solution being the active extraction of CO_2 from the atmosphere through promoting the growth of marshes and wet peat soil. Retaining rainwater within the peat soil during winter also prevents dehydration during summer months [21]. However, this is only relevant when the peat soil is not covered by clay or sand and peat layer of at least 40 cm thick. This indicates that a 3D model of subsurface information would be beneficial but would have to include a level of detail that allows to identify this minimum thickness requirement.

Sandy soils on the other hand are known to be able to retain water, which is useful to relieve the water system. In particular, by storing water in regions nearer to the origin of a river or stream (upstream), it's possible to alleviate pressure on the water system downstream. Achieving this involves enhancing the natural sponge effect in the upstream area to facilitate water retention. This enhanced sponge effect will replenish the underlying groundwater and prolong the release of surface water. Consequently, this climate buffer serves to mitigate downstream flooding while also establishing a reservoir of freshwater for periods of drought. For this purpose, an opportunity map was created highlighting elevated parts of the Netherlands where groundwater is insufficiently replenished in times of precipitation surpluses. The best opportunities are found in the areas in which less than 50% of precipitation is absorbed into the soil, where the sponge effect will represent a considerable improvement because they are most likely to retain water. The map was done on a national level and one of the locations used for the spatial interventions (Voordorp) is indicated as one of one of the best opportunities areas [21].

The National Hydrological Model (LHM) was employed to calculate the proportion of groundwater recharge relative to precipitation surplus for the years 2011-2018. This involved initial determination of the long-term precipitation surplus, achieved by subtracting total evaporation from the cumulative precipitation during the specified period. Subsequently, the annual average groundwater recharge derived from the LHM was divided by the annual average precipitation surplus, with the result expressed as a percentage [21].

The enhancement of rainwater infiltration in the soil, is not only useful when supplementing the groundwater, but also for general urban rainwater infiltration, being an adaptation for waterlogging and flooding. However, not all soil types are equally suitable for rainwater infiltration and thus a location's suitability for rainwater infiltration depends on information regarding the soil and the subsoil [22].

Infiltration opportunities are related to:

- Large Infiltration capacity: A large soil infiltration capacity presents an opportunity for rainwater infiltration. This means that precipitation will quickly infiltrate into the soil. This characteristics is related to the soil type, being sandy soil the one with largest capacity.
- Large Storage Capacity: Rainwater infiltration benefits from a large soil storage capacity, which in practice means low groundwater level
- Low Slopeness: It is also benefitial for rainwater infiltration when the Earth's surface does not slope too much in the area where the rain reaches the ground
- Sufficient Subsurface Room: For rainwater to be absorbed and stored, it is necessary for the subsurface to present enough room for its storage. A congested subsurface thus would not be opportune for rainwater infiltration

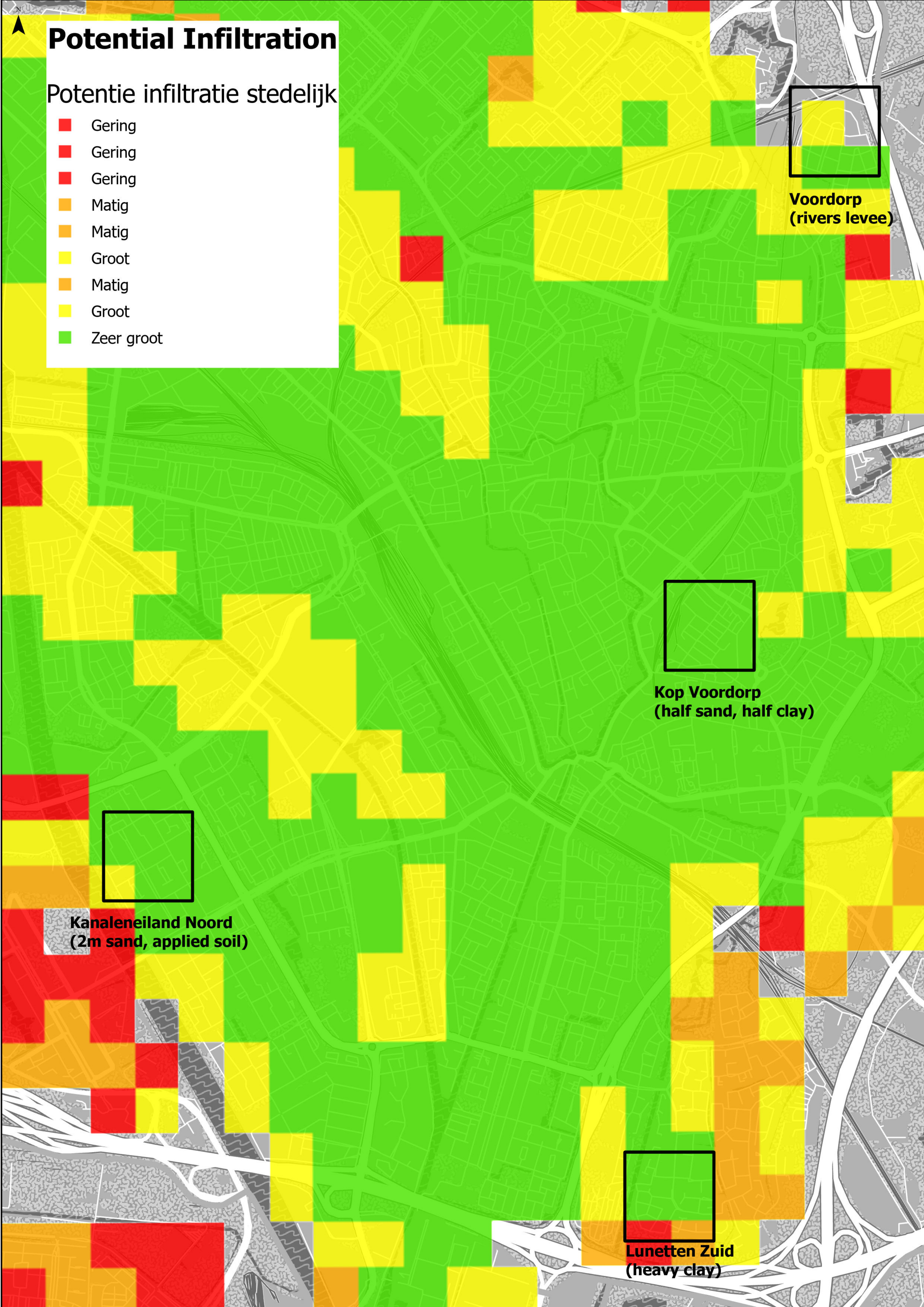
A national level opportunity map was developed, based on a combination of the location's scores in terms of infiltration capacity, storage capacity, and surface level slope. This map was created using GeoTOP and NL3D subsurface models to determine a location's infiltration capacity, the Netherlands Current Elevation Data (Actueel Hoogtebestand Nederland - AHN) for the slopeness, and the Mean Highest Groundwater Level, which was calculated using the National Hydrological Model for the storage capacity [22]. A closer look into the spatial interventions areas make it possible to identify that most of the areas, with exception of Voordorp, present great potential for infiltration. As mentioned earlier, even if Voordorp does not present a great opportunity for rainwater infiltration, at least no in the whole 500 x 500 meter area, it presents a greater opportunity for supplementing groundwater.

The table below shows how the infiltration opportunity scores have been estimated on the basis of a location's infiltration capacity, storage capacity, and slope. This scoring method was defined by Deltares.

Opportunity Score	Infiltration Capacity	Storage Capacity	Slope Level
3	Sand and gravel	Mean Highest Groundwater Level < 0.7 m below surface level	-
2	Cayey sand, sandy clay, loam, and limestone	Mean Highest Groundwater Level 0.7 m - 1 m below surface level	0% - 10% and > 10% if infiltration capacity value 3
1	Peat and clay	Mean Highest Groundwater Level > 1 m below surface level	> 10%
0	-	No Data	No Data

Table 2.1: Rainwater Infiltration Opportunity Scores

However, in urban areas there is a warning that the map could be inaccurate [22]. Thus in urban areas, at a local level, a more specific map can be developed using local data and expertise, such as a local soil map, drilling profiles, and knowledge of fill methods used. This is also necessary to check the subsurface available room, as infiltration obstructions, such as cables and pipes are often only presented at a local level [22].


Potential Infiltration
Potentie infiltratie stedelijk
Gering
Gering
Gering
Matig
Matig
Groot
Matig
Groot
Zeer groot
Voordorp
(rivers levee)
Kop Voordorp
(half sand, half clay)
Kanaleneiland Noord
(2m sand, applied soil)
Lunetten Zuid
(heavy clay)

2.2. Local Climate Adaptation Design and the Subsurface

Local climate adaptation design consist of using design interventions with the intention to adapt to a climate challenge, such as flood or heat stress. These design interventions are, most often than not, related to subsurface properties. These properties are four:

- Groundwater Level: Groundwater level indicates the infiltration capacity of a certain area, in especific the highest groundwater level. From the previous map, it is known that the average highest groundwater level should be lower than 0.7 meter below surface level for optimal infiltration opportunity [21].
- Subsurface Congestion: The presence or lack of subsurface congestion, e.g. the presence of cables, pipes and tree roots, indicate the compactness level required for an intervention.
- Soil Type: Soil type in local climate adaptation design is mainly linked to the infiltration capacity of a soil or to its suitability for building. As mentioned beforehand, sandy soil is the soil type with the largest infiltration capacity, while clay and peat limit the infiltration capacity. In addition these last two limit the weight of new buildings, being more prone to subsidence.
- Geomechanics: The geomechanics capacity indicates the weight capacity of a measured area. This property indicates to designers if the weight in the design solution must be limited or not, defining the choice of intervention or material.

The combination of these subsurface properties indicate a designer which local climate adaptations are more or less suitable to the project area. An area that suffers from flood due to rain can, for example, benefit from direct rainwater infiltration through permeable pavements. This is particularly suitable in favorable conditions, such as a sandy soil and a highest groundwater level of below 0.7 m. However, the same intervention would not be suitable for the same area if the subsurface conditions were different. For example, if instead of sand, the main soil type was clay and the average highest groundwater level was 2 m, the area would be way more suitable to artificial ways of collecting and storing water, without infiltrating the ground. Such local design solution could be, for example, a water roof, that would collect the rainwater on top of buildings. Moreover, the choice of designing a new building and the choice of materials for this building depend again on another subsurface property, geomechanics.

In short, climate adaptation local design is related to the subsurface in the way that the suitability for local design interventions depend on the four subsurface properties: groundwater level, subsurface congestion, soil type, and geomechanics.

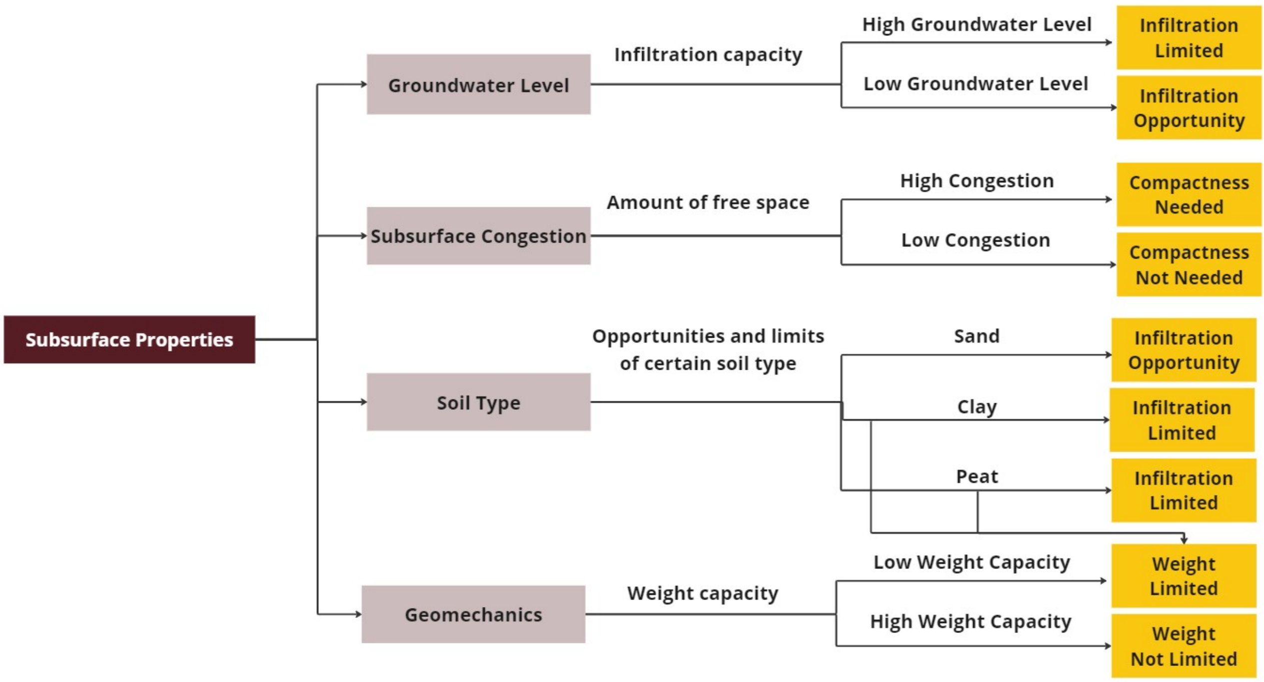


Figure 2.1: Local Design and Subsurface Decision Tree

3

Barriers for Using Subsurface Models in Urban Design

3.1. Institutional Barriers: The Need For Interdisciplinary

Heinemman once stated that ”we are born into this world as quasi-interdisciplinary creatures, and the older we get, and the more we identify knowledge packages resulting from knowledge acquisition and personal reflection, the more we tend to become disciplinary creatures” [23]. However, the literature argues that to deal with emerging complex problems, such as climate adaptation and mitigation, the integration of multiple expertise in related disciplines is needed [2] [24].

The integration of information models in climate adaptation design is thus part of the so-needed interdisciplinary approach when dealing with climate change. There are two ways to achieve this goal: through the addition of T-shaped expertise or through interactional expertise. Both solutions face institutional barriers related to the way the disciplines of Geoinformatics and Urban Design are taught in educational environments and to how GIS was introduced in urban design and planning environments.

From the literature related to T-shaped expertise: ”The horizontal aspect of the ‘T’ represents a breadth of expertise, an ability to engage with other experts across a variety of systems and intellectual and disciplinary cultures; the vertical part of the ‘T’ represents a depth of expertise in a specific knowledge domain.” [24]. In the context of this thesis, a T-shape expertise would be a professional with a deep vertical understanding of one of the two related fields, namely Geomatics and Urban Design, but able to expand this knowledge horizontally. From the experience of the author, interviews, and literature, students are still not trained to be T-expertise in these and many other fields of study. The thesis argues that this calls for changes in established curriculum that are divided by disciplinary expertise [24].

As a more broad term, ”interactional expertise” refers to learning the ”language” of another expertise without having to master all the aspects of a certain discipline [25], or the ability to interact about topics related to a certain discipline without being a practitioner [26]. In the context of this research, it would mean for example for a designer to be able to understand what he or she requests from a data model without fully understanding the informatics aspect of how the data model works. Or to be able to relate subsurface properties to different design interventions without having full knowledge of Unified Modeling Language.

However, this common ground for knowledge trade faces a barrier that is not only related to how the two disciplines are taught in universities but also to how GIS was integrated in urban design and planning departments once it became commercially available.

As an historical overview, GIS origins can be traced back to the 1960s when computers and early quantitative and computational geography concepts began to take shape. During this period, the academic community played a pivotal role in conducting significant research in the field of GIS. Under the leadership of Michael Goodchild, the National Center for Geographic Information and Analysis played a crucial role in formalizing research related to essential topics in geographic information science, such as spatial analysis and visualization [27]. In the following years, advancements in computation capacity allowed continuous improvement of GIS software tools. However, it was only twenty years later, in the early 1980s, that GIS tools became commercially available. In 1986, the Mapping Display and Analysis System (MIDAS), the first GIS desktop product, became available for the DOS operating system. Later, in 1990, it was rebranded as MapInfo for Windows when it was adapted for the Microsoft Windows platform. This transition marked the commencement of the shift of GIS from the research sector into the realm of business applications [28].

This early version of commercial GIS, when introduced into planning departments in the 1980s and early 1990s, was received with fear, hesitation and even opposition towards its use [29]. These negative reactions were not surprising as the GIS software available at the time was not intuitive and often required command-line operations. Furthermore, GIS specialists frequently found themselves in the role of technical support staff, even those with planning backgrounds, something that is still often observed in urban design offices today. The available data layers were often incomplete, and the considerable time spent on data creation and maintenance limited the capacity of GIS specialists to apply GIS for decision support in planning or design [29].

Thus, how GIS technology was introduced into design did not promote an integrated interdisciplinary approach, and only aggravated the segregation between the fields of Geoinformatics and Urban Design, and for a data model approach while designing. Even on the occasions in which there was T-shape expertise with knowledge of GIS and a background in planning, this professional assumed a monodisciplinary role. Additionally, designers and planners were not educated on data creation and maintenance, making the task of integrating these new technologies into spatial decisions very time-consuming. Currently, students and professionals face similar barriers even decades after the first introduction of GIS into design and planning, not being educated or able to assume a T-shaped expertise or interactional expertise role. In addition, with GIS technologies rapidly evolving and cities producing more and more diversified data, this institutional barrier is aggravated by technological and semantic barriers.

3.2. Technological Barriers: The Need for Data Models

In addition to an institutional barriers that divides professionals with knowledge in data models and professionals with expertise in design, data-related issues increasingly become an issue as cities move from data-poor to data-rich environments. Emerging from technological, institutional, social, and business innovations, there is a proliferation of new data sources regarding cities, significantly expanding the opportunities available to urban research. Thus there are challenges regarding innovative approaches to accessing existing data sources and new methods for linking data from various domains and owners are giving rise to interconnected data systems in addition to the traditional barriers to integrating GIS to urban planning and design found by previous research [30].

While adaptation is required, research shows that through the integration of extensive data, planners can attain a comprehensive understanding of the urban environment. A data-rich environment enables, for example, the identification of critical vulnerability zones that necessitate strategic intervention [31]. However, to fully benefit from the opportunities of a data-rich environment, this data needs to be processed and made readable to planners.

In this context, urban informatics emerges as an interdisciplinary approach to understanding, managing and designing urban systems through information and communication technology, grounded in contemporary developments of computers [32]. It remains a relatively new concept, being the term used for the first time in an article published in 2003 by Rheingold [33], and was disciplinarily grouped as a single research lab for the first time in 2011 [34]. At the time of the publication, part of this research lab focus was on real-time information to inform new design approaches and information interfaces that contributed to a low-carbon future [34].

This is just an example of a combination of geoinformatics and design to tackle a complex urban challenge by data modelling, where choices were made regarding the presentation and standardization of the collected data. The use of existing data models in combination with new forms of data, or through data-driven urban data modeling, allows urban processes and behaviours to be in a new, and arguably more time-efficient, manner [35]. In addition, the knowledge discovery aspects of data-driven models can attract the attention of citizens and decision-makers on urban problems and stimulate new hypotheses about urban phenomena, which could potentially be rigorously tested using inferential new data models [35].

The EU adaptation strategy clearly states that digital transformation is critical to achieving the Green Deal adaptation objectives. New instruments such as Destination Earth and Digital Twins hold great promise to boost our understanding of present and future climate impacts at a planetary and local scale. Ocean measurements and observation will also be further strengthened [36].

For example, a case study in New York concluded that combining different data sources regarding energy in one model was crucial for CO_2 reduction city planning [37]. In particular, the paper analyzed the status quo and tested different scenarios for a district in Brooklyn, using Web 3D data models to handle the spatial and temporal data diversity, making it possible to quantify the energy and CO_2 contributions of different urban sectors by combining data regarding electricity consumption, food related consumption and organic waste. The information provided by the data model allowed planners to identify that a cooling set point increases and lowering infiltration losses could reduce the annual cooling demand by 63%, reducing heating demand by 12% [37]. This exemplifies how data models can contribute to quantifying aspects of sustainability in urban design and lead to more well-informed solutions and realistic road maps for cities' climate mitigation.

In addition, models in three dimensions provide the advantage of offering a more user-friendly visualization, given that 3D objects closely mimic human interactions with city objects. For example, it is arguably more intuitive for a person to think of a simple building as a 3D solid instead of a rectangle. Because humans move and interact with objects in three dimensions, and because these objects are also 3D, we perceive cities as three-dimensional [38]. An extensive literature exists on the use of 3D data models for participatory design [39] [40] and to solve societal and environmental urban challenges [41] [42] [43]. However, the literature often covers only above surface urban data models.

A digital twin is often used for urban design integrating 3D data models, that is a virtual replica of a physical object, such as a building, or an entire system, such as a city. Digital twins make the physical aspects of the urban environment more apparent. This is particularly interesting for the underground, a space in the urban environment which is often not visible. This made risks and potentials in the subsurface finally emerge, adding a new dimension to the urban design task at hand.

This is particularly interesting for aspects of climate mitigation and adaptation that are directly related to the underground, such as many aspects of urban climate adaptation or mitigation and energy transition. For example, a subsurface 3D data model could indicate which surface is more adequate for water infiltration due to their soil type or indicate where to place a new sustainable energy network on a congested urban underground.

Furthermore, research suggests that a 3D spatial data model that can integrate above surface and subsurface elements will have a significant impact on engineering, spatial and urban planning, and the built environment. [44] This type of data model combines the well-studied benefits in urban planning and design of above-surface 3D elements with the often hidden information about the underground.

In the Netherlands, urban design and planning have proven benefits from 3D subsurface data models when tackling the following urban challenges: energy transition, housing crisis, and climate adaptation. [45] This is mainly because these challenges are highly related to the social and morphological characteristics of the country. The Netherlands is a densely populated country, where space is scarce, both below and above the surface. In addition, it is largely below sea level, making challenges related to climate change and sea-level rise particularly important.

To simplify the data used to solve some of these challenges, a system of basic registers has been developed in the Netherlands. This information is publicly available through the web service of the 3D Key Registry for the Subsurface. This service is however is still underused for concrete climate adaptation actions and one of the reasons for this is related to climate adaptation definitions, where often a lack of standardization poses a barrier in relating a design intervention with the best data model to be integrated to it.

3.3. Semantic Barriers: The Need for Standards

Standards are often the hidden backbone of many aspects of daily life, ensuring consistency and quality across everything from products to global systems. The International Standard Organization refers to standards as the answer to a simple question: “What’s the best way of doing this?” [46] In the context of climate change, they provide a structured approach to both adaptation and mitigation strategies. Specifically in climate adaptation, standards regulate design methods and standardize the crucial data needed for testing these strategies. However, despite progress in standardizing design and data models separately in the Netherlands, there's a missing piece: a unified framework that brings these standards together. This gap hampers our ability to effectively tackle climate change comprehensively.

From the design side of standardization in climate adaptation, there is an ongoing effort of a national standardizing design guidelines for adaptation design as a response to climate change. These guidelines emerge a structure to give substance to this term. Examples of such guidelines are the Leidraad 2.0 [13] and the Klimaateffectatlas. [47]. The first presents specific guidelines from different regions of the country, when existing, about specifications and requirements for design interventions. It also present, for each requirement, interventions that are related to that requirement. The requirements are organized based on different climate challenges, namely flooding, drought, heat stress, subsidence, biodiversity, floods and drinking water management.

The second one present the same climate challenges however it goes more in detail on how these challenges related to their surrounding, emphasizing how different adaptation design interventions depend on their location, being directly related to above and/or bellow the surface. These design interventions are often more generic than in the Leidaard, for example, the Klimaateffectatlas refer to water bodies as a design intervention while the Leidaard present different examples of water bodies such as urban waterways, urban wetlands, water squares, among others. An integration of the two documents would be therefore interesting for designers, combining the local requirements with the (sub)surface characteristics that are related to different groups of design interventions. But where to find information regarding these characteristics? Are they also standardized?

The answer is yes and no. The information is standardized in the "data" meaning of the word but it is however not yet standardized to be used for design purposes. Present information regarding the subsurface in the Netherlands is derived from borehole logs, cone penetration tests, and groundwater measuring points. The predominant source of existing data on the Dutch subsurface involves boreholes that are commonly drilled beyond 100 meters, employing lightweight drilling equipment, and occasionally, deeper boreholes using heavy drilling machinery. [10]

The Basisregistratie Ondergrond (BRO), also known as the Key Registry for the Subsurface, is designed to offer transparent and easily accessible information about the subsurface. It operates in accordance with the government's open data policy. [10]. The Key Registry for the Subsurface (BRO) is integrated into the network of key registers, which consolidates fundamental data about the Netherlands, encompassing topography, addresses, buildings, individuals, and vehicle registrations. The BRO contributes to this array of information by including data and details about the subsurface. [11] TNO is responsible for developing and managing the subsurface aspect of the Key Register.

While these models are organized and can be combined between them, there is still not an integrated system combining or relating the existing models, which contain crucial information for climate adaptation design, to the national design guidelines. This thesis aim to fill this gap and relate the different design interventions and requirements to the data models where the needed information about the subsurface can be found. The goal is to create an

”information roadmap” for designer to understand where to find the needed information and for geoinformaticians to understand what are the use cases in urban design for their models.

In addition, standardization plays a role on how the models are presented and how can users interact with them, by, for example, adding representation of their desired design intervention as a 3D layer to the model. Standards that support web services facilitate this interaction. Previously, individuals utilizing subsurface data and BRO models had to download and modify them independently to integrate them into geographic software. In collaboration with the Ministry of the Interior and Kingdom Relations, the Geological Survey of the Netherlands (TNO), ESRI, and the Land Registry developed BRO 3D web services to simplify this process. By presenting data and models as accessible 3D web services through an API interface, they can be directly utilized in various standard 3D viewers (such as ArcGIS and CesiumJS version 1.99) and game engines (like Unity and Unreal via SDKs). Open OGC standards are employed for this purpose, [12] providing a user-friendly web interface which does not require any previous knowledge of GIS software. Through the website, users can add and remove different layers from ESRI Living Atlas in addition to 3D BRO data layers. It is clear of the potential of a web service for the integration of these models in design activities.

Related literature also addresses the standardization of land administration plans, encompassing urban design plans. Standardized urban plans are essential to internationally share information regarding urban design and planning, and moreover to share the results of local climate adaptation through urban design plans. The Land Administration Domain Model (LADM) establishes a unified terminology for Land Administration (LA), providing a communal ontology. LADM Edition I introduces support for spatial units in 3D, alongside a seamless integration of 2D and 3D spatial representations [48]. The design and evolution of LADM Edition II are centered on the incorporation of rights, restrictions, and responsibilities (RRRs) related to spatial plan information and 3D representations. Specifically, Part 5 of LADM Edition II addresses spatial planning information and encompasses urban planning zoning, resulting in RRRs, while Part 6 is anticipated to focus on the implementation of LADM, developed in conjunction with the Open Geospatial Consortium (OGC) [49].

Part II

What is a Common Ground?

The previous part of this study was focused on demonstrating the relationship between climate adaptation and the subsurface. However, to make this information useful, it is necessary to understand what are these specific interventions and how do they relate to specific subsurface properties. It is a follow up question for once the need for the common ground is stated: what exactly does a common ground consists of?

To answer this question, this part presents the different definitions and guidelines used in design and policy guidelines. Thus one chapter will consist in presenting all different definitions, some of which consist of punctual local scale design interventions, while others are national level general guidelines, defining what they consist off and what are the information needs that they imply. Regarding the design interventions that are used as a basis to better understand information requirements, this thesis used a document from the Dutch government that defined the twenty most commonly employed climate adaptation design interventions in the Netherlands [3].

These standardized local interventions are then related to different other standardized definitions and guidelines and to different existing information models. This is something that to the knowledge of the author and her mentors has not been done in the Netherlands before. By relating different guidelines and standards to existing relevant information models, a way of categorizing and organizing the local interventions is created. This will be fundamental for part three, where this information is presented as a catalogue subdivided into the twenty five climate adaptation design interventions, having their information needs directly linked to an information source.

From the different information models, particular attention was paid to subsurface models due to their relevance in climate adaptation design. Thus a whole chapter focus on assessing these models for the purpose of climate adaptation design. The goal is to better understand if these models suffice the needs of design, and if not, how can these models be improved or which other models should be provided to suffice climate design needs.

Finally, to make these associations more clear, an information model was created. This model consist of an Unified Modeling Language (UML) diagram, or a general-purpose visual modeling language that is intended to provide a standard way to visualize a system [50], in this case the system consist of all the standardized information needed in local climate adaptation in the Netherlands. The intention with this methodology, was to make the different relationships and information regarding standardized climate adaptation more visible, and overall more FAIR (findable, accessibe, interoperable and reusable).

Thus, in this part, the following subquestions are answered:

- What specific design interventions are commonly employed in Dutch climate adaptation? How do they relate to the subsurface?
- How comprehensive and accurate are the current national-level 3D subsurface information models in the Netherlands? Can we improve them?

4
Standardized Climate Adaptation Information

4.1. Standardized Climate Adaptation Information Systems

Climate services encompass mechanisms for providing climate information to end-users in formats that are usable and accessible. Their objective is to aid decision-making regarding climate change adaptation, mitigation, and risk management. A diverse array of methods and products exists for interpreting, analyzing, and conveying climate data, frequently integrating various sources and types of knowledge [51].

In the Netherlands, national level climate effect data is standardized and available through a geoportal. The Klimateffectalas, or Climate Effect Atlas in Dutch, was created in 2007 in response to the need for accessible national climate information recognized by several provinces and research institutes. Since 2012, the Climate Adaptation Services (CAS) foundation has managed the Atlas. Starting from 2020, CAS has been operating under the Ministry of Infrastructure and Water Management, ensuring regular updates, expansions, and improvements to the Climate Impact Atlas [52].

The website consists of a map viewer and narratives, which are brief explanations to the main maps available on the viewer. The viewer grants access to diverse maps illustrating the potential impacts of climate change on your locality, with emphasis on waterlogging, drought, heat, flooding, and water quality. These maps are categorized into five sections: climate change, physical impacts, impacts, basic maps, and borders. Users can explore specific areas either by zooming in or utilizing the search function to locate a particular area of interest.

Other than the online viewer, user with experience in GIS softwares can integrate the data into GIS environments by accessing it through online map services in WMS format (Web Mapping Services) or by utilizing it as content on ArcGIS Online via the ArcGIS website.

The map narratives offer detailed explanations for essential maps, clarifying the depicted information and assisting users in utilizing the provided data. Often, they include suggestions for potential solution approaches. However, these solutions are often tailored to citizens and not designers, being the design related suggestions not necessarily a local design intervention.

The maps on the Klimaeffectatlas are based on national data and can be often too broad for local design. In many cases, similar maps can be found on a higher level of detail through the geoportals of local provinces or municipalities. The geoportal of the province of Utrecht, for example, contains more detailed data on heat, drough and waterlogging [17]. The municipality of Utrecht's geoportal also contain similar maps [18]. Both of these geoportals also provide a very accessible viewer and the option to download and visualize the data on GIS environment. Designers dealing with local interventions thus may benefit from the higher level of detail of maps provided by local authorities. It is however interesting how the country has a geoportal on a national level which contains data presented through a viewer of climate effect in a very accessible way.

Moreover, there has been an attempt to standardized climate information on a global level in the past two years. The Open Geospatial Consortium (OGC) has a Climate Resilience Domain Working Group (DWG) which aims to establish a collaborative platform for exchanging ideas and showcasing the integration needs, practical scenarios, trial projects, and application of OGC Standards within diverse climate-related challenges. Key efforts will encompass defining, gathering, and disseminating data needed for climate resilience, along with harnessing raw data to create meaningful visualizations and insights [53].

The Climate Resilience DWG address both technological aspects and policy matters concerning geospatial information and technology, particularly in relation to climate change mitigation and adaptation. It will also explore how these concerns can be effectively integrated into the OGC standards development process. Thus, the mission of the Climate Resilience DWG is to pinpoint interoperability hurdles within the realm of geospatial data that hinder climate-related initiatives. Subsequently, it aims to explore solutions to these obstacles by leveraging existing OGC Standards or by crafting new geospatial interoperability standards within the framework of the OGC [53].

The OGC's Climate Resilience project states that to create FAIR (findable, accessible, interoperable and reusable) data services, it is necessary to create FAIR building blocks. From the different building blocks involved in the process of making FAIR climate services, this thesis focus in two: semantic models and catalogs. A FAIR semantic model for Dutch climate adaptation design and information system is proposed in section 5.1, while a FAIR Dutch climate adaptation virtual catalog is discussed in chapter 6.

4.2. Standardized Climate Adaptation Design

In 2020, the Ministry of the Interior and Kingdom Relations initiated a study to investigate the prevalent climate adaptation measures in practice. The primary outcome of this research is summarized in a table containing an overview of twenty five climate adaptation design interventions. The table not only identifies the types of measures but also includes indicative investment costs and maintenance expenses where assessed. While primarily applicable to new construction projects, it is also relevant for existing buildings and refurbishments. Moreover, the table contains a picture of the described intervention and indicates to which themes the intervention aims to be an adaptation to. These themes are similar to ones used in the Klimateeffectatlas: drought, flooding, waterlogging, and heat, with one additional one, biodiversity.

The table also indicates, for each intervention, which soil type they are related to [3]. However, for the majority of the interventions this section is filled with ”All” or ”Not applicable”. This is true even for infiltration related measures, which from other sources, such as the Klimateffectatlas or the Leidraad 2.0, it is known that subsurface properties such as soil type and groundwater level are fundamental. This document lacks a more in depth discussion on subsurface properties for each intervention, and their respective information needs. For this reason, this study decided to use the positive aspect of having a list of the twenty five most used design climate adaptation interventions in a standardized manner, but decided to add the information needs on subsurface properties for each intervention.

For that purpose, other design guidelines can be used. The Leidraad 2.0 document, Dutch for Guideline 2.0, aims to provide concrete guidelines to concepts that are often broad in design such as ’subsidence-resistant’ and ’nature-inclusive’. The document describes the application of agreements and requirements regarding climate adaptation in building and design solutions as defined in 2022 and is intended to be used by public and private project developers. The core of the Leidraad 2.0 is the process description of climate-adaptive area development [13].

Chapter 4 on this document provides an overview of goals and requirements regarding flooding, drought, heat, subsidence, biodiversity, and flood control. These are derived from the established goals and performance criteria formulated by the Province of South Holland, the Amsterdam Metropolitan Area, and the Province of Utrecht [54].

It is interesting to notice that some of these requirements vary based on subsurface characteristic, for example the requirements for subsidence do not apply to higher sandy soils [54]. Thus, climate adaptive design interventions dealing with subsidence would benefit from a subsurface data model that could indicate soil types. Another solutions such as water storage depend on above surface characteristics but have a direct connection with the subsurface, being the water stored on the surface for expansion locations in polder areas but potentially in the subsurface in infill locations [54]. This particular case would highly benefit from a 3D subsurface data model to design where to store water.

From this document the most relevant topics to the integration of 3D subsurface data models are the solutions related to rainfall collection, such as some of those which are an adaptation to waterlogging and drought. This challenges are related to soil types and the management, ground water monitoring and underground spatial management.

The Leidraad is also available in an interactive website, the Bouwadaptief [55]. In this website, the described guidelines available for the Province of Utrecht, Amsterdam and South Holland can be selected by climate theme and by region and are usually indicated by a letter, for example the guidelines related to waterlogging start with an N, followed by a number, e.g. N2.

The website also contains a section called ”Measures” where, in a similar fashion to the table from the government made in 2020 [3], users can read the description of several climate adaptation design measures. The ones described in that document are also present in the website, with a longer description due to the different format. These descriptions usually go more in depth regarding the subsurface properties that the intervention is related to in constrt with the document from 2020. However, the second presents other informations, such as cost of construction and management, that the Bouwadaptief often does not contain.

An overview of all the twenty five interventions presented in the document from the Dutch government but containing information regarding the subsurface taken from the Leidraad, and local guidelines (for the city of Utrecht) is presented. Conclusions regarding the information requirements can be drawn from combining these different sources. The related local standards indicates to which climate theme the intervention is an adaptation for. Standards starting with B are related to biodiversity, N to waterlogging, V to flood, D to drought, and H to heat. A more visual representation of these relationships is found in the diagram in section 5.1 and a more in depth explanation, including images and examples, is found in the virtual catalog, discussed in chapter 6.

Table 4.1: Interventions Information Requirements

Name	Subsurface Model Requirements	Local Standards
Green Façade	Model of cables and pipes. Scale of a tree for root simulation. Model/map of building suitability	B1, B2, B3, H3
Façade Garden	Model of cables and pipes. Scale of a tree for root simulation, Model/map of building suitability	B1, B2, B3, H3, N1
Green Garden	Model of cables and pipes. Scale of a tree for root simulation, Model/map of building suitability	B1, B2, B3, H2, H3, N1, D1
Green Roof	Model/map of building suitability	B1, B2, B3, N1
Green Fence	Model of cables and pipes. Scale of a tree for root simulation, Model/map of building suitability	B1, B2, H3
Tree Planting	Model of cables and pipes. Scale of a tree for root simulation. Model of the soil type with enough resolution of tree root scale.	B1, B2, B3, H1, H2
Animal Boxes	Not applicable	B3
Rain Barrel	Model of cables and pipes. Model of the soil type. Model of groundwater level. The infiltration layers must be in high resolution.	N1, N2, N3, D1, D2
Lowered Verge	Not applicable	N1, V1
Light Color	Not applicable	H3, H4
Blinds	Not applicable	H4
Permeable Pavement	Model of cables and pipes. Model of the soil type. Model of groundwater level. The infiltration layers must be in high resolution.	N1, D1
Cool Places	Model of cables and pipes. Scale of a tree for root simulation.	H1, H2
Shadow Routes	Model of cables and pipes. Scale of a tree for root simulation.	H1, H2
Natural Playground	Model of cables and pipes. Model of the soil type. The infiltration layers must be in high resolution.	B1, B2, B3, N1, D1
Wadis	Model of the soil type. Model of groundwater level. The groundwater system should be clear.	B1, B2, B3, N1, N2, N3, D1, D2
Surface Water	Model of cables and pipes. Model of groundwater level. The groundwater system should be clear.	B3, N1, N2, N3
Infiltration Crates	Model of cables and pipes. Model of the soil type. Model of groundwater level. Resolution compatible with crate size.	N1, N2, N3, D1, D2
Building Water Storage	Model of cables and pipes. Model of groundwater level. Resolution compatible with project size and depth.	N1, N2
Water Square	Model of cables and pipes. Resolution compatible with storage size.	N1, N2, V1
Rural Waterways	Model of groundwater level. The groundwater system should be clear.	None
Water Roof	Not applicable	N1, N2
Ground Elevation	Model of the soil type. Model of geomechanics. Lower resolution models allowed (high scale project).	V1, V2, V3, V4
Soil Improvement	Model of the soil type. Model of geomechanics. Lower resolution models allowed (high scale project).	B3, N1, N2, N3, D1, D2
Pavement Water Storage	Model of cables and pipes. Resolution compatible with project area size and depth.	N1, N2

Other than local guidelines, designer must follow a national guideline, the Maatlat. The Maatlat, ruler in Dutch, is a seven page document which was annexed to a letter from the Ministries of the Interior and Kingdom Relations, Infrastructure and Water Management and Agriculture, Nature and Food Quality which was sent to the House of Representatives regarding the 'National ruler for a green, climate-adaptive built environment' with the underlying building blocks report [14]. With this letter, the ministers informed the House of Representatives about the results of the research into a national green standard, which can be summarized into the seven page document which is often referred to as Maatlat [15].

The Maatlat outlines objectives and performance standards, offering guidance on topics such as flooding, drought, heat, biodiversity, subsidence, and waterlogging. The same climate themes as the previous documents. It does not indicate particular measures, meaning that the guidelines often seem to be more generic compared to the local ones by the provinces. This is because these guidelines are suppose to be the basis on which local governments would build their own local guidelines, tailored to the specific climate needs of their regions.

4.2.1. Data Resolution Requirements for Climate Adaptation Design

The twenty-five local climate adaptation design interventions mentioned previously vary largely on information requirements, but also on the resolution in which this information must be delivered. To better understand these requirements, a catalog was created. In the catalog, each one of the twenty interventions is represented in an individual sheet. The five out of the twenty five which are not in catalog were not considered because they are not related to subsurface properties, for example insect boxes or blinds. On the top of the sheet there is the title of the intervention, along with a technical drawing on the scale the intervention is usually represented, and a picture exemplifying the intervention.

The subsurface information requirements are then represented in a graph indicating with colors how sensitive the intervention is to data accuracy and resolution, being red an intervention that is highly sensitive, orange not necessarily dependent, and white not sensitive or not related to the information category.

A Python script was created to generate the information requirement bar for each intervention. In this script there were three possible values for each one of the four subsurface properties (soil type, geomechanics, subsurface congestion and groundwater level). If Bouwadaptatief or other relevant sources, such as product manuals or design guidelines, would explicit indicate that an intervention was sensitive to a property, for example soil improvement methods are explicitly related to the soil type, this value will be defined as 100. If the information was relevant but not necessary, for example solutions that include natural water infiltration would benefit from subsurface congestion but if this data is not accurate or present, infiltration can still be done. This is not the case for solutions related to artificial water storage for example, that requires not only space for the infiltration at the time of the rainfall but also physical space for the water to be stored. Therefore in the case where data was relevant but not the intervention would not particularly suffer from the lack of it, the value was defined as 50. Finally, if all relevant sources did not indicate a necessity for a certain subsurface property, the value of this property was defined as 0. The Python script is included as an annex in the end of this thesis. The result is a matrix containing the need for subsurface properties for all the twenty relevant interventions.

Once the information requirements were described for each relevant subsurface property, the technical drawing and dimensions of the intervention were considered to defined the resolution requirements. In general, five classes can be identified:

- Trees: Interventions containing the addition of trees used the average root size of a tree to define resolution requirements. As a rule of thumb, tree roots usually reach the first 0.5 to 2 meter depth and spread widely in a radius that is half of its height. This dimensions should be used as resolution requirement.
- Element unit: Intervention that could be subdivided into units, such as infiltration crates or water storage solutions, the dimension of that unit was taken into consideration. These were more often than not in cubic shape, having a dimension of around 50 cm in each direction.
- Natural Infiltration: Interventions related to natural infiltation have a particular information interest in the shallow subsurface (first 50 cm) and therefore this measure can be used as vertical resolution requirement.
- Waterways: Canals, wadis, and other waterways usually have a standardized depth and width. These values are usually around 50 to 200 cm. These values were used to define resolution requirements.

- Enclosed spaces: Intervention that consisted of a new space enclosed by ”walls”, such as water storage spaces underneath buildings or a water square, had their resolution requirements based on the resolution requirements for interventions of similar size in the surface, such as a normal square or a parking lot.

The complete catalog with the resolution requirements for each intervention can be found as an appendix at the end of this thesis.

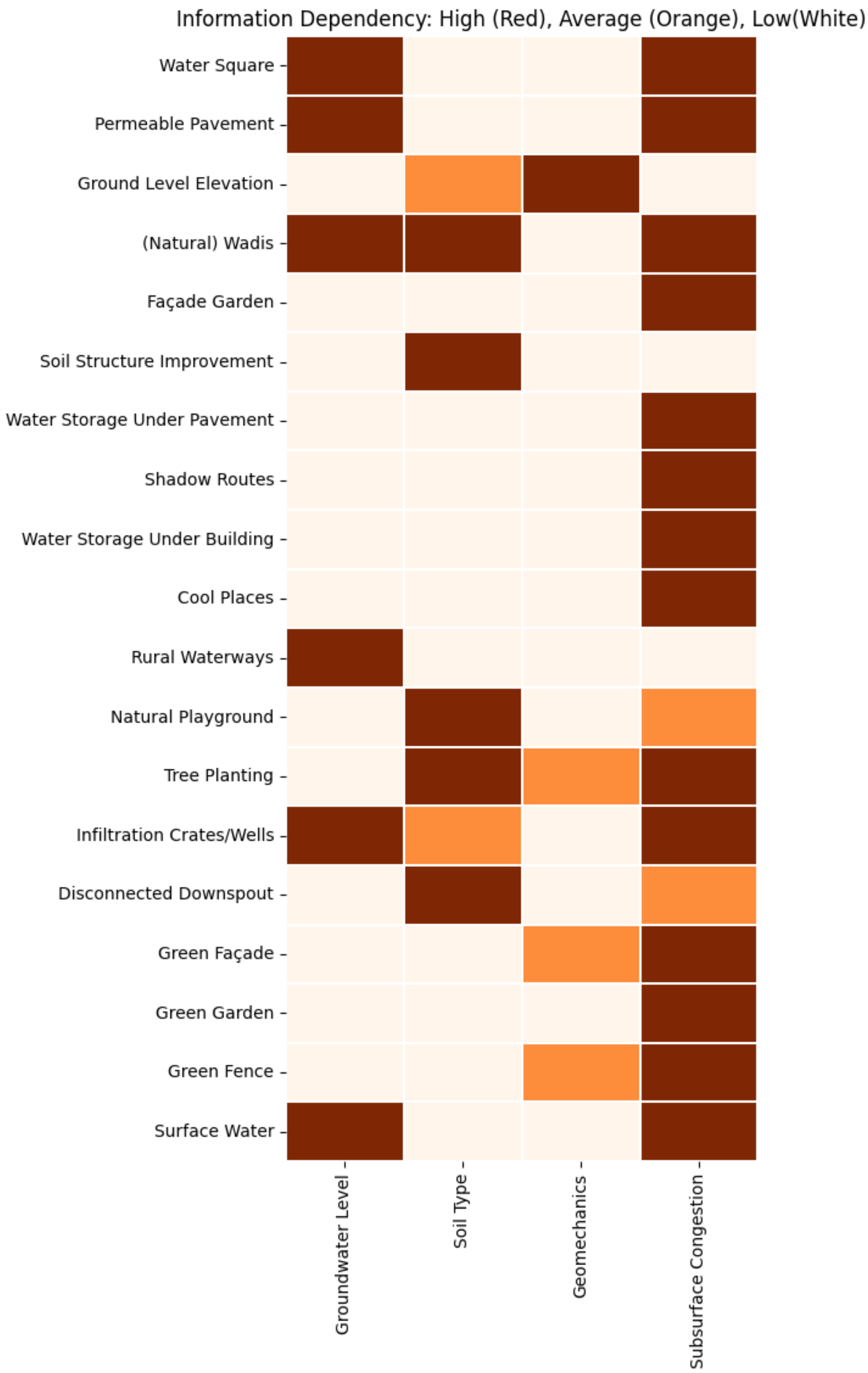


Figure 4.1: Matrix containing information requirements

4.3. Standardized Planning Information Models

The collection of urban design interventions can be indicated in a plan and shared with different entities. For this to happen, it is necessary that the urban planning information is standardized. Standardized urban plans can be shared internationally, increasing the knowledge regarding different urban design and planning approaches, and, in this case, the knowledge on local climate adaptation approaches.

The Land Administration Domain Model (LADM) establishes a unified vocabulary for Land Administration (LA), offering a shared ontology. Edition I encompasses support for spatial units in 3D, along with a smooth fusion of 2D and 3D spatial representations [48].

The design and development of LADM Edition II is based on the inclusion of rights, restrictions and responsibilities (RRRs) concerning, among others, spatial plan information and 3D representations. In particular, Part 5 of LADM Edition II deals with spatial planning information and includes urban planning zoning, resulting in RRRs, while Part 6 is planned to be about implementation of the LADM developed in collaboration with the Open Geospatial Consortium (OGC) [49].

The LADM standard defines the “process of determining, recording and disseminating information about the relation between people and land” where land is defined, im the LADM Edition II, as the “spatial extent to be covered by rights, restrictions and responsibilities and encompass the wet and dry parts of the Earth surface, including all space above and below” [49].

Several workshops were organized for the revision LADM Edition. From these, the main outcome was the interest of the LADM community in the integration of spatial plan information within the LADM and the provision of LA in 3D (below, on and above the surface) on land as well as at sea. This interest is clearly linked to the topics discussed on this thesis, as it defends that the standardization of 3D subsurface data models are crucial for interdisciplinary climate adaptation design.

From the identified requirements, the Requirement 5-2 ‘Plan Information Dissemination’ is defined as ”Spatial plan information systems using this part of LADM shall allow open dissemination and clear visualization (2D/3D) plan information.

In addition, in the first edition of the LADM, the term ‘land administration’ refers to geographical areas encompassing water, land, and elements both above and below the earth’s surface. In response to the Standards Council of Canada’s input, a broader term, ‘georegulation,’ is introduced. Georegulation is defined as the “activity involving the delimitation and enforcement of control over geographical spaces through regulatory measures.” [49].

Extensive utilization of land vertically has led to intricate legal connections among diverse spatial units like land, marine, air, underground parcels, and infrastructure objects. Consequently, employing 3D models becomes essential not just to vividly depict real estate and its related rights but also to illustrate 3D representations of limitations and obligations. These stem from both private and public law, emphasizing the necessity for clear representation [49].

The Spatial plan information package [56] utilizes fundamental LADM classes from the party package and administrative package to depict the involved parties in spatial planning procedures. This package models these parties, engaged in incorporating legal aspects (RRRs) in spatial planning, utilizing Party package classes from Part 2.

The use of a standard tailored for sharing urban planning information could facilitate the international sharing of plans that contain climate adaptation interventions, aiding the creation and sharing of FAIR climate adaptation information systems. For the purpose of this thesis, subclasses were created based on the existing classes and properties contained in Land Administration Part 5. The new subclasses thus inherit all the attributes from the existing classes but have additional new attributes tailored for climate adaptation design.

All classes and subclasses respect the first requirement, which is to comply with part 5 of ISO 19152 LADM. They are based on the LADM core, which includes Party, RRR, BAUnit, SpatialUnit, 2D/3D representations (from ISO 19107), and VersionedObject, all derived from source documents.

In addition, spatial plan information systems using this standard must enable open dissemination and clear visualization of plan information in both 2D and 3D formats (requirement two) and support participatory plan monitoring to identify challenges and assess alternative intervention scenarios, aiding in the achievement of SDGs (requirement three). While this is out of the scope of this thesis, the fact that the subclasses and build on top of classes that are proven to respect all these three requirements, it is possible to assume that the subclasses respect these requirements as well.

The basic classes of the LADM Spatial Planning package are plan groups, plan blocks, plan units and plan permits. The following subsections will describe these classes and explain how the climate adaptation subclasses were created using existing attributes and adding new relevant ones.

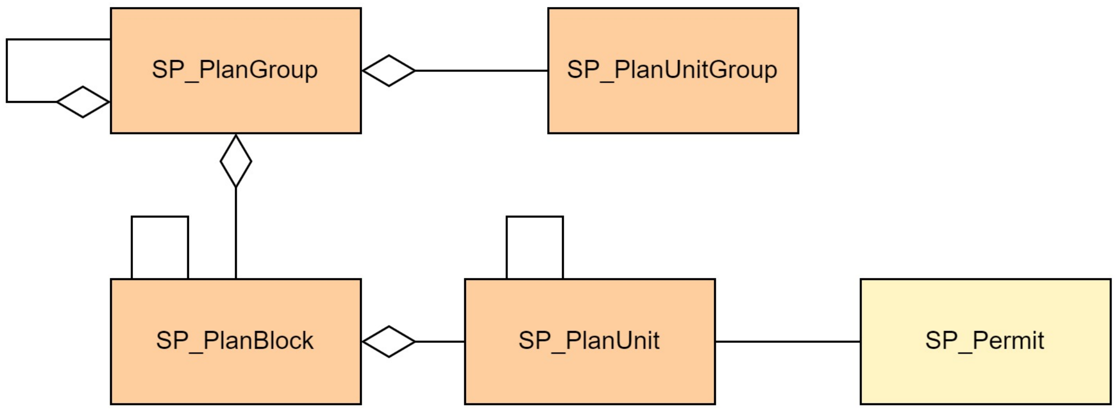


Figure 4.2: Basic classes of the Spatial Planning (SP) Package

4.3.1. LADM Plan Group and CLIMA_PlanGroup

A plan group is an administrative hierarchy within the Land Administration Domain Model (LADM) that organizes spatial plans. In this structure, more detailed lower-level plans are integrated to align with the broader intentions of less detailed higher-level plans. For example, a masterplan of a region has a higher hierarchy than a local plan for a neighborhood. The second "follows" the masterplan. For climate adaptation design, this class is useful to include hierarchy between different plans and aspects of planning.

This follows requirement six, which states that spatial plan information must support planning hierarchy (from national to local) via hierarchical plan groups.

The attributes of the SP_Plangroup are: the identifier of a plan group (pgID), the level of hierarchy the plan group has (hierarchyLevel), the name of hierarchy in spatial planning (label), and a reference of geometry point (referencePoint).

The subclass CLIMA_Plangroup contains all the attributes of the class SP_Plangroup but adds attributes aiming to inform who is the responsible for a certain plan group (responsible) and the source to the plan group (source).

4.3.2. LADM Plan Block and CLIMA_PlanBlock

An instance of the SP_PlanGroup class represents a group of spatial planning blocks. Thus a plan block is another basic class of the Spatial Planning Package (SP). Each spatial planning block group is associated with exactly one instance of SP_PlanGroup.

The class SP_PlanBlock contains the many attributes relevant to climate adaptation design such as an identifier (pbID), a label (blockName), a type of planned function (functionType), a type of protected zone (protectedSite), a type of natural risk and safety area (naturalRiskSafetyArea), including risk for flood and storm. All these, and others, are useful and relevant for plans that include climate adaptation design. These attributes indicate, for example, the current and future planning use and natural risks of a neighborhood or specific design area.

However, for climate adaptation design new attributes are relevant. These allow the storage of information regarding the most relevant climate themes, soil type, subsurface congestion, groundwater level and geomechanics. Most of those are related to a code list with options previously discussed in this thesis, such as the five main climate themes and the three main soil types.

4.3.3. LADM Plan Unit and CLIMA_PlanUnit

According to requirement four, a spatial plan compliant with LADM Part 5 must organize plan units in plan blocks. A plan unit is the smallest planning unit from all the basic classes.

The SP_PlanUnit is thus used to represent homogenous smallest areas and spaces of a plan. In the case of local climate adaptation design, this refers to the specific climate adaptation intervention selected for an area. This intervention is part of a neighborhood or other local plan (CLIMA_PlanBlock) that refers to a bigger national, regional or municipal plan, following a hierarchy (CLIMA_PlanGroup).

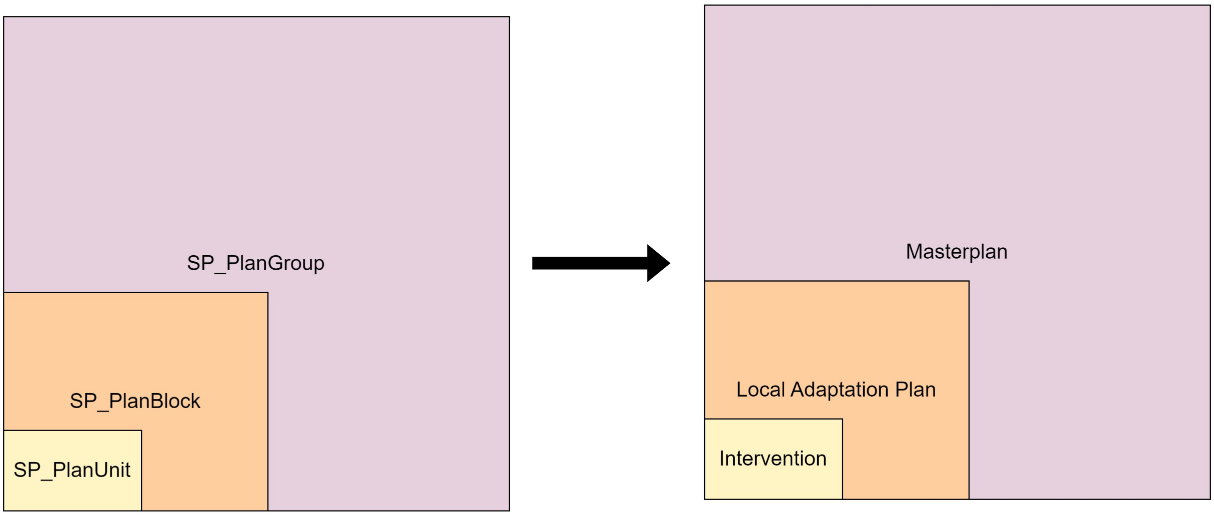


Figure 4.3: An intervention is part of a local adaptation plan and follows a masterplan

The basic class SP_PlanUnit contains many intersting attributes for local design, such as an identifier (puID), the description of the type of plan unit (subFunctionType, subFunctionName), the current and maximum volume, area and height, the status of an area, i.e. if the area is in use of not (statusType), and the relationship with the surface, i.e. if the intervention is above, bellow or mixed in the surface (surfaceRelation).

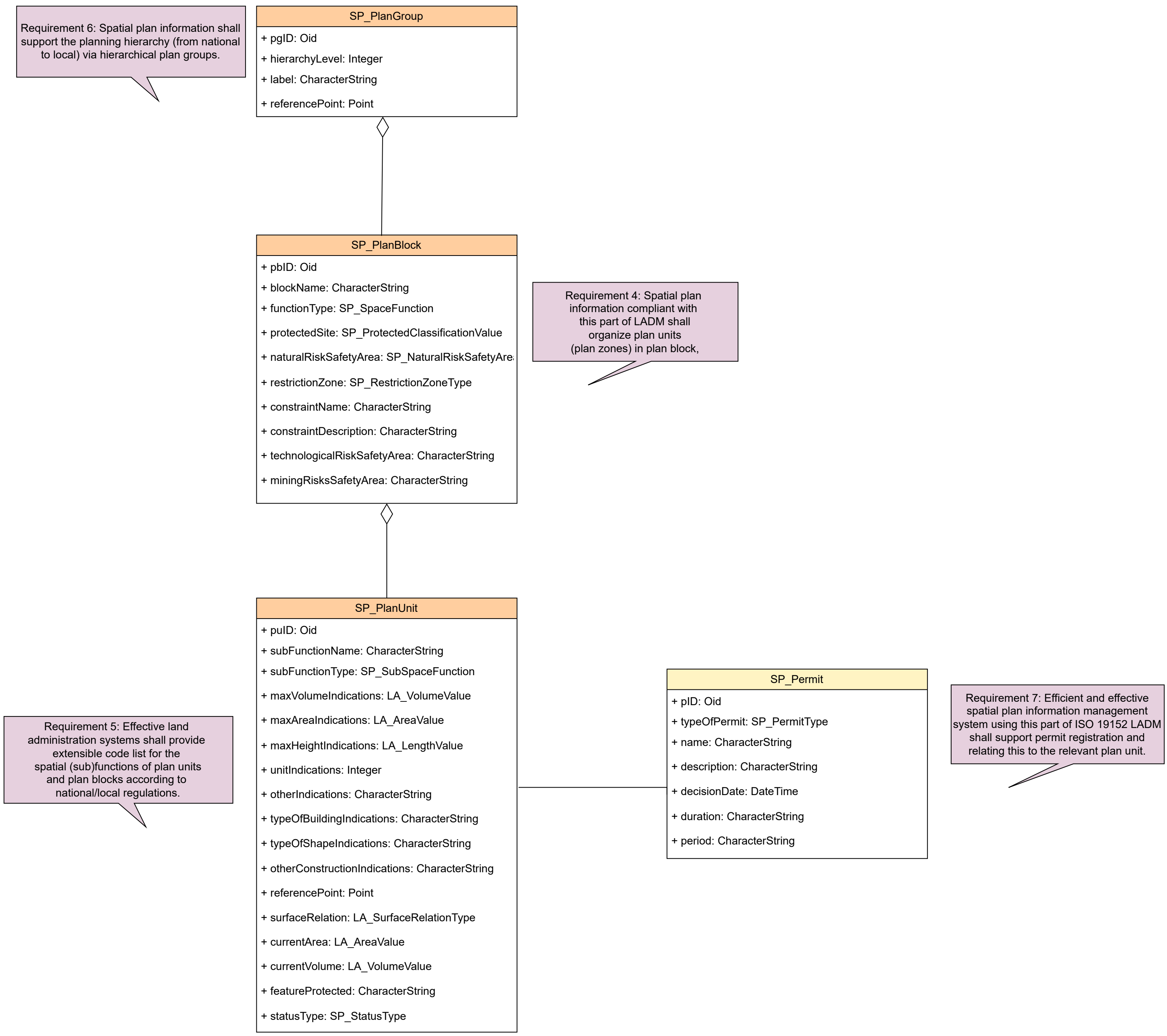
For the purpose of local climate adaptation, new attributes were added to the existing ones. These are the subsurface requirements needed for an intervention (subInfoRequirements), the depth needed underground in mm (depthUndergroundMm), the resoultion requirements, and the relevant national and local guidelines. For the attribute subInfoRequirements, a code list is provided with the identified main relevant subsurface properties, namely soil type, groundwater level, subsurface congestion and geomechanics.

4.3.4. LADM Permit Registration

According to requirement seven, a planning information management system using LADM Part 5 should support permit registration and relating this type of information to a plan unit.

The class SP_Permit contains permit related information to be associated with zero or more plan units. This aspect is not as relevant for the purpose of this study because the thesis includes design exploration examples rather than existing plans with permits. However, being one of the basic classes from the Spatial Planning package, it is important to mention the existence of this class and that, in a scenario with real plans, this class would have aided the inclusion of permit related information into climate adaptation design.

LADM Part 5


Requirement 6: Spatial plan information shall support the planning hierarchy (from national to local) via hierarchical plan groups.
SP_PlanGroup
+ pgID: Oid
+ hierarchyLevel: Integer
+ label: CharacterString
+ referencePoint: Point
SP_PlanBlock
+ pbID: Oid
+ blockName: CharacterString
+ functionType: SP_SpaceFunction
+ protectedSite: SP_ProtectedClassificationValue
+ naturalRiskSafetyArea: SP_NaturalRiskSafetyAre
+ restrictionZone: SP_RestrictionZoneType
+ constraintName: CharacterString
+ constraintDescription: CharacterString
+ technologicalRiskSafetyArea: CharacterString
+ miningRisksSafetyArea: CharacterString
Requirement 4: Spatial plan information compliant with this part of LADM shall organize plan units (plan zones) in plan block,
SP_PlanUnit
+ puID: Oid
+ subFunctionName: CharacterString
+ subFunctionType: SP_SubSpaceFunction
+ maxVolumeIndications: LA_VolumeValue
+ maxAreaIndications: LA_AreaValue
+ maxHeightIndications: LA_LengthValue
+ unitIndications: Integer
+ otherIndications: CharacterString
+ typeOfBuildingIndications: CharacterString
+ typeOfShapeIndications: CharacterString
+ otherConstructionIndications: CharacterString
+ referencePoint: Point
+ surfaceRelation: LA_SurfaceRelationType
+ currentArea: LA_AreaValue
+ currentVolume: LA_VolumeValue
+ featureProtected: CharacterString
+ statusType: SP_StatusType
Requirement 5: Effective land administration systems shall provide extensible code list for the spatial (sub)functions of plan units and plan blocks according to national/local regulations.
SP_Permit
+ pID: Oid
+ typeOfPermit: SP_PermitType
+ name: CharacterString
+ description: CharacterString
+ decisionDate: DateTime
+ duration: CharacterString
+ period: CharacterString
Requirement 7: Efficient and effective spatial plan information management system using this part of ISO 19152 LADM shall support permit registration and relating this to the relevant plan unit.

Adaptation LADM Part 5 to Climate Adaptation

4.4. Standardized Subsurface Models

There are multiple standardized 3D data models for above surface in the Netherlands, including models with trees, buildings, and realistic city elements. However when it comes to subsurface 3D data models, this number is reduced. These chapter discusses the existing, to the author's knowledge, standardized information models for each subsurface property that was identified as relevant to climate adaptation design.

4.4.1. Soil Type Information Models

The different soil types can be visualized in the Key Register 3D webservice (3D BRO) [12]. From the four different information models present in the 3D Key Register GeoTOP, REGIS II, Geotechnical CPT investigation and Ground water, the most relevant one to identify the soil type of a design area is GeoTOP.

GeoTOP is a three-dimensional model representing the subsurface up to a depth of 50 meters below NAP, depicted in blocks (voxels) measuring 100 x 100 x 0.5 meters. This model offers insights into the layer composition and soil types (such as sand, gravel, clay, or peat) within the shallow subsurface of the Netherlands. Regarding its coverage, in spring 2020, the model's coverage expanded to encompass North Brabant, North Limburg, and Central Limburg. By spring 2023, updates were made for Zeeland and Goeree-Overflakkee, with the addition of Almere in fall 2023. Incrementally, efforts are underway to extend the model's coverage nationwide, including the inclusion of the IJsselmeer, the Wadden Sea, and other inland water bodies. However, the subsurface of the Dutch Continental Shelf is not part of the GeoTOP model [57].

It is important to notice that information models regarding soil type are always based on a probability because it is an interpolation of different punctual collection of data regarding the soil. The highest probability is what is showed in the information model, however when there is a design or planning intervention it is usually necessary to locally confirm the soil type. The percentage number of probability for a represented soil type is shown in the information model in the case of GeoTOP. For example, a layer may indicate a sandy soil type, but when clicking on it, the user can see that the probability of that layer to be sand is actually 85%.

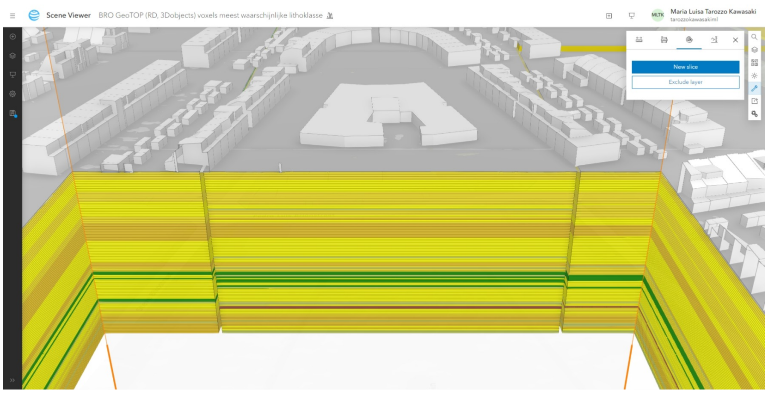


Figure 4.4: GeoTOP model visualization using 3D BRO webservice

GeoTOP proves valuable in scenarios where the shallow subsurface is a determining factor. This includes applications in the preliminary stages of infrastructure projects, groundwater research, prediction of subsidence caused by peat oxidation, assessment of foundation depth, evaluation of dike failure risks, and calculation of surface mineral volumes such as clay, sand, and gravel [57]. This is also the case for many interventions related to waterlogging and drought adaptation, that are related to the infiltration of rainfall in the shallow subsurface.

However, due to the significant size of the voxels, GEOTOP is perfect for national and municipal design use, while some smaller interventions could require a smaller voxel resolution. In the design exploration, the information from the 3D GeoTOP model was used as an indication of the most probable soil type due to its vicinity with other similar voxels with the same properties. In a practice, GeoTOP may require additional information. As the website awarns: ”Without additional data, GeoTOP is not suitable for local applications, for example at street or building level. Before use, it is advisable to consult an expert when interpreting the model, such as a hydrologist, geologist or geotechnical engineer.” [57] Time and costs constrains did not allow for this additional information to be added to the project.

GeoTOP is available through the 3D BRO webservices [58]. Through this website, users can visualized the voxels from a selected location and interpretate it using a provided legend. In the same website, users can also create sections, rotate and move the model.

Thus, GeoTOP is an information model that successfully represents soil type information in 3D. The model is currently proved to be suitable for climate adaptation design on a national and municipal level but the suitability for local design is tested in the design exploration part of this thesis.

4.4.2. Subsurface Congestion Information Models

The city of Utrecht is represented in a 3D model through a digital twin model of not only its above-surface elements, namely buildings and trees, but also subsurface elements, in this case the city’s main cables and pipes. Thus, information regarding subsurface congestion, necessary for some interventions regarding local climate adaptation design, can be visualized in the 3D webviewer provided by the municipality [20]. The information presented in this viewer is sufficient for local design.

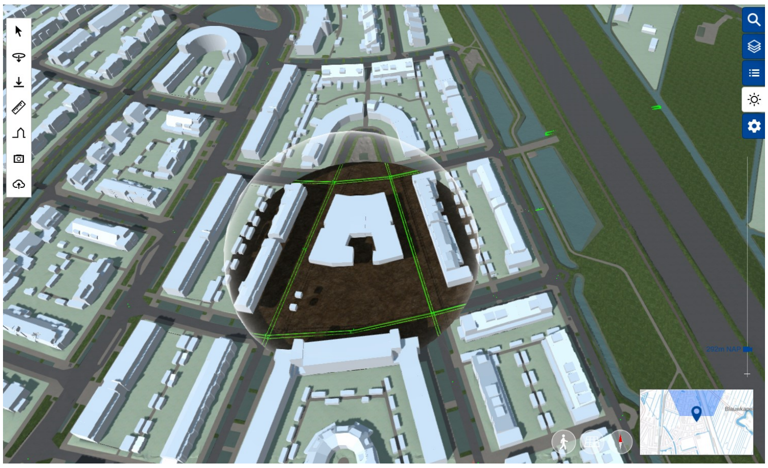


Figure 4.5: Subsurface congestion visualized using 3D Utrecht webservice

4.4.3. Geomechanics Information Models

Gomechanics is defined as the subsurface property related to the mecahnics of the ground, i.e. its capacity to handle weight and pressure. This indicates the suitability of a subsurface for construction. Understanding the suitability of subsoil for construction is crucial for implementing local climate adaptation interventions. One significant aspect to consider is weight constraints, as they directly impact the choice of construction methods and materials. In the province of Utrecht, this map illustrates the suitability of subsoil for traditional construction, which typically involves structures made of stone or concrete with foundations on steel or piles, and infrastructure without pile foundations. The mapping process takes into account factors such as settlement sensitivity and minimum foundation depth. In regions like western peat bogs, where thick clay and peat layers increase settlement susceptibility, the foundation depth map provides additional spatial insights. While the legend offers a relative scale, defining 'suitability' lacks universally quantified classes due to the variability of construction methods. However, assuming a fixed construction method could enable such quantification on a broader scale. It's worth noting that data for the municipality of Vijfheerenlanden, incorporated into Utrecht since January 1, 2019, is not yet available [19].

This map can be found through Atlas, a geoportal of the province of Utrecht that consists of a webviewer, where users can select different available layers and select its opacity. The map is on a provincial level and can be used for municipal design applications but it is only indicative for local design and information from other sources, such as CPTs, or from a expert, need to be added to it.

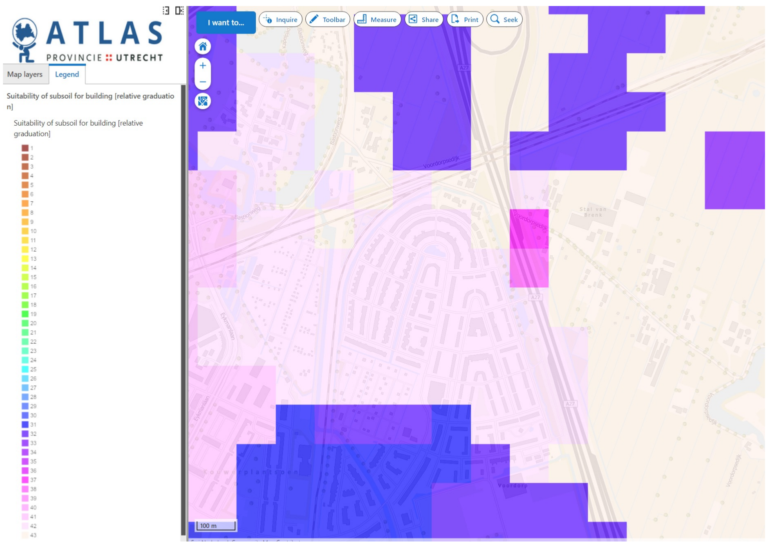


Figure 4.6: Building suitability visualized using Atlas webservice

In geotechnical CPT investigations, the resistance encountered by the cone (located at the tip of the CPT rod) during descent is measured. A graphical representation of this journey, known as the CPT profile, illustrates the force needed to penetrate various soil layers. Typically, less force is required to penetrate clay or peat (indicating low cone resistance) compared to sand (indicating high cone resistance). This data enables deduction of the mechanical properties of the substrate and assessment of its load-bearing capacity. Over time, the probe has undergone advancements enabling a broader range of measurements.

In the Netherlands, this data predominantly informs foundation design, yet its applications extend beyond this domain [59].

In the BRO 3D webservice, CPTs are visually represent CPTs in 3D as brown tubes, omitting the measured values. They provide instant insight into the distribution and depth of CPTs. A direct connection within the pop-up leads to the BROloket, where graphs displaying the pertinent measurement data are available [60]. This CPTs graphs CPTs usually require a geomechanical expert for interpretation, thus, while this information is publicly available, it is necessary to request assitance from an expert to apply this knowledge into design.

Figure 4.7: CPT boreholes visualized using 3D BRO webservice

4.4.4. Groundwater Level Information Models

The highest groundwater level, essential to understand a subsurface suitability for water infiltration, is available on a 2D map provided by the Klimateffectatlas. This map displays the Average Highest Groundwater Level (GHG) under current conditions, typically occurring during winter months. Factors contributing to this distance include urban reclamation requirements, dewatering practices, maximum water level regulations, and extensive pavement coverage [16].

The map draws on data from the National Water Model, offering a national-scale overview of groundwater conditions. However, local variables can substantially influence groundwater levels, which are not accounted for in this modeling. As mentioned before, this map is part of the Klimateffectatlas, which consolidates national climate data to provide an initial assessment of flood, waterlogging, drought, and heat risks and are derived from KNMI’14 climate scenarios.This map layer is provided by Esri Netherlands Content, delivering nationwide data and services for use within the ArcGIS platform. Being this a standardized ESRI map, the data can be visualized through an ArcGIS webviewer or incorporated through the LivingAtlas when using an ArcGIS software [16].

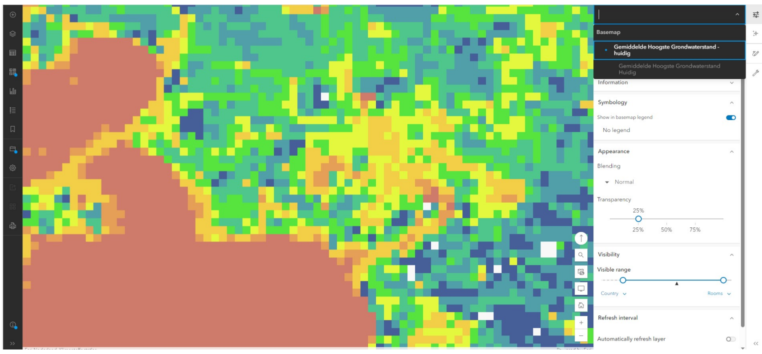


Figure 4.8: Average highest groundwater level visualized using GIS webservice

As all the other maps provided by the Klimateffectatlas, these 2D representations are purposely created on a national level, due to its purpose to inform the whole country regarding climate effect impacts. Thus, while this map, and other Klimateffectatlas maps, are a good indication and starting point for local climate adaptation design, they are more suitable for national, regional, and municipal level of design. Local design needs integration of other data sources or experts.

In 3D, the 3D Key Register contains information on the groundwater measuring well, the objects used to measure the quantity (levels) and quality of groundwater. The layer Grondwatermonitoringputten in the 3D BRO webservice viewer shows the groundwater monitoring wells in 3D as a blue tube, with the filters in dark blue. The pop-up contains information about the well, pipes and filters, as well as a link to the well data on BROloket: a schematization of the well and the groundwater level time series and groundwater quality data measured in the well [61]. Similar to the geomechanical information on the CPTs graphs, the information regarding the measurements in the wells is publicly available but it is necessary to consult an expert, usually an hydrologist, to use this information in urban planning or design.

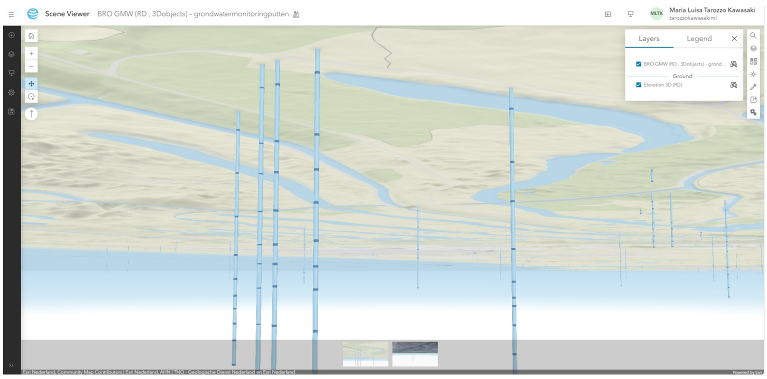


Figure 4.9: Groundwater monitoring wells visualized using 3D BRO webservice

5

Combining Different Information

From the research presented in this thesis previously, one can conclude that local climate adaptation design in the Netherlands presents different information dependencies. Moreover, standardizing design interventions create more dependencies, linking the design to climate and planning local standards and guidelines.

A common ground consists of a common understanding of how different information relate to each other. A first step to better understand these relationship dependencies is illustrating them graphically through relational diagrams. A relational diagram can represent how to combine information from existing subsurface information models to the information requirements for each intervention. In addition, the same diagram can indicate how to combine the interventions to existing standardads and guidelines. In simple terms, the graph can work as a roadmap for designers and data providers to understand what information is needed and where to find them.

From all the different ways to represent the dependencies, it was opted to create different databases to store information regarding interventions and information models, and to use an Unified Modeling Language (UML) diagram to represent their relationships. The reason behind this methodology is, firstly, the possibility to query, filter or search for, specific information which is possible to do through relational databases. Secondly, due to the simplicity, yet standardized format, of representing information relationships through an UML diagram.

5.1. Relational Diagrams

A relational diagram is a graphical representation of the relationships between various elements within a system, in this case within standardized local climate adaptation design. The term is often used in database management and denotes a diagram illustrating the relationships between different tables in a relational database, showcasing how they are connected through common attributes or keys.

Due to the double degree aspect of this thesis, this typically informatics oriented representation was chosen to be applied to urban design. The choice for this methods is the usefulness that the author believed this type of diagram could have to areas other than databases, aiding in understanding the structure and connections within any system and facilitating effective general modeling and design.

There are many ways of representing the relationships within a system. In particular, an Unified Modelling Language diagram is a graphical representation of a system using the Unified Modeling Language (UML). It depicts various aspects of the system, such as its structure, behavior, and interactions between components.

Using standardized local climate adaptation in the Netherlands as a system, an UML diagram was created to visually represent different relationships, indicating the need and the ways information can be combined.

The center of the diagram presents the twenty five most commonly employed standardized climate adaptation interventions in the Netherlands [3], each one of them is then connected to the subsurface properties that they depend on, namely geomechanics, groundwtater level, soil type and subsurface congestion. For each one of these properties there is a link to the information model where this information can be found and the data standard this model uses.

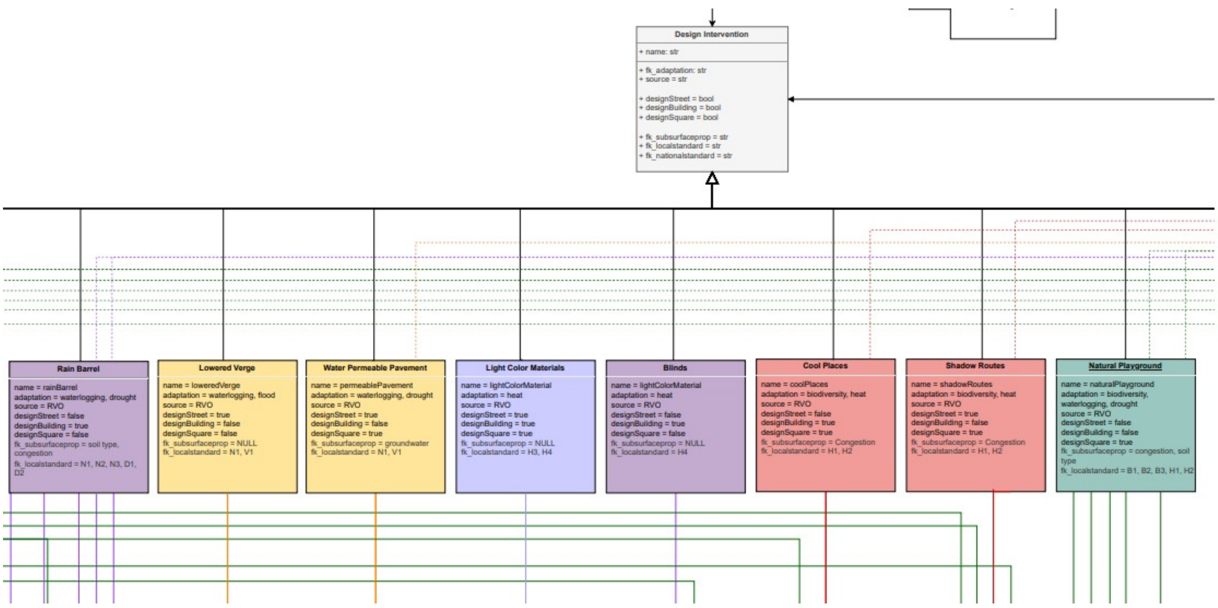


Figure 5.1: Center of UML diagram are the design interventions

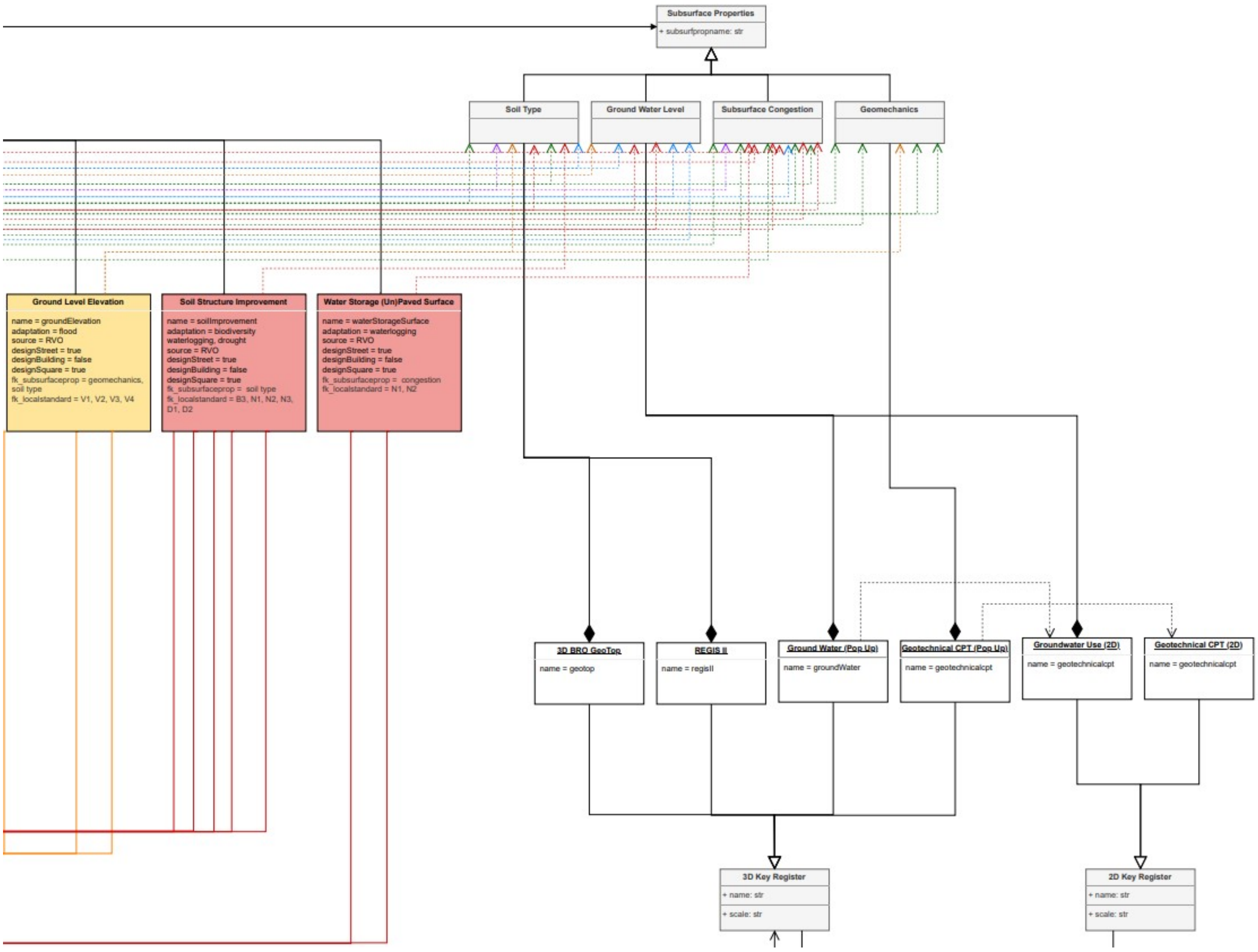


Figure 5.2: Each intervention is related to subsurface properties, which is linked to its source

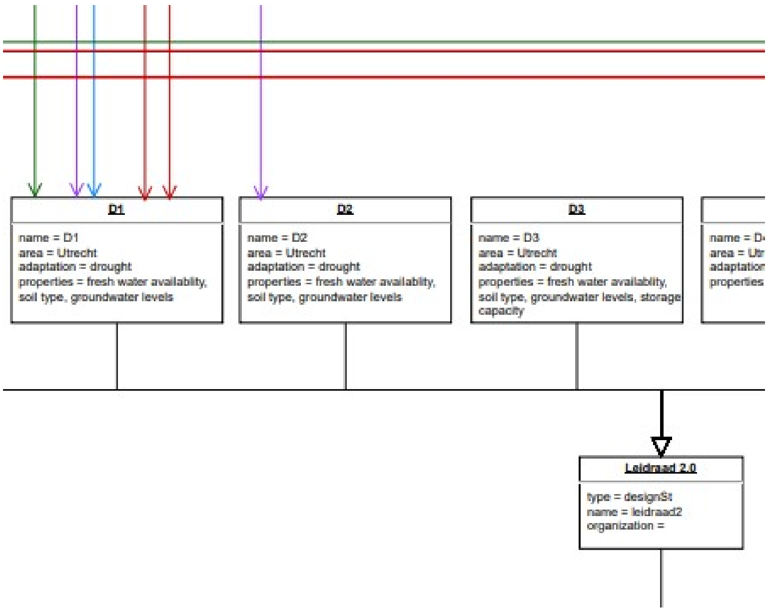


Figure 5.3: Each intervention is also linked to guidelines

Moreover, for each intervention there is a link to relevant design and planning standards or guidelines. And for each one of these there is a link to the source where this information can be find.

The UML diagram successfully visually indicates the information dependencies for standardized local interventions, creating a road map where the user can understand for each intervention what information is necessary and where to find it.

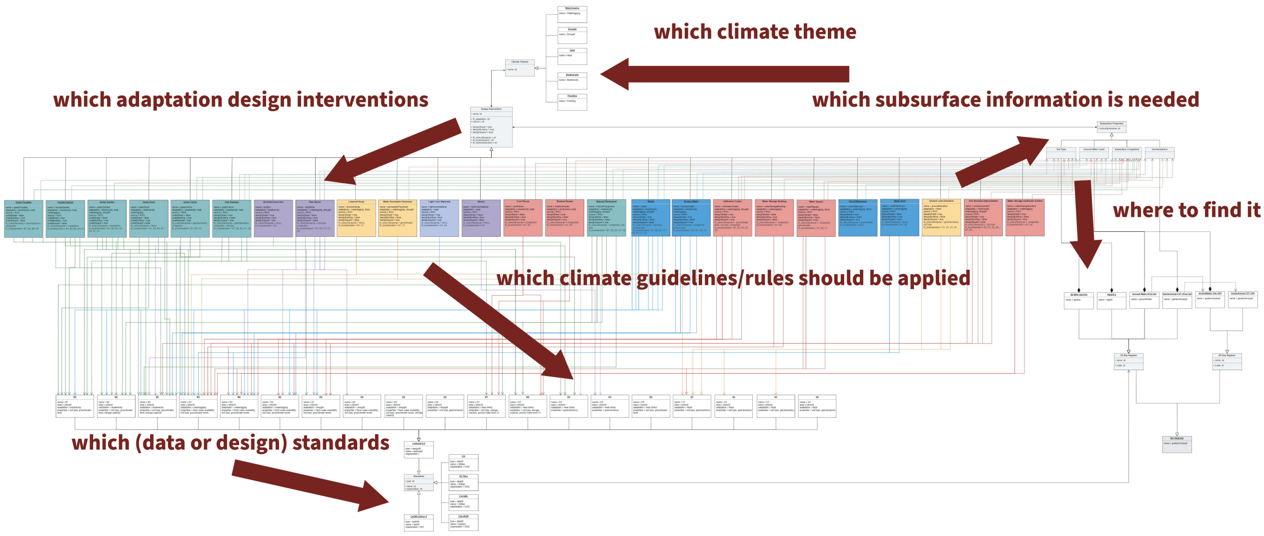
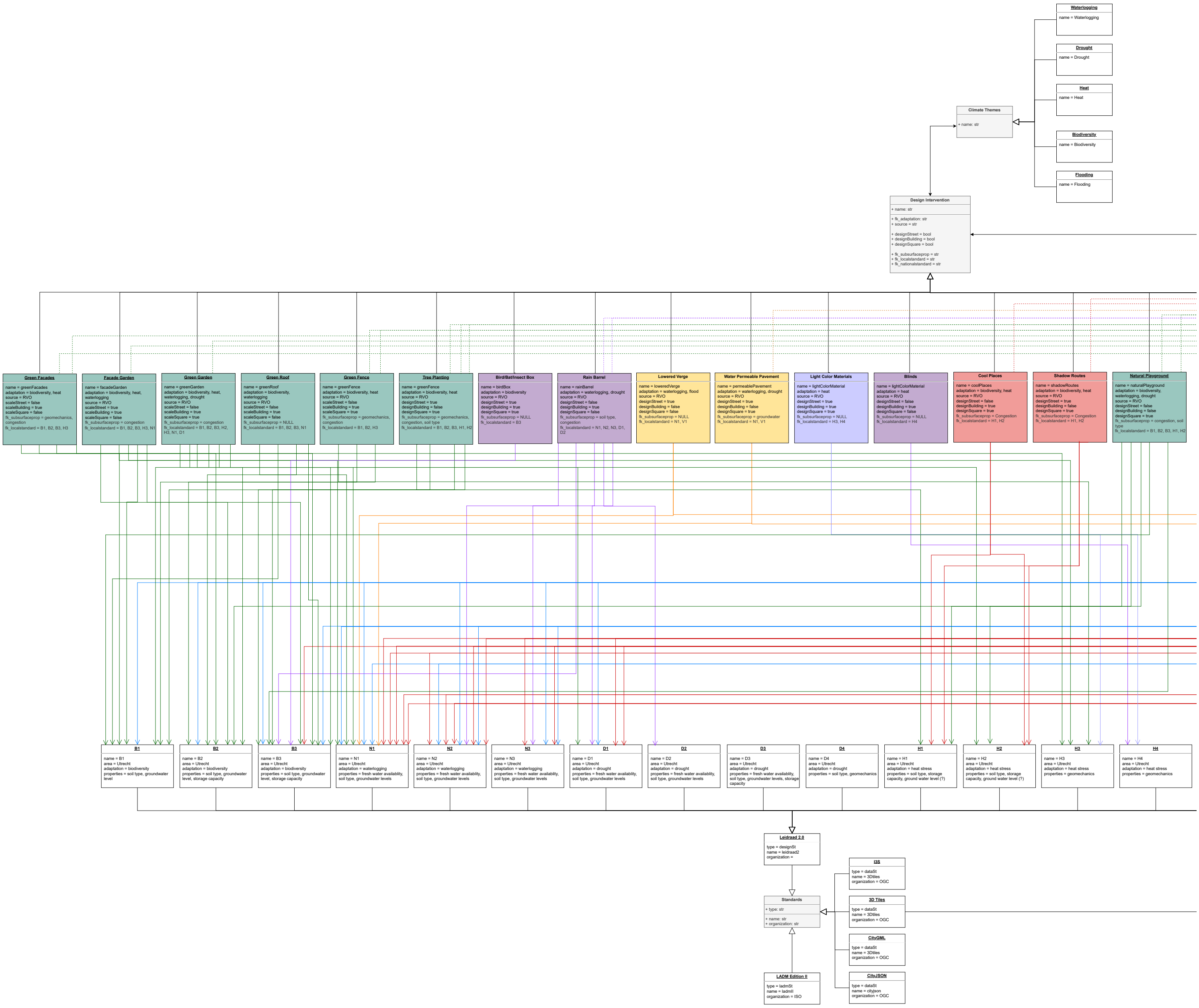
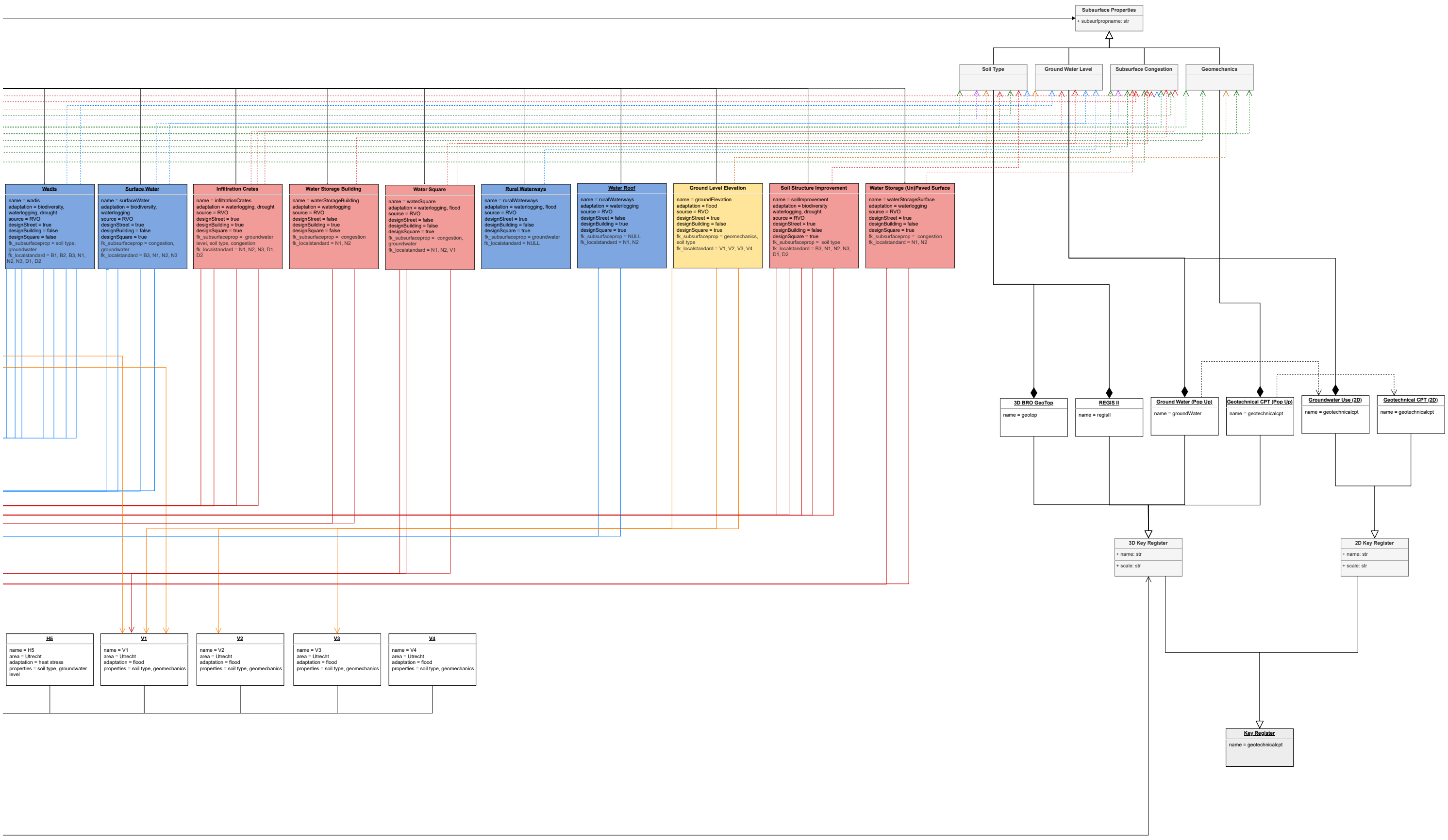


Figure 5.4: UML diagram explained



Waterlogging
name = Waterlogging
Drought
name = Drought
Heat
name = Heat
Biodiversity
name = Biodiversity
Flooding
name = Flooding
Climate Themes
+ name: str
Design Intervention
+ name: str
+ fk_adaptation: str
+ source = str
+ designStreet = bool
+ designBuilding = bool
+ designSquare = bool
+ fk_subsurfaceprop = str
+ fk_localstandard = str
+ fk_nationalstandard = str
Green Facades
name = greenFacades
adaptation = biodiversity, heat
source = RVO
scaleStreet = false
scaleBuilding = true
scaleSquare = false
fk_subsurfaceprop = geomechanics, congestion
fk_localstandard = B1, B2, B3, H3
Facade Garden
name = facadeGarden
adaptation = biodiversity, heat, waterlogging
source = RVO
scaleStreet = true
scaleBuilding = true
scaleSquare = false
fk_subsurfaceprop = congestion
fk_localstandard = B1, B2, B3, H3, N1
Green Garden
name = greenGarden
adaptation = biodiversity, heat, waterlogging, drought
source = RVO
scaleStreet = false
scaleBuilding = true
scaleSquare = true
fk_subsurfaceprop = congestion
fk_localstandard = B1, B2, B3, H2, H3, N1, D1
Green Roof
name = greenRoof
adaptation = biodiversity, waterlogging
source = RVO
scaleStreet = false
scaleBuilding = true
scaleSquare = false
fk_subsurfaceprop = NULL
fk_localstandard = B1, B2, B3, N1
Green Fence
name = greenFence
adaptation = biodiversity, heat
source = RVO
scaleStreet = false
scaleBuilding = true
scaleSquare = true
fk_subsurfaceprop = geomechanics, congestion
fk_localstandard = B1, B2, H3
Tree Planting
name = greenFence
adaptation = biodiversity, heat
source = RVO
designStreet = true
designBuilding = false
designSquare = true
fk_subsurfaceprop = geomechanics, congestion, soil type
fk_localstandard = B1, B2, B3, H1, H2
Bird/Bat/Insect Box
name = birdBox
adaptation = biodiversity
source = RVO
designStreet = true
designBuilding = true
designSquare = true
fk_subsurfaceprop = NULL
fk_localstandard = B3
Rain Barrel
name = rainBarrel
adaptation = waterlogging, drought
source = RVO
designStreet = false
designBuilding = true
designSquare = false
fk_subsurfaceprop = soil type, congestion
fk_localstandard = N1, N2, N3, D1, D2
Lowered Verge
name = loweredVerge
adaptation = waterlogging, flood
source = RVO
designStreet = true
designBuilding = false
designSquare = false
fk_subsurfaceprop = NULL
fk_localstandard = N1, V1
Water Permeable Pavement
name = permeablePavement
adaptation = waterlogging, drought
source = RVO
designStreet = true
designBuilding = false
designSquare = true
fk_subsurfaceprop = groundwater
fk_localstandard = N1, V1
Light Color Materials
name = lightColorMaterial
adaptation = heat
source = RVO
designStreet = true
designBuilding = true
designSquare = true
fk_subsurfaceprop = NULL
fk_localstandard = H3, H4
Blinds
name = lightColorMaterial
adaptation = heat
source = RVO
designStreet = false
designBuilding = true
designSquare = false
fk_subsurfaceprop = NULL
fk_localstandard = H4
Cool Places
name = coolPlaces
adaptation = biodiversity, heat
source = RVO
designStreet = false
designBuilding = true
designSquare = true
fk_subsurfaceprop = Congestion
fk_localstandard = H1, H2
Shadow Routes
name = shadowRoutes
adaptation = biodiversity, heat
source = RVO
designStreet = true
designBuilding = false
designSquare = true
fk_subsurfaceprop = Congestion
fk_localstandard = H1, H2
Natural Playground
name = naturalPlayground
adaptation = biodiversity, waterlogging, drought
source = RVO
designStreet = false
designBuilding = false
designSquare = true
fk_subsurfaceprop = congestion, soil type
fk_localstandard = B1, B2, B3, H1, H2
B1
name = B1
area = Utrecht
adaptation = biodiversity
properties = soil type, groundwater level
B2
name = B2
area = Utrecht
adaptation = biodiversity
properties = soil type, groundwater level, storage capacity
B3
name = B3
area = Utrecht
adaptation = biodiversity
properties = soil type, groundwater level, storage capacity
N1
name = N1
area = Utrecht
adaptation = waterlogging
properties = fresh water availablity, soil type, groundwater levels
N2
name = N2
area = Utrecht
adaptation = waterlogging
properties = fresh water availablity, soil type, groundwater levels
N3
name = N3
area = Utrecht
adaptation = waterlogging
properties = fresh water availablity, soil type, groundwater levels
D1
name = D1
area = Utrecht
adaptation = drought
properties = fresh water availablity, soil type, groundwater levels
D2
name = D2
area = Utrecht
adaptation = drought
properties = fresh water availablity, soil type, groundwater levels
D3
name = D3
area = Utrecht
adaptation = drought
properties = fresh water availablity, soil type, groundwater levels, storage capacity
D4
name = D4
area = Utrecht
adaptation = drought
properties = soil type, geomechanics
H1
name = H1
area = Utrecht
adaptation = heat stress
properties = soil type, storage capacity, ground water level (?)
H2
name = H2
area = Utrecht
adaptation = heat stress
properties = soil type, storage capacity, ground water level (?)
H3
name = H3
area = Utrecht
adaptation = heat stress
properties = geomechanics
H4
name = H4
area = Utrecht
adaptation = heat stress
properties = geomechanics
Leidraad 2.0
type = designSt
name = leidraad2
organization =
Standards
+ type: str
+ name: str
+ organization: str
LADM Edition II
type = ladmSt
name = ladmII
organization = ISO
I3S
type = dataSt
name = 3Dtiles
organization = OGC
3D Tiles
type = dataSt
name = 3Dtiles
organization = OGC
CityGML
type = dataSt
name = 3Dtiles
organization = OGC
CityJSON
type = dataSt
name = cityjson
organization = OGC



Subsurface Properties
+ subsurfpropname: str
Soil Type
Ground Water Level
Subsurface Congestion
Geomechanics
Wadis
name = wadis
adaptation = biodiversity, waterlogging, drought
source = RVO
designStreet = true
designBuilding = false
designSquare = false
fk_subsurfaceprop = soil type, groundwater
fk_localstandard = B1, B2, B3, N1, N2, N3, D1, D2
Surface Water
name = surfaceWater
adaptation = biodiversity, waterlogging
source = RVO
designStreet = true
designBuilding = false
designSquare = true
fk_subsurfaceprop = congestion, groundwater
fk_localstandard = B3, N1, N2, N3
Infiltration Crates
name = infiltrationCrates
adaptation = waterlogging, drought
source = RVO
designStreet = true
designBuilding = true
designSquare = true
fk_subsurfaceprop = groundwater level, soil type, congestion
fk_localstandard = N1, N2, N3, D1, D2
Water Storage Building
name = waterStorageBuilding
adaptation = waterlogging
source = RVO
designStreet = false
designBuilding = true
designSquare = false
fk_subsurfaceprop = congestion
fk_localstandard = N1, N2
Water Square
name = waterSquare
adaptation = waterlogging, flood
source = RVO
designStreet = false
designBuilding = false
designSquare = true
fk_subsurfaceprop = congestion, groundwater
fk_localstandard = N1, N2, V1
Rural Waterways
name = ruralWaterways
adaptation = waterlogging, flood
source = RVO
designStreet = true
designBuilding = false
designSquare = true
fk_subsurfaceprop = groundwater
fk_localstandard = NULL
Water Roof
name = ruralWaterways
adaptation = waterlogging
source = RVO
designStreet = false
designBuilding = true
designSquare = true
fk_subsurfaceprop = NULL
fk_localstandard = N1, N2
Ground Level Elevation
name = groundElevation
adaptation = flood
source = RVO
designStreet = true
designBuilding = false
designSquare = true
fk_subsurfaceprop = geomechanics, soil type
fk_localstandard = V1, V2, V3, V4
Soil Structure Improvement
name = soilImprovement
adaptation = biodiversity waterlogging, drought
source = RVO
designStreet = true
designBuilding = false
designSquare = true
fk_subsurfaceprop = soil type
fk_localstandard = B3, N1, N2, N3, D1, D2
Water Storage (Un)Paved Surface
name = waterStorageSurface
adaptation = waterlogging
source = RVO
designStreet = true
designBuilding = false
designSquare = true
fk_subsurfaceprop = congestion
fk_localstandard = N1, N2
3D BRO GeoTop
name = geotop
REGIS II
name = regisII
Ground Water (Pop Up)
name = groundWater
Geotechnical CPT (Pop Up)
name = geotechnicalcpt
Groundwater Use (2D)
name = geotechnicalcpt
Geotechnical CPT (2D)
name = geotechnicalcpt
3D Key Register
+ name: str
+ scale: str
2D Key Register
+ name: str
+ scale: str
Key Register
name = geotechnicalcpt
H5
name = H5
area = Utrecht
adaptation = heat stress
properties = soil type, groundwater level
V1
name = V1
area = Utrecht
adaptation = flood
properties = soil type, geomechanics
V2
name = V2
area = Utrecht
adaptation = flood
properties = soil type, geomechanics
V3
name = V3
area = Utrecht
adaptation = flood
properties = soil type, geomechanics
V4
name = V4
area = Utrecht
adaptation = flood
properties = soil type, geomechanics

5.2. Relational Databases

The presented UML diagram was used as the basis for the creation of several databases that contained relevant information for standardized Dutch climate adaptation design. For this purpose, five tables to store information was created: a table with the twenty five design intervention, a table with national guidelines (Maatlat), a table with local standards (Leidraad), a table with subsurface properties and a table with the different climate themes.

The table containing information regarding the design intervention refers to all the other four tables, having something that in relational databases is called a foreign key. Foreign keys are extremely important in relational databases because they establish a relationship between the two tables based on the values stored in the foreign key columns. In practice it means that if the column in the design intervention table stores ”soil type” on its subsurface properties column, this value refers to the same value in the subsurface table.

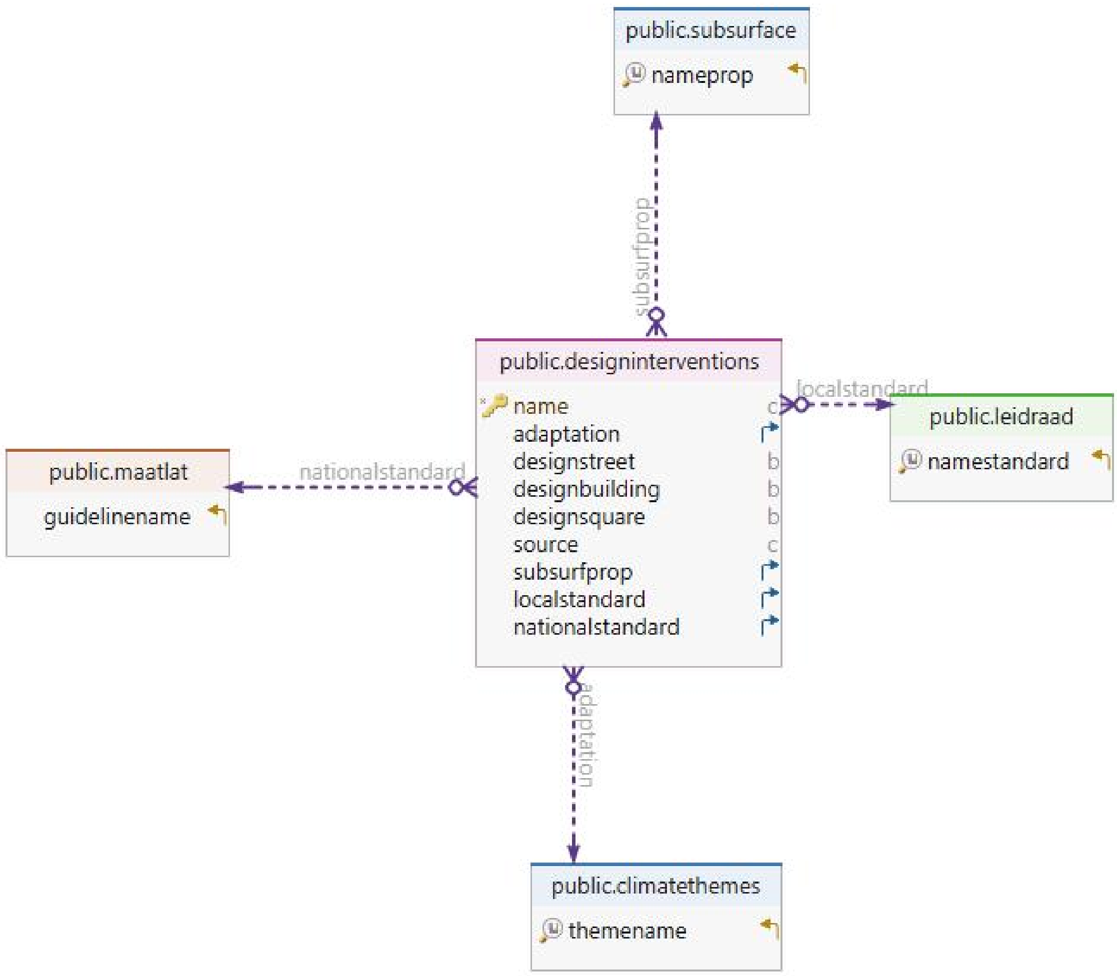


Figure 5.5: Relating different tables

The main purpose of creating different databases is the fact that it is possible to query information inside the tables, which means retrieving specific information from a database using SELECT statements.

An example of a coding used for retrieving information from the created tables is:

```sql
SELECT *
FROM public.designinterventions
WHERE adaptation LIKE '%heat%'
OR adaptation LIKE '%waterlogging%'
AND designbuilding = false;
```

The result of this query is the selection of all the design interventions stored inside of the interventions tables that are an adaptation to heat or waterlogging and are related to the design of a building. The results of this selection can be seen in the following image. The code used ton create the different tables is provided in the Annex part of this thesis.

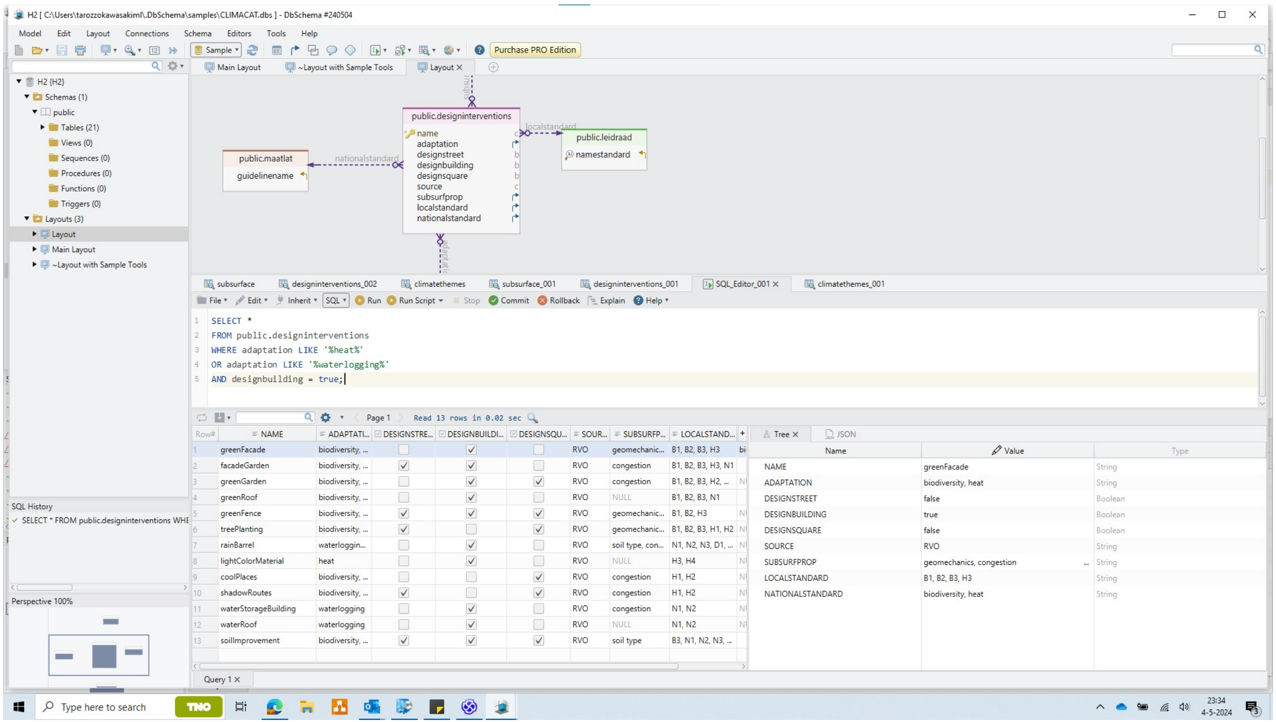


Figure 5.6: Querying data inside the database

Part III

How to Reach a Common Ground?

While the previous two parts were mainly focused on the definition of which information is needed for Dutch standardized climate adaptation design and the dependencies of interventions to subsurface information and climate standards, Part III focus on the investigation of these dependencies through the creation of concrete examples. This part is thus the conclusion of the previous two in practical explorations on the topic.

This is done in two main ways. In Chapter 6, a tool is created to facilitate the integration of different information that was identified as needed in the previous chapters and was illustrated through the creation of an Unified Modelling Language diagram in Chapter 5. The result is an online catalog, created using ArcGIS StoryMaps.

The aim of establishing an online catalog is to enhance the existing UML diagram and database. While the diagram and tables hold significant data and depict the relationships between various elements, an online catalog elaborates on this further and provides deeper insights into certain attributes. For instance, while the UML diagram and relational database indicate the connection between an intervention and soil type, the online catalog offers textual descriptions detailing the nature of this relationship, along with technical illustrations specifying the required scale and resolution to represent the intervention and soil type accurately.

With mainly designers and data providers as the main end user, the interface is similar to a semi interactive website, where the twenty interventions are indicated with an example in the city of Utrecht. The website also contains information of the relationship between climate adaptation design and the subsurface and an example on how to use the online catalog for design purposes.

The website is used in Chapter 7 where different design proposals make use of all the different information models, guidelines and standards presented in the thesis are tested and used for standardized local climate adaptation design in practice. In this chapter, critical reflection is made regarding the usability of existing models and the resolution requirements.

Through spatial interventions, the requirements outlined in Part II undergo testing across various interventions. While Part II theoretically explores the data resolution necessary for localized climate adaptation to leverage information models, Part III demonstrates this concept in action, evaluating whether the theoretical benefits translate into practical results.

The design proposals are then evaluated using an online survey to compare the design decisions with the decisions made by designers that did not have access to subsurface information. One of the plans is also standardized using the LADM Part 5 subclasses described in section 4.3. Finally, some considerations are done regarding methods to improve data resolution and accuracy.

Thus, in these chapter the following reserch questions are answered:

- What data resolution or scale is necessary for diverse climate adaptation interventions? To what degree must models be precise to meet design requirements?
- What is the additional value of integrating information models into climate adaptation design? Can this value be quantified?
- What methodologies can be established for integrating subsurface information models into urban design?

Part III is concluded with a Conclusion and Recommendations chapter, where the author reflects on the answers to the different research questions that it was proposed to answer.

6

Online Catalog: CLIMACAT

The Open Geospatial Consortium (OGC) defines that one of the building blocks for FAIR (findable, accessible, interoperable and reusable) climate information data services are FAIR climate information catalogs [53]. Aligned with this definition, the thesis concluded that one of the ways in which a common ground could be reached, and information regarding local climate adaptation design could be combined, was through the creation of a FAIR climate catalog. The idea was to join all the relevant information discussed in this thesis in one online place.

The digital Dutch climate design catalog, CLIMACAT in short, introduces the user to climate themes topics and to the relationship between subsurface information, design standards, and climate adaptation design. The potential users for this website are urban designer, data providers and citizens. Designers benefit from better understanding the information needed for their climate adaptation design, along with where to find relevant information. Data providers benefit from better understanding what are the data requirements for design, using it as basis to improve their own information and data models. Finally, citizens can use it to better understand climate adaptation in the Dutch context.

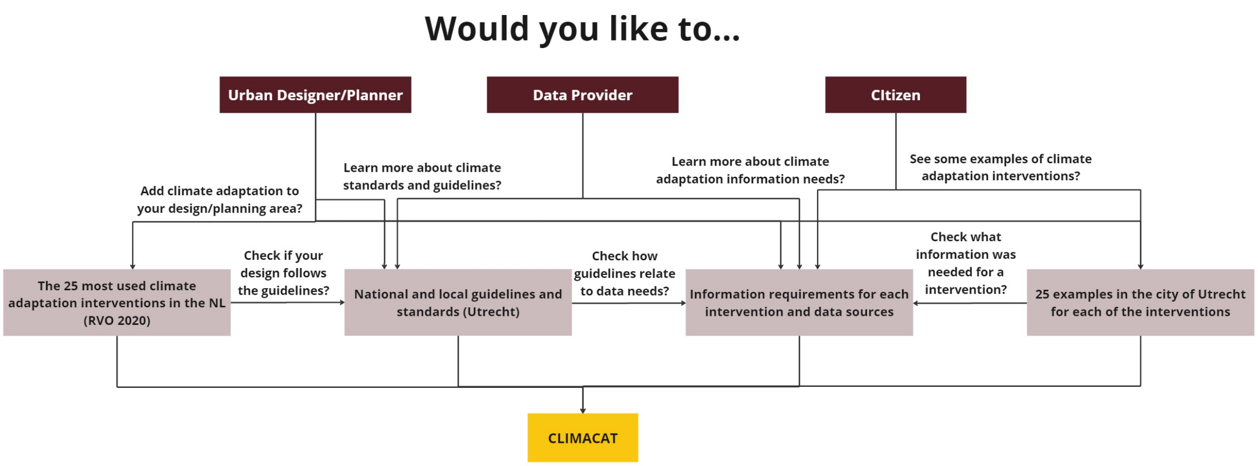


Figure 6.1: CLIMACAT Potential Users

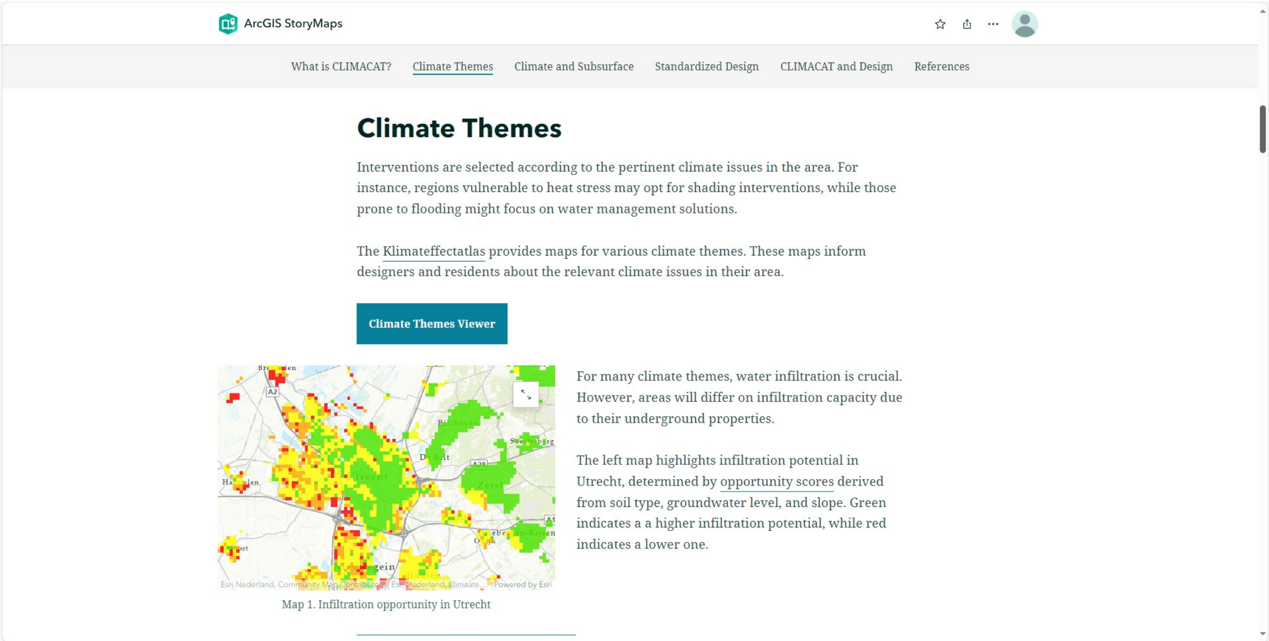


Figure 6.2: CLIMACAT Climate Themes

The catalog then indicates the twenty five most commonly used climate adaptation interventions in the Netherlands [3], with a geolocated example in a map of the city of Utrecht, alongside with relevant information.

For each intervention there is an explanation on how the intervention is an adaptation to the related climate theme [3] [55] [9]. This explanation often includes a link to technical drawings of the intervention. It then discusses the relevant subsurface properties, based on information from the Bouwadaptief [55]. The subsurface property name is a link to a webviewer or geoportal where this information can be find. It then indicates relevant national guidelines, taken from the Maatlat [15] and local standards for the city of Utrecht, taken from the Leidraad [54].

The online catalog is concluded with an example use of this tool when designing. In the example, a neighborhood in Utrecht, Voordorp, has its information requests and subsurface limitations and opportunities identified. It then exemplifies how a potential intervention, in this case infiltration crates, has all the identified information needs answered in one single place through the catalog. This proved how a common ground can be found through a climate adaptation design catalog that is FAIR. CLIMACAT is publicly available at `https://storymaps.arcgis.com/stories/41d0869e36bb4d2ab13de8adea2fd738`

Figure 6.3: CLIMACAT Subsurface

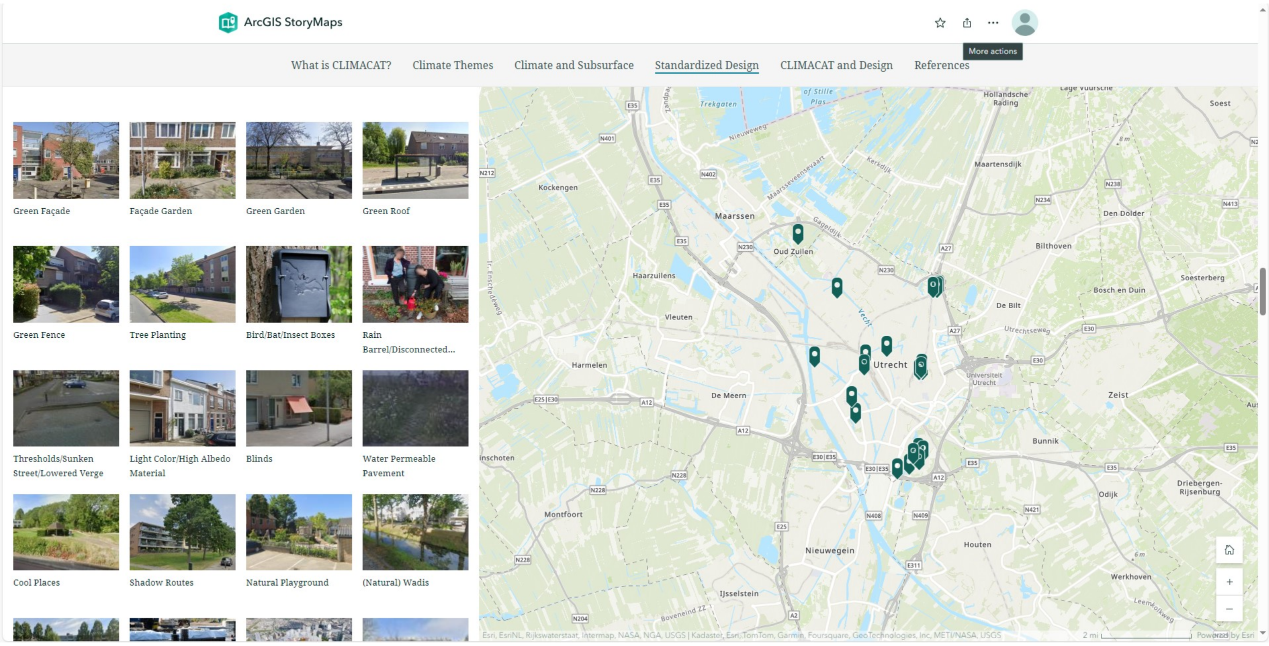


Figure 6.4: CLIMACAT Standardized Interventions

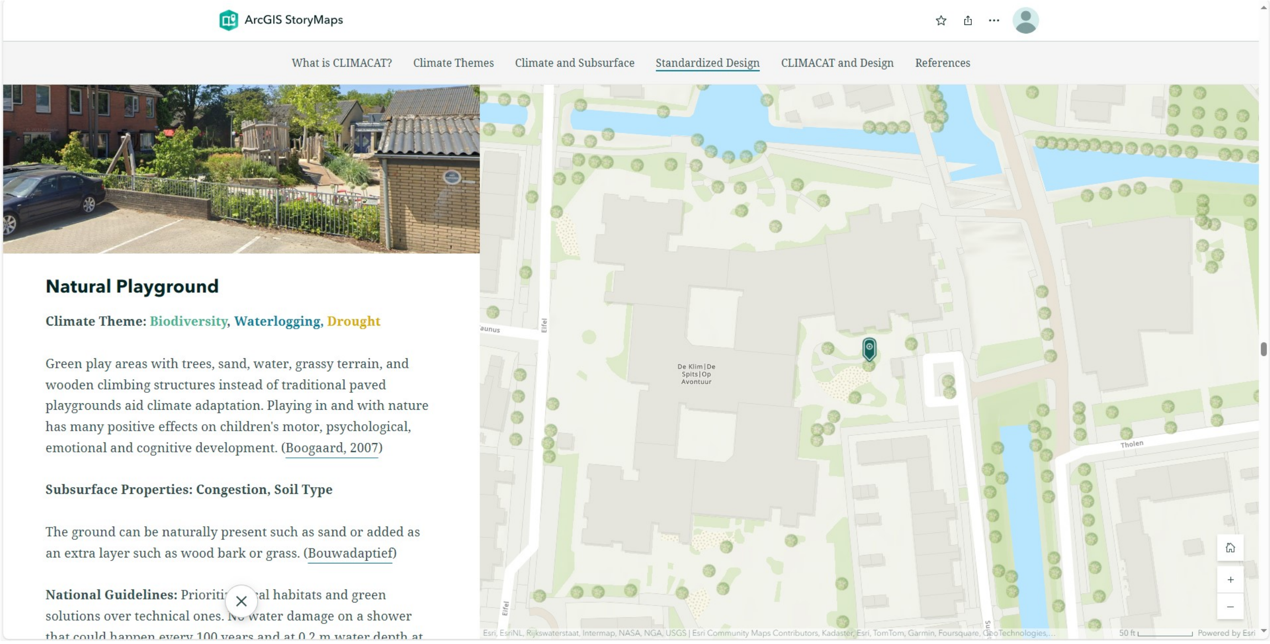


Figure 6.5: CLIMACAT Standardized Intervention Example

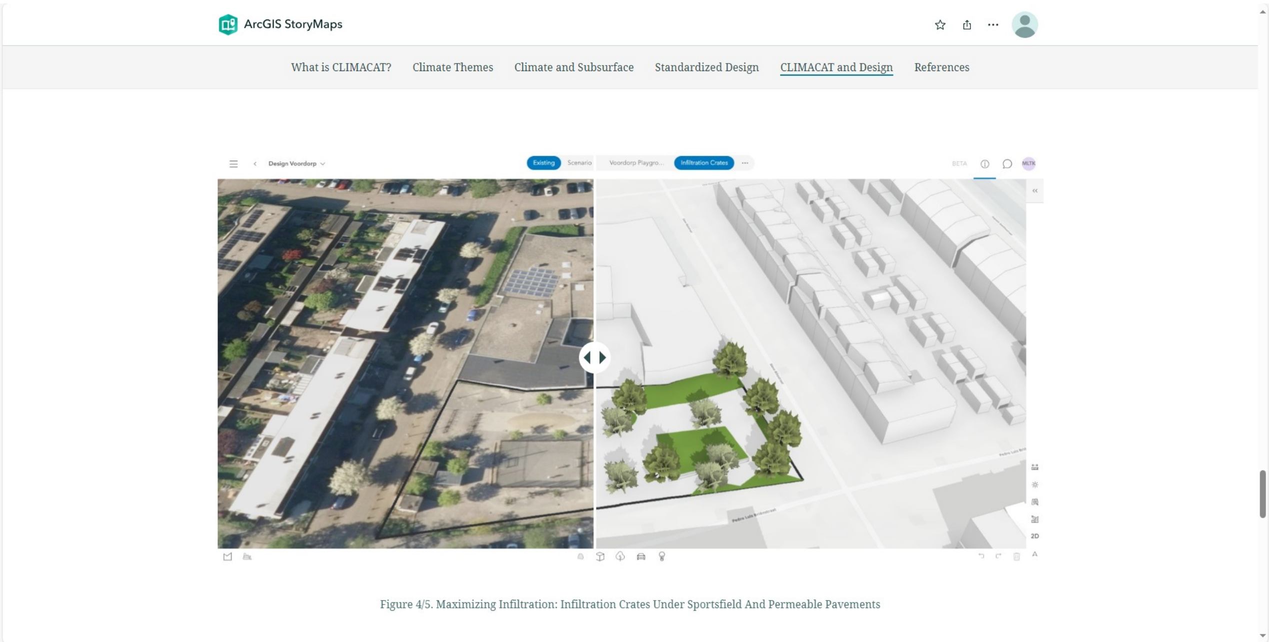


Figure 6.6: CLIMACAT Design Example

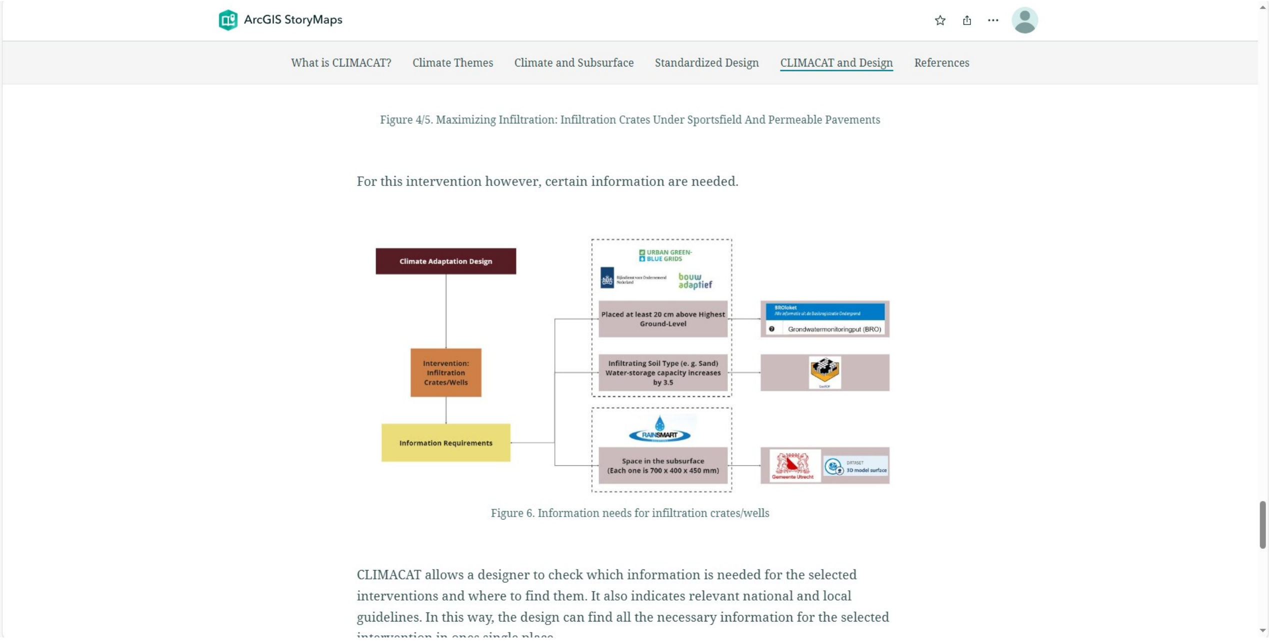


Figure 6.7: CLIMACAT Design Example

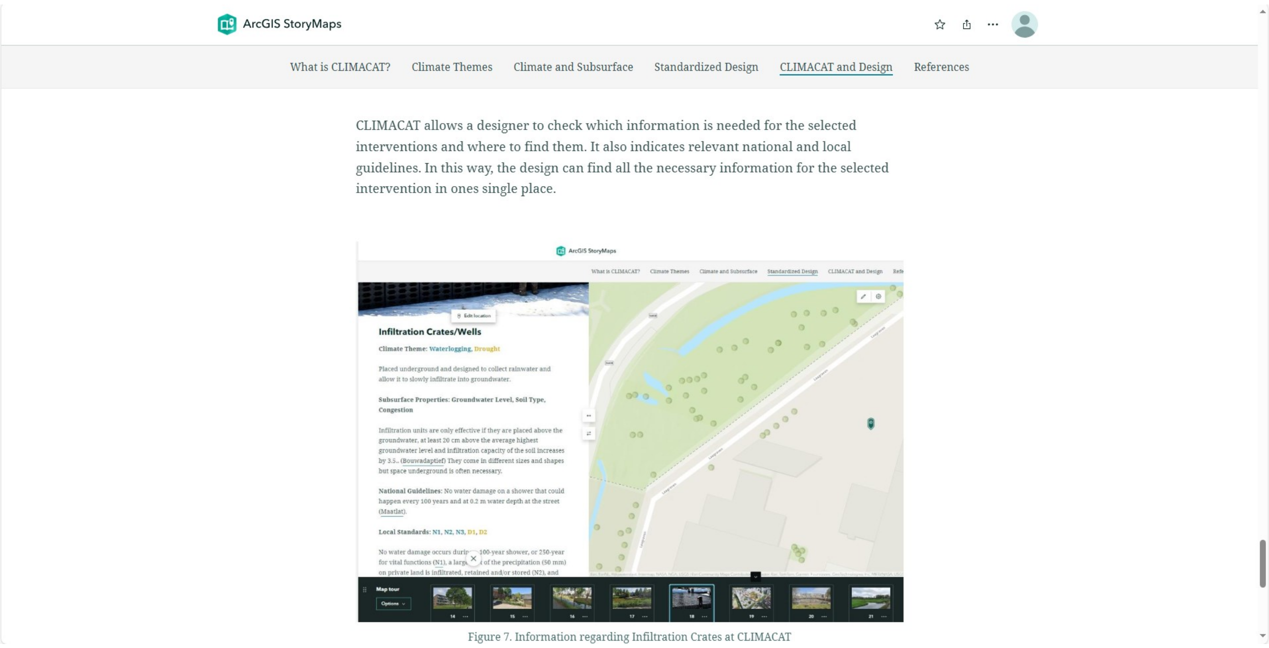


Figure 6.8: CLIMACAT Design Example

7

Design Proposals

This chapter delves into the critical evaluation of design outcomes to validate or challenge the hypothesis regarding the efficacy of information models in facilitating climate adaptation efforts within the Netherlands. Central to this phase of the research is the rigorous testing of urban design making use of information models, with a keen focus on potential enhancements of both the models and the design derived from this comprehensive exploration.

Utrecht, the focal point of this design exploration, exhibits a diverse landscape comprising four distinct main landscapes. This unique division provides an ideal framework for integrating information models into climate adaptation design across four distinct scenarios. Each scenario is meticulously delineated by a 500 by 500-meter square, and ensures uniformity in factors such as urban density, morphology, and land use, thereby isolating the focus of the design and information assessment to subsurface characteristics. These designated areas are in the residential neighborhoods of Kop Voordorp, Lunetten Zuid, Kanaleneiland Noord, and Voordorp. These areas were chosen with the help of the city's municipality urban and landscape designers.

Because the main focus of the design is on local climate adaptation, information regarding climate themes were used. This information was visualized through maps on existing webviewer or by importing data into a GIS software.The main reason for studying relevant climate themes for each area is for the design to be an adaptive response to climate changes that are currently occurring on each area.

Regarding waterlogging, rain shower scenarios were used. In particular, the design took into consideration the climate scenarios used by Leidraad and Utrecht local regulations regarding waterlogging. The Leidraad often mentions a climate scenario defined in 2018 of a rainfall that reoccur every 100 years with an intensity of 70 mm/hour. [8]. Furthermore, Utrecht has established three regulations pertaining to waterlogging, which were instrumental in delineating storm scenarios:

- *N1: Within the planning area, no water-related damage should arise from a rainfall event expected once every 100 years. Essential services and vulnerable infrastructure, such as power supplies and care facilities, should remain operational even during a rainfall event anticipated once every 250 years. As of 2018, these thresholds stood at*

70 mm for the 100-year event and 90 mm for the 250-year event [8]

- *N2: A significant portion of precipitation (50 mm) occurring on private property must be infiltrated, retained, or stored either on-site or in designated additional facilities within the planning area or within the confines of the water system. Based on a one-hour rainfall event of 70 mm for the 100-year scenario, this necessitates the storage of 50 mm. To alleviate strain on urban water systems, this stored water must be gradually discharged over a period extending at least 24 hours post-rainfall (at a rate of approximately 2 mm per hour). The storage capacity should be replenished within 60 hours to accommodate subsequent rainfall events. Exceptions to discharge times apply to controlled water storage systems utilizing weather forecasts. However, it must be demonstrated that such controlled storage can effectively manage the required 50 mm precipitation*
- *N3: Development initiatives must maintain water neutrality and refrain from imposing additional burdens on water supply/drainage systems. Rainwater should be retained and repurposed to the fullest extent feasible within the planning area. Accordingly, preference should be given to interventions facilitating rainwater retention and reuse*

With the 100-year rainfall threshold set at 70 mm and regulations governing rainwater retention and reuse in Utrecht, two distinct scenarios were formulated. Given that short, intense local downpours lasting an hour often dictate flooding in urban locales [8], one scenario entails reaching the 70 mm threshold within a single hour, followed by sustained rainfall at the same intensity for another hour. In contrast, an alternate scenario simulates a longer-duration storm, with the 70 mm threshold reached over the course of two hours. Consequently, the spatial interventions are based on two storm event scenarios: a two-hour rainfall totaling 140 mm (or 70 mm/hour), and a two-hour rainfall accumulating 70 mm.

Based on the main relevant climate challenge, the subsurface properties of each area were carefully studied through relevant information models. Thus the selected interventions for each area are based on opportunities and challenges of existent subsurface properties, recognized through subsurface (3D) information models.

Social and ecological aspects of the area, such as the major age groups, urban activities, trends on the densification of an area, and the quality of public and green spaces were also took into consideration. Even though the focus of the design remained on improving the climate adaptability of a space, attention was paid to improve urban qualities of the space while remaining sensitive to local social and ecological aspects.

Finally, the design proposals took into consideration local and national guidelines and standards regarding climate adaptation, as discussed in Part II of this thesis. The national guidelines used came from the Maatlat [15] while local legislation and guidelines the city of Utrecht were found at the Leidraad [13]. The local interventions for each design are also standardized, those are all taken from the standardized twenty five most common used climate adaptation design interventions, as defined by the Dutch Government in 2020 [3]. The use of a tool such as the CLIMACAT website [62] was fundamental for the design. The visualization of all the standardized interventions, along with their information requirements, facilitated the design process.

In short, in this chapter, the knowledge gained was put in practice and tested through design practical examples. By using the information models to solve a climate adaptation, the suitability of the models for this purpose was proved. In addition, by using subsurface properties to choose local standardized climate adaptation interventions, more about the information needs for these interventions was identified. In short, the following questions are answered:

- What is the data resolution or scale needed for different climate adaptation interventions? How precise do models have to be to suffice design needs?
- What is this added value of integrating information models to climate adaptation design? Can this added value be quantified?

7.1. Area 1: Kop Voordop

The area of location one, in Kop Voordorp, lies right next to Sonnenborgh Park and includes part of Het Spoorweg Museum, a museum on railways located inside of a railway station from the 19th century. Despite its cultural and ecological richness, the main public space right in front of the museum lacks ecological and social qualities, being currently just a paved area with a couple of tables and seats. Thus, for this 500 by 500 meter area, the focus is on re-qualifying this public space, while adapting to relevant climate themes.

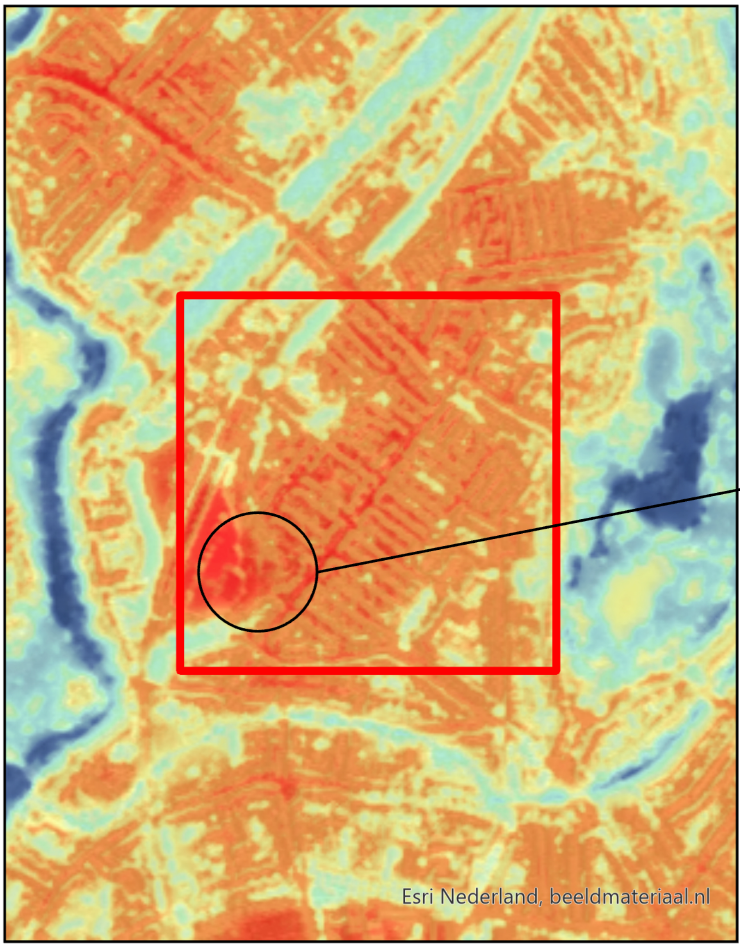
Regarding climate challenges, the area suffers from heat stress, especially in the selected smaller design area right in front of the museum. This can be seen in a map provided by the municipality geoportal, where the air temperature during a heat wave at 1.5 meter is higher on this spot.

In addition, the area suffers from a lack of greenery. In a map from the geoportal of a province of Utrecht, the percentage of greenery in different neighborhoods is mapped. From this map it is possible to identify that two of the selected 500 by 500 meter particularly suffer from this: location one and location three. The lack of greenery is particularly interesting for location one due to its closeness to the Sonnenborgh Park, in the greenery map indicated as the green empty space close to location one. This means that by adding greenery, an increase of biodiversity could be added to the neighborhood, by providing space for fauna and flora that would come from the close park.

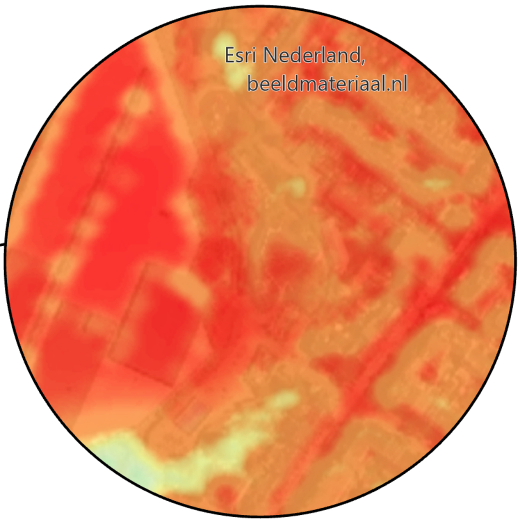
However, the area present some subsurface properties that need to be taken into consideration. The area present a thick clay soil layer, which minimized the capacity of the area for water absorption. The area also presents a high mean highest groundwater level, 1 to 1.5 meter bellow the ground surface. As discussed in Chapter 2.1, a research made on infiltration scores by Deltares indicates that any mean highest groundwater level above 0.7 meter bellow surface is too high to present a potential for infiltration [22]. This score changes based on the soil type, a sandy soil for example can still present a good infiltrating score even if the mean highest groundwater level is above 0.7 meter. However, in this case, clay does not impacts the infiltration score in a positive manner.

Climate Challenges: Location 1 Kop Voordorp

Heat: Air Temperature at 1.5 m on a heat wave (Scale 1:1000)



Zoom Scale 1:3000

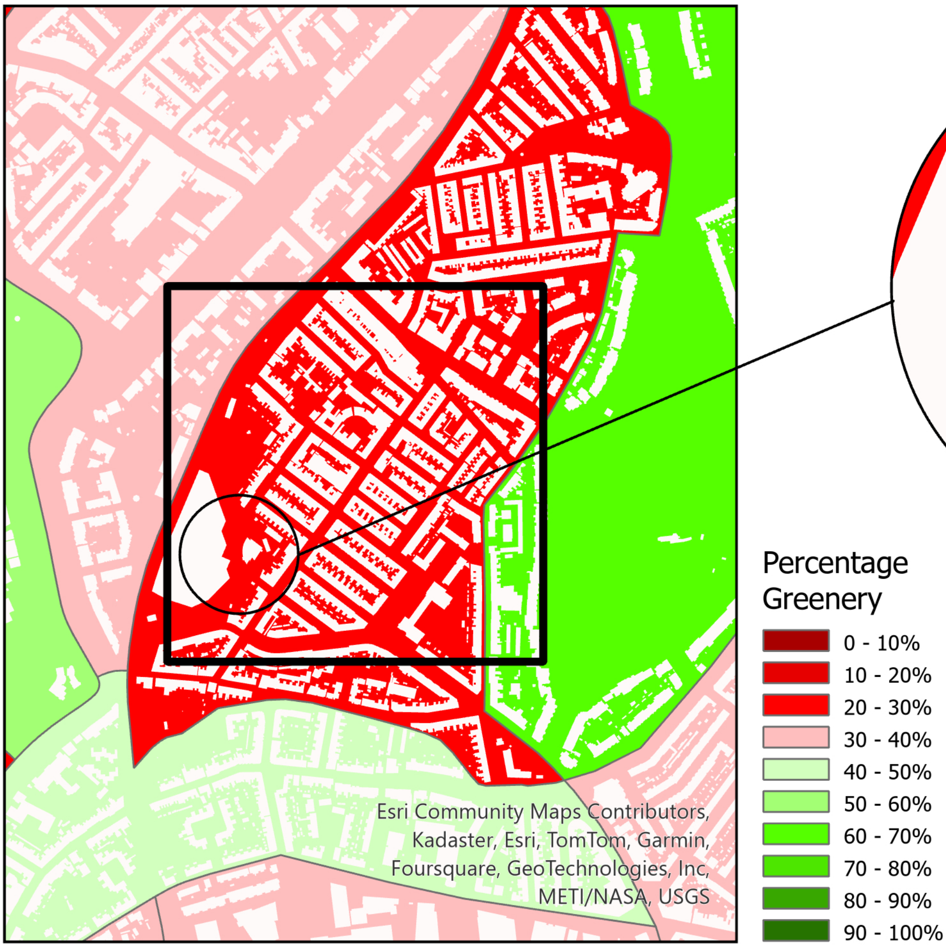


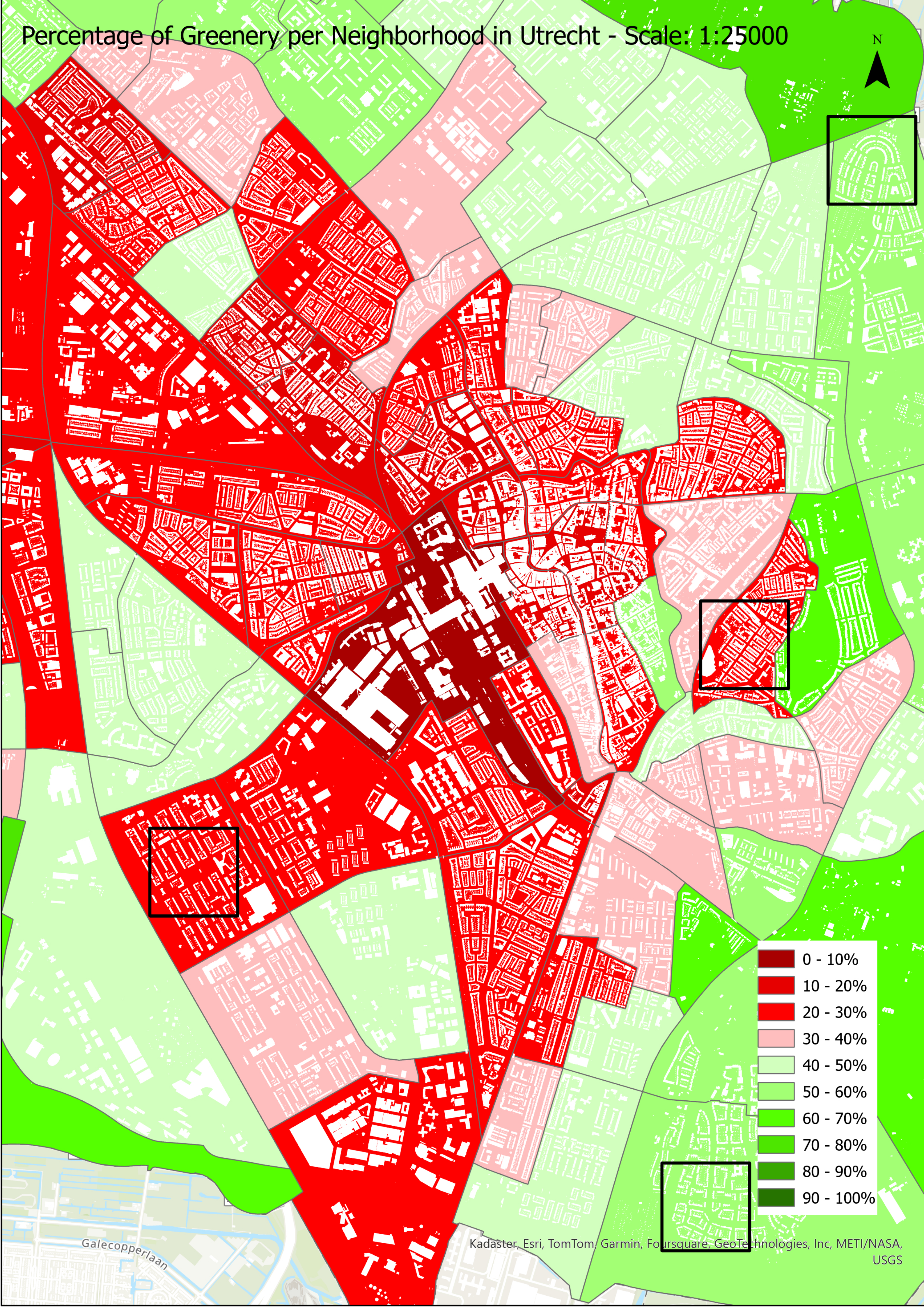
During a heat wave, the public area in front of the museum suffer from intense heat stress.

Zoom Scale 1:3000

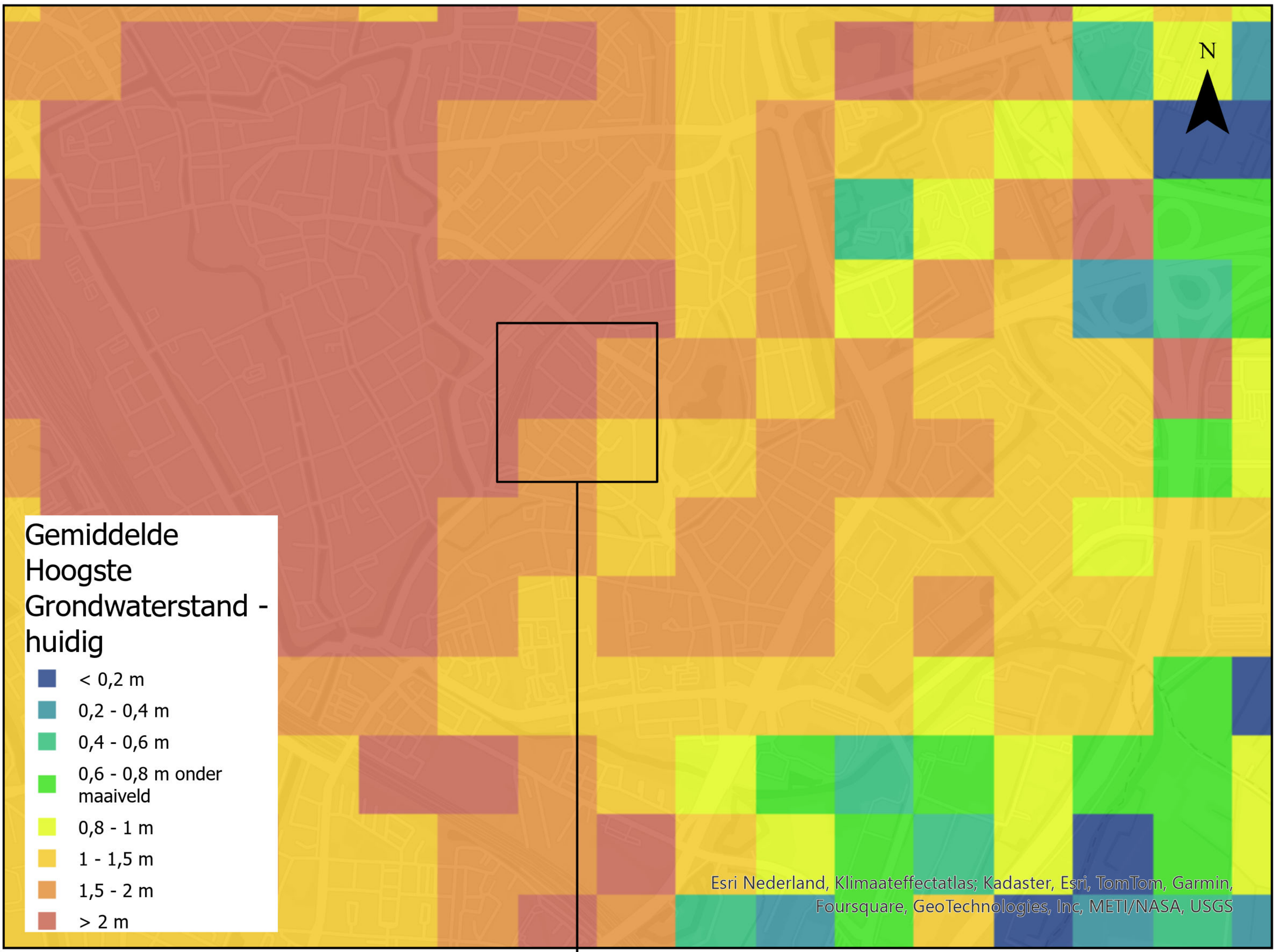
This area also suffers from a lack of greenery compared to surrounding neighborhoods

Biodiversity: Lack of greenery (Scale 1:1000)

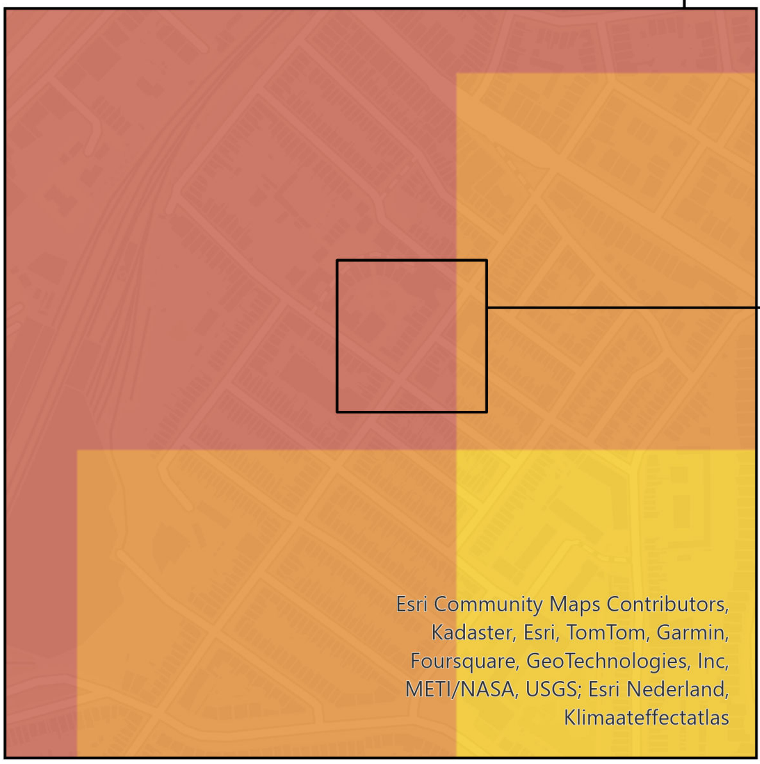



Percentage of Greenery per Neighborhood in Utrecht - Scale: 1:25000
N
0 - 10%
10 - 20%
20 - 30%
30 - 40%
40 - 50%
50 - 60%
60 - 70%
70 - 80%
80 - 90%
90 - 100%
Galecopperlaan
Kadaster, Esri, TomTom, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

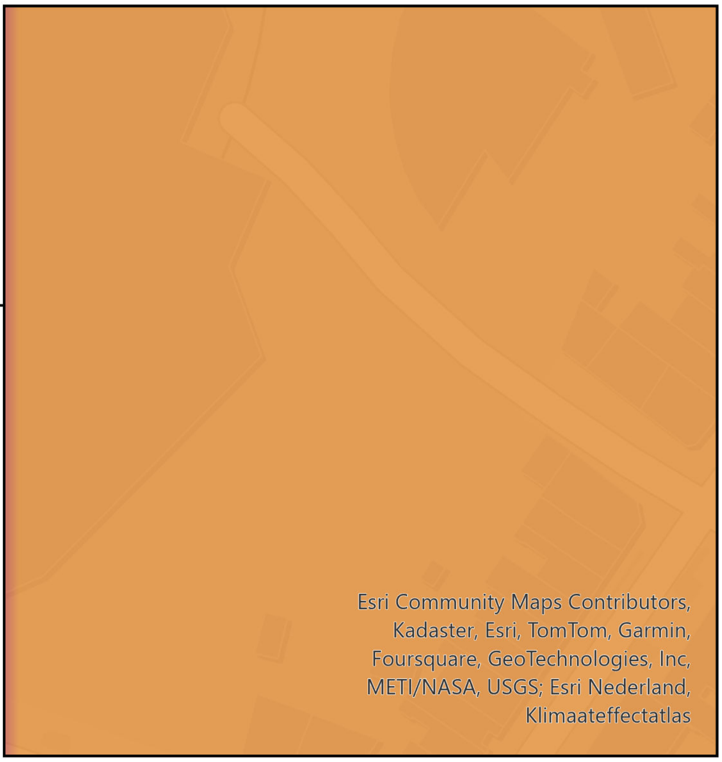
Mean Highest Groundwater Level - Current: Location 1 (Kop Voordorp)



Mean Highest Groundwater Level Macro (Scale: 1:20000)



Mean Highest Groundwater Level 500x500m (Scale: 1:5000)



Mean Highest Groundwater Level design area (Scale: 1:1000)

Moreover, using the digital twin of the subsurface in Utrecht, provided by the webviewer Utrecht3D [20], it is possible to see that there is a lack of subsurface congestion, meaning that there is free space underground and the size of underground intervention does not need to be necessarily reduced. The surface also does not require a reduced size or weight for the interventions because a 2D map on the Atlas geoportal of the province of Utrecht [19] indicates that the area is suitable for building and can handle weight.

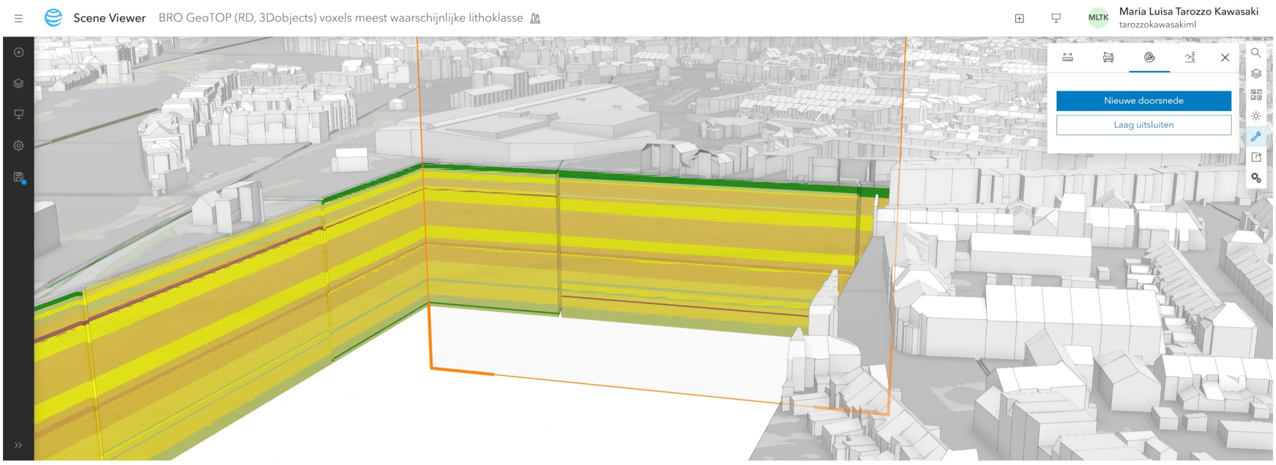


Figure 7.1: Kop Voordorp and clay (green) subsurface soil

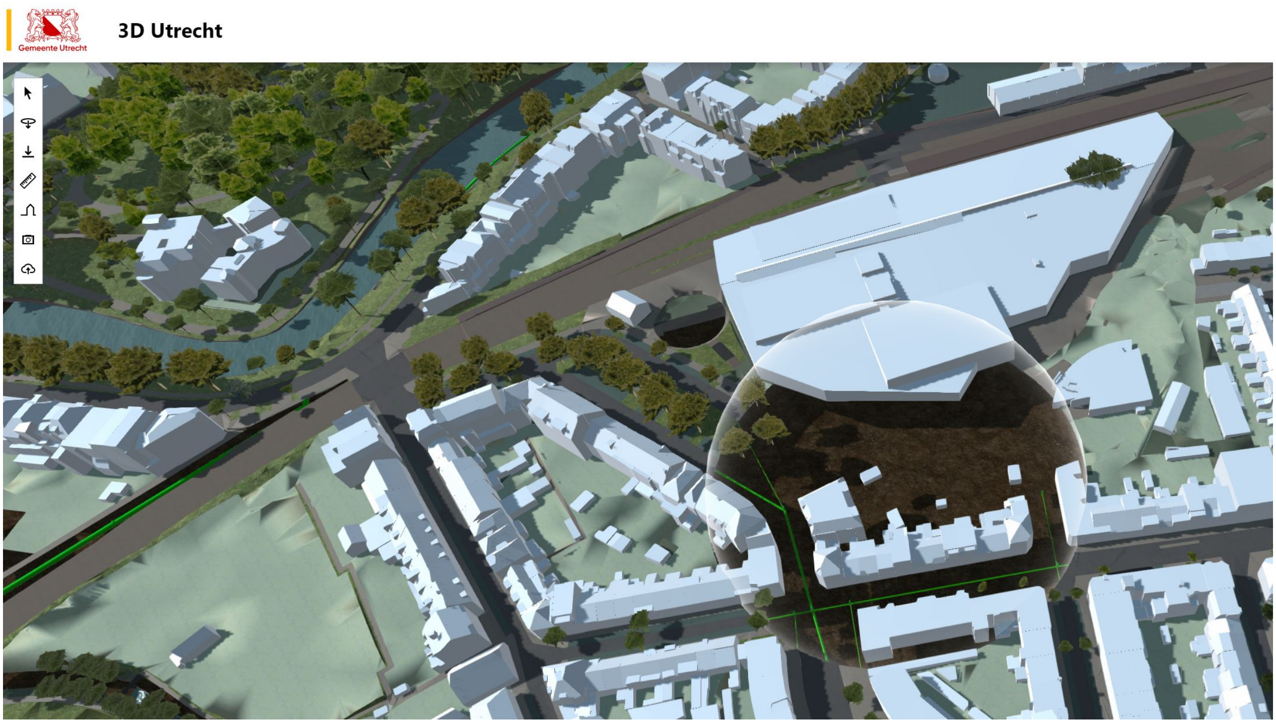


Figure 7.2: Kop Voordorp presents a lack of subsurface congestion

Social and ecological aspects of the area were also taken into consideration to the design. The neighborhood has been losing inhabitants numbers ever since 2016, when it has 5255 inhabitants. In 2022 it reached its lowest number in the past ten years: 4970. [63] The museum that is part of the 500 by 500 meter studied area present one of the biggest

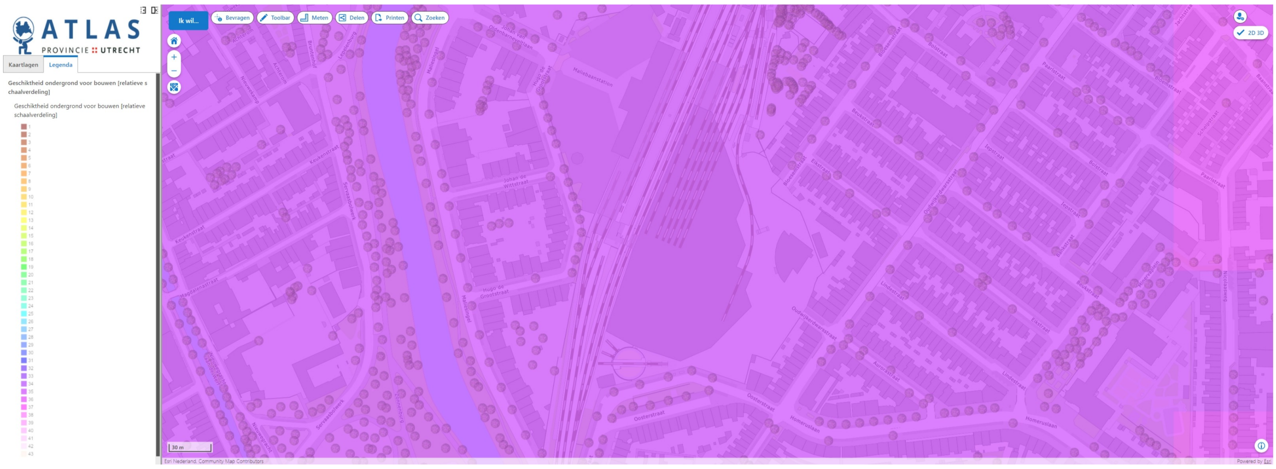


Figure 7.3: Kop Voordorp can support the weight of new buildings

attractions of the neighborhood, having more than ten thousand reviews online [64] from not only locals. Including more urban and ecological qualities aims to improve a public space that seemingly presents an important role in the social life of the neighborhood, bringing a better space for locals but also attracting new inhabitants.

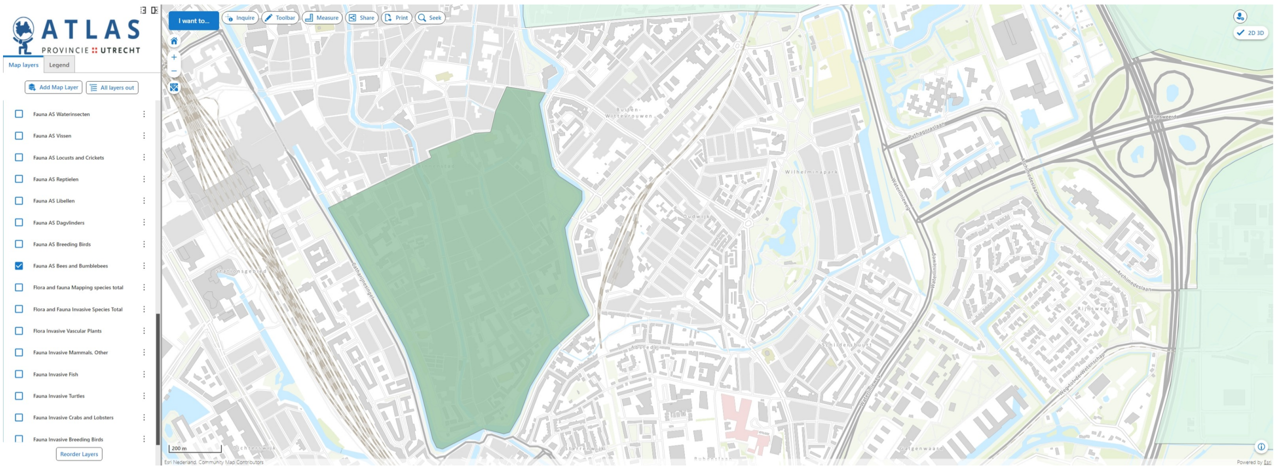
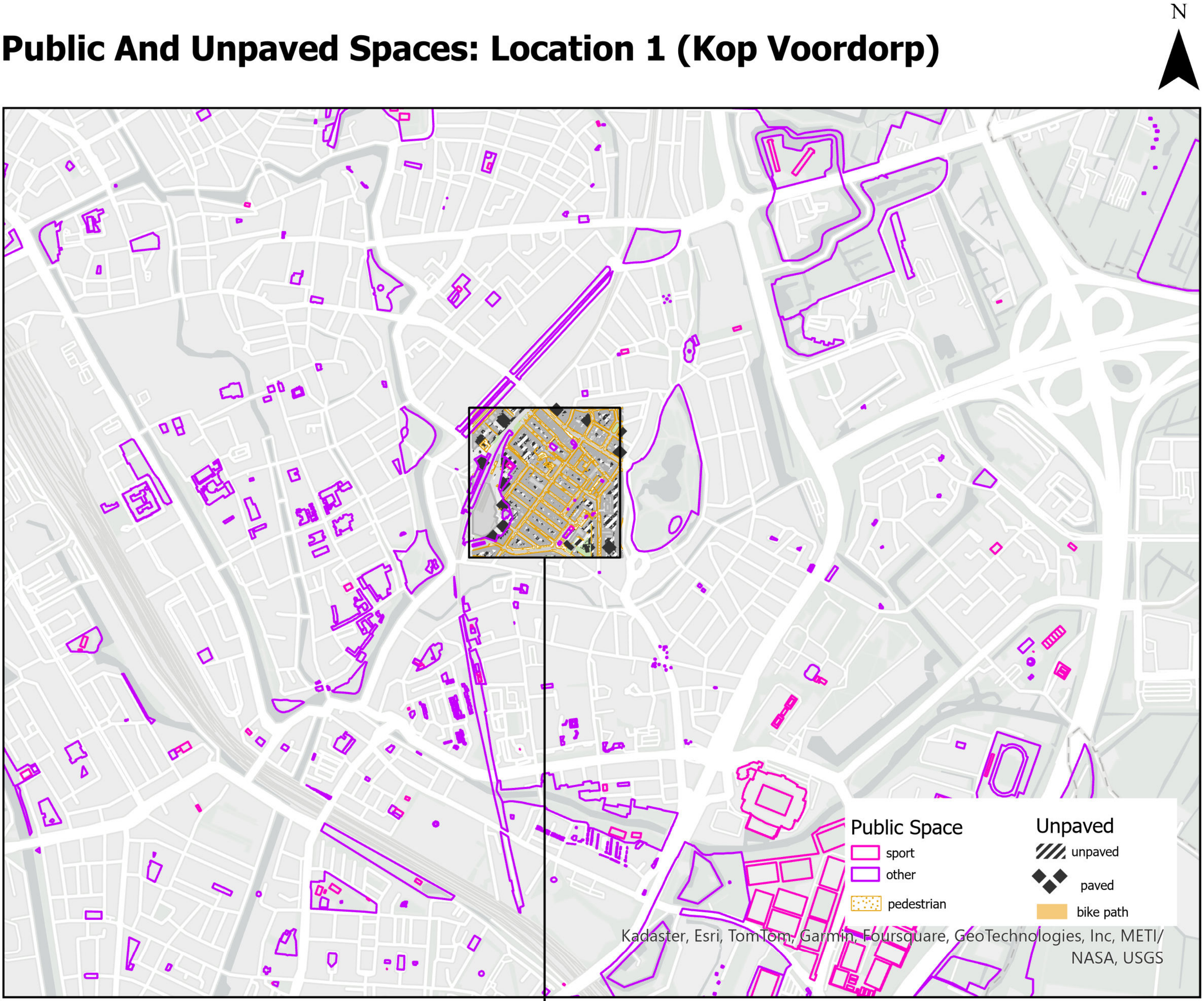


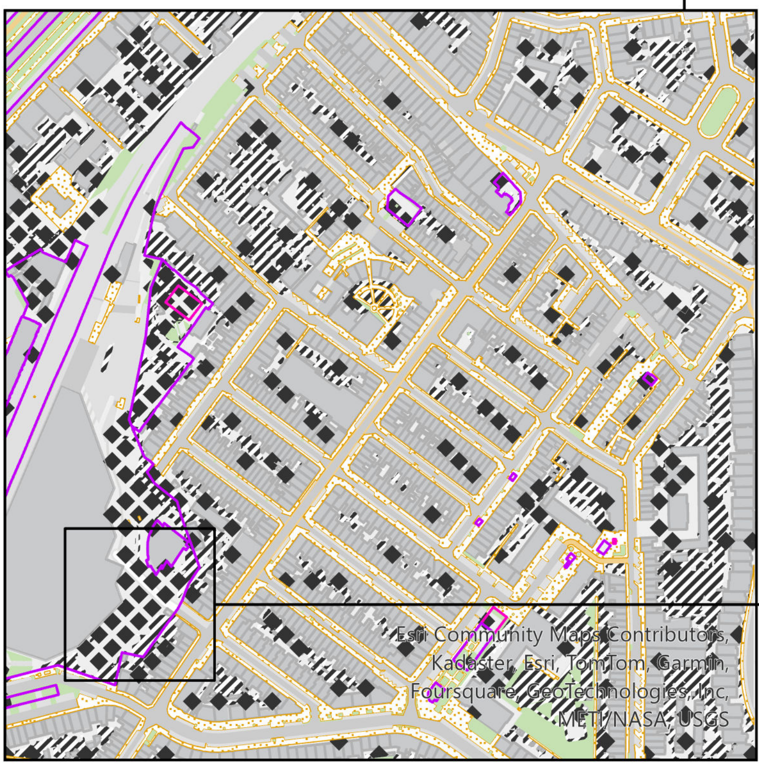
Figure 7.4: Kop Voordorp and the presence of bees

From an ecological point of view, a study was made on relevant species that could be introduced to the neighborhood via the Sonnenborgh Park, creating an ecological continuation while introducing biodiversity to an area that already lacks greenery. The park presents a concentration of bees, in particular bumblebees that could be introduced to the area. In addition, the park and the neighborhood already seem to be connected by the presence of bats, that eat insects including bees. Insect and bat boxes could be introduced in the design to facilitate nesting for these animals.

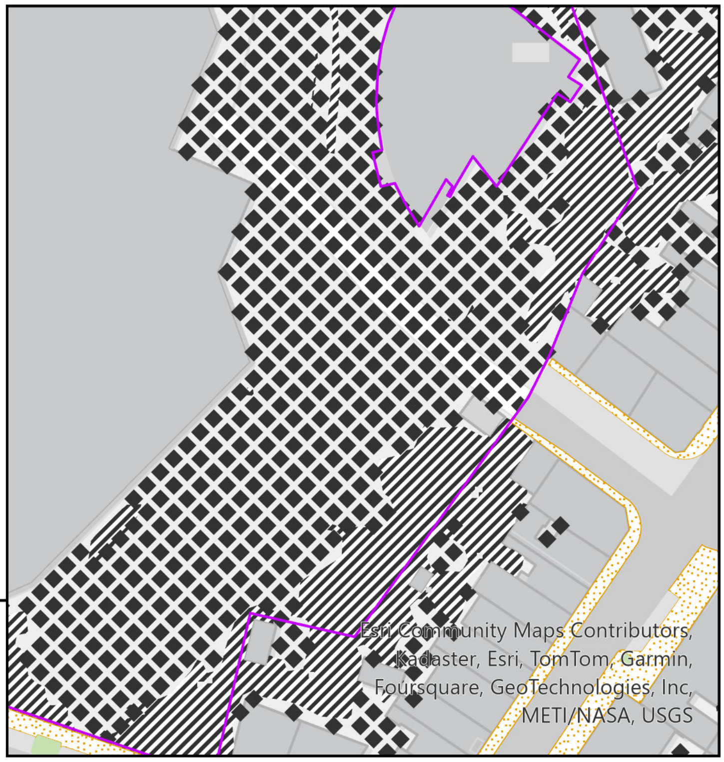
Public And Unpaved Spaces: Location 1 (Kop Voordorp)



Public/Unpaved Spaces Level Macro (Scale: 1:20000)



Public/Unpaved Spaces 500x500m (Scale: 1:5000)



Public/Unpaved Spaces design area (Scale: 1:1000)

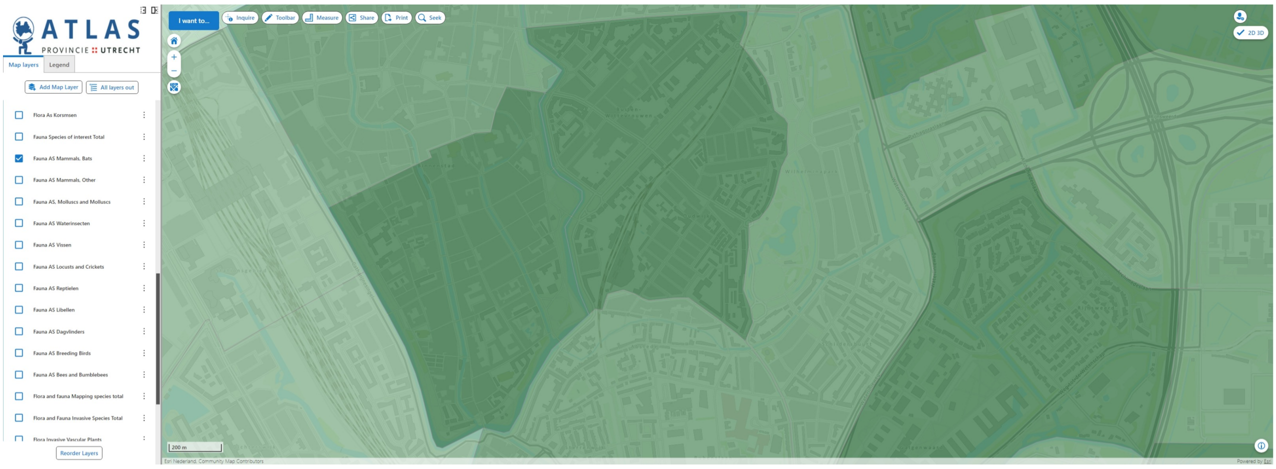


Figure 7.5: Kop Voordorp and the presence of bats

The choice for fauna and flora takes into consideration these species, while the choice of urban furniture and urban qualities take into consideration the social aspects. Moreover, all choices are based on the subsurface properties that were identified. For example, certain trees species are known to benefit from a clay soil while attracting bumblebees, such as the wild horse chestnut [65] [66]. This large tree's root can reach a significant depth, and thus would benefit from an area that lacks subsurface congestion, such as this one.

During spring, from May to June, wild horse chestnuts present tall white flowers, which would add aesthetic qualities to the public space. On the rest of the year, other flowers could be introduced that are also known for attracting bumblebees such as Christmas roses, that flower from January to April [67]. This flower is also known for attracting bees and for benefiting from clay soil.

Flower and smaller plants could be introduced on the ground level but also as a green rooftop, adding a new built space for public activities to the area, such as a coffee, small restaurant or other public and commercial facility. As noticed before, the area can handle the weight of new construction, especially a building with the added weight of a green rooftop.

Regarding local standards and guidelines, the chosen interventions are related to local standards regarding biodiversity such as: ecological solutions are preferable to 'grey' solutions (B1), where 30% of the surface is greenery (B2) and local fauna preserved (B3). All these are respected in this design, especially through the introduction of a green roof when it comes to B2. [54] Regarding heat, local standards for the city of Utrecht request that a minimum of 40% shade for rest areas and slow-moving traffic zones during peak sun exposure (21 June), and 30% shade coverage at the neighborhood level (H1), with cool shaded resting spots are available within a 300-meter walk and open to the public (H2), [54] the introduction of shadow provided by the chestnut tree, the new building and the introduction of greenery. On a national level, the Maatlat indicates that is necessary to prioritize local habitats, that green solutions are preferred over technical ones, and maintain a neighborhood level of greenery [15]. All of this is done in this design through the study of local ecological qualities and tge indification where there is a lack of greenery. This national guideline also indicates that 40-50% of the area must be heat-resistant, which is done through the introduction of greenery and shadowing. Moreover, the Maatlat states that green roofs never count as paving, adding to the percentage of unpaved surfaces even where the building will be built. It is interesting to notice that the percentages indicated by local standards and guidelines provide a numerical way of evaluating the design and the benefits of using subsurface information during the design process.

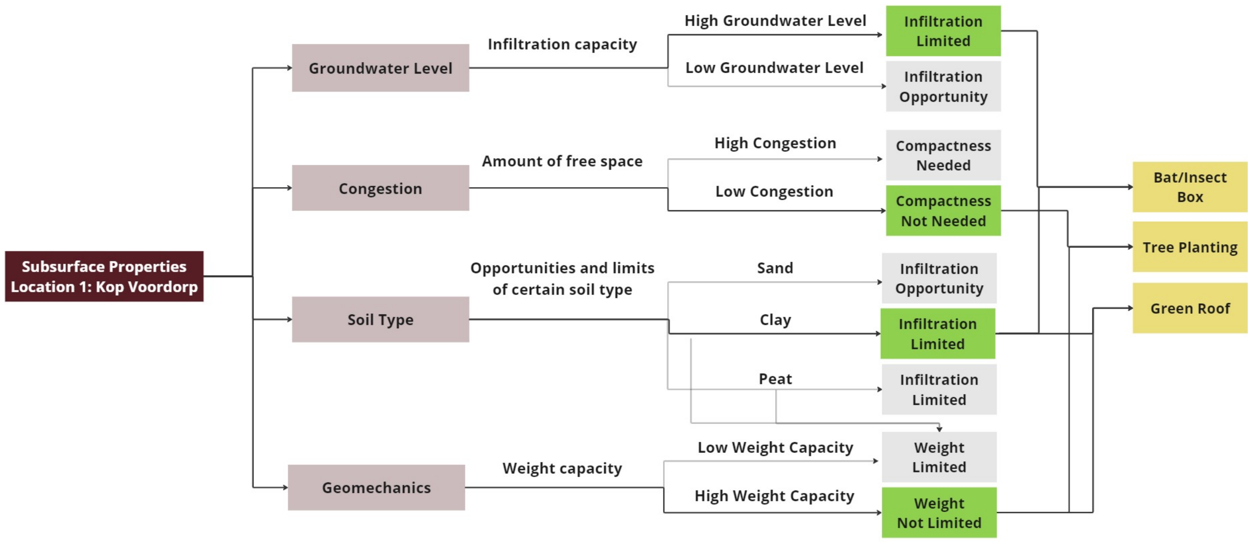


Figure 7.6: Kop Voordorp Design Decision Tree

Area 1 (Kop Voordorp): Adaptation Design Plan

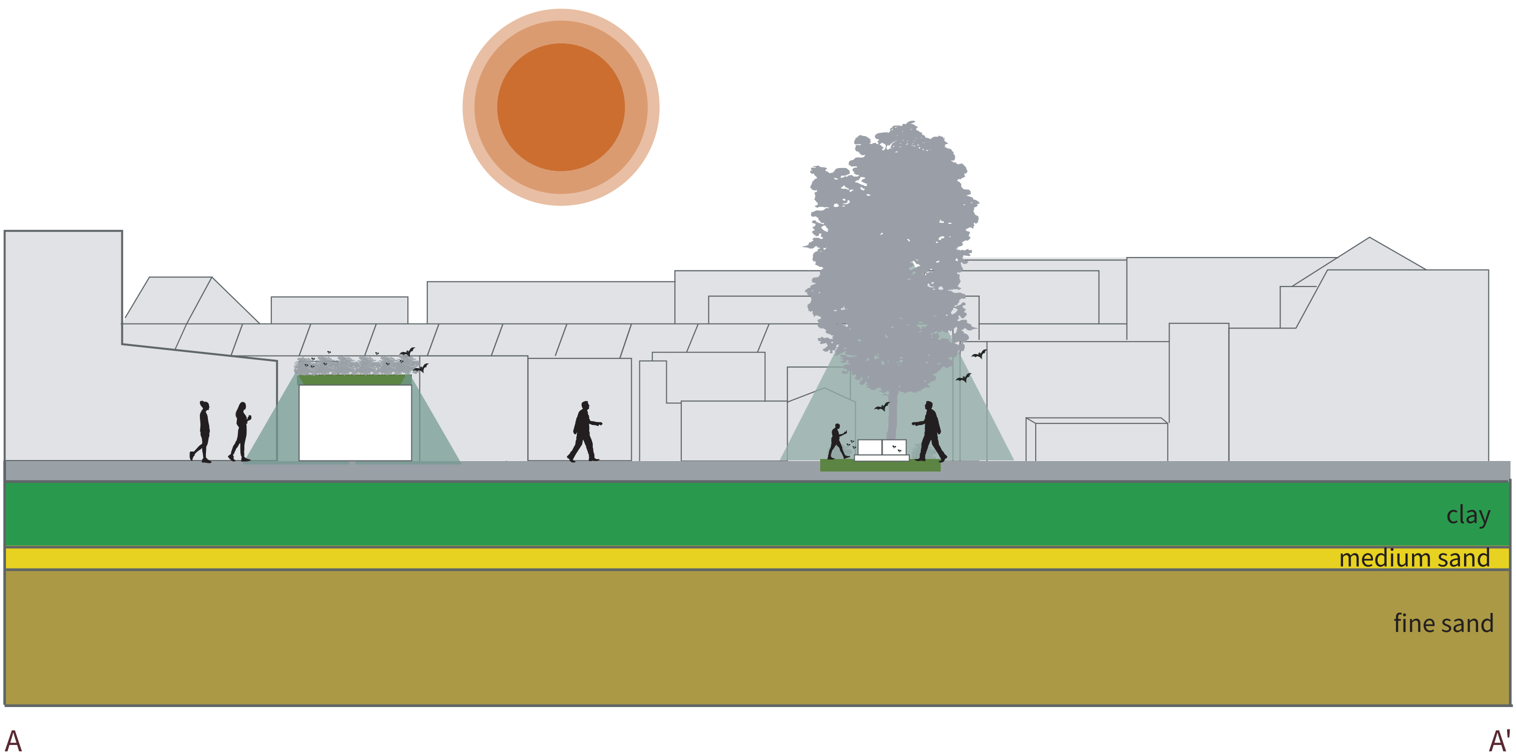
Green Roof

Tree Planting

Bird/Bat/Insect Box

Area 1 (Kop Voordorp): Adaptation Design Impression

Area 1 (Kop Voordorp): Adaptation to Heat and Lack of Biodiversity



Regarding data resolution requirements, more resolution would have been useful, in particular for the tree planting aspect. In a more detailed section, one can see that the vertical resolution of 50 cm is enough but the horizontal resolution of 100 m is not as detailed as it would have been necessary for such a punctual intervention.

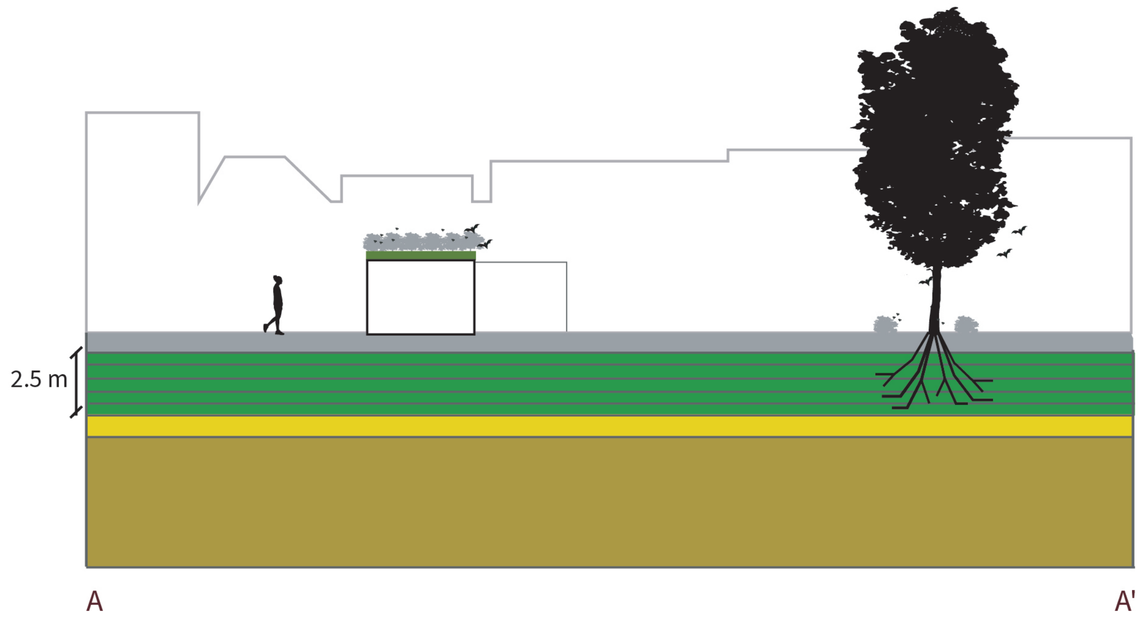


Figure 7.7: Detailed tree root section

7.2. Area 2: Lunetten Zuid

A map from the Klimateffectatlas indicates the flood depth on a large to medium probability [9]. This is a national scale map but is is still possible to identify that flood is more or less relevant to the different studied area. From all the four areas, Lunetten Zuid has the highest flood depth, indicating that this is its most relevant climate issue.

On the other hand, heat stress adaptation is aided by a concentration of greenery and shadow in certain roads. From a map by the municipality of Utrecht of the air temperature during a heat wave [18], it is possible to identify the cooler roads, which cross the area horizontally. These roads are indicated in the map in blue. The design for Lunetten Zuid decided to also take into consideration ways in which the neighborhood is already adapting to a climate challenge and improve these areas.

Regarding the subsurface, the first few layers of Lunetten Zuid consists of clay, a soil type with low infiltration capacity [12]. In addition, the area contains cables in the main waterway and on the main street (Simplonbaan street) but not on the crossing street along the main waterway, which is where the design focuses.

The infiltration capacity is also limited by the high groundwater level in the area [17], being interventions related to water infiltration not suitable for this area, even if water infiltration is

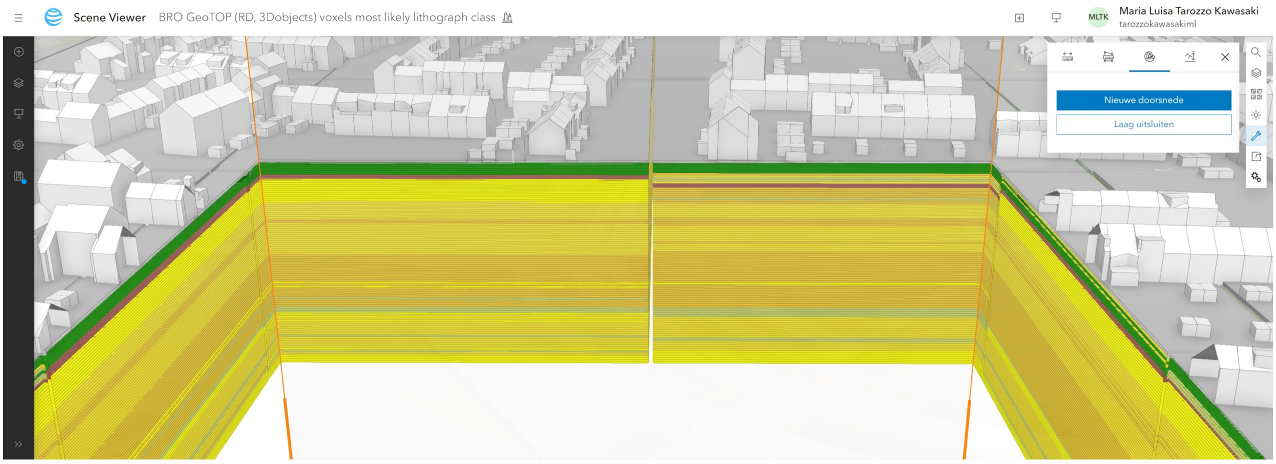
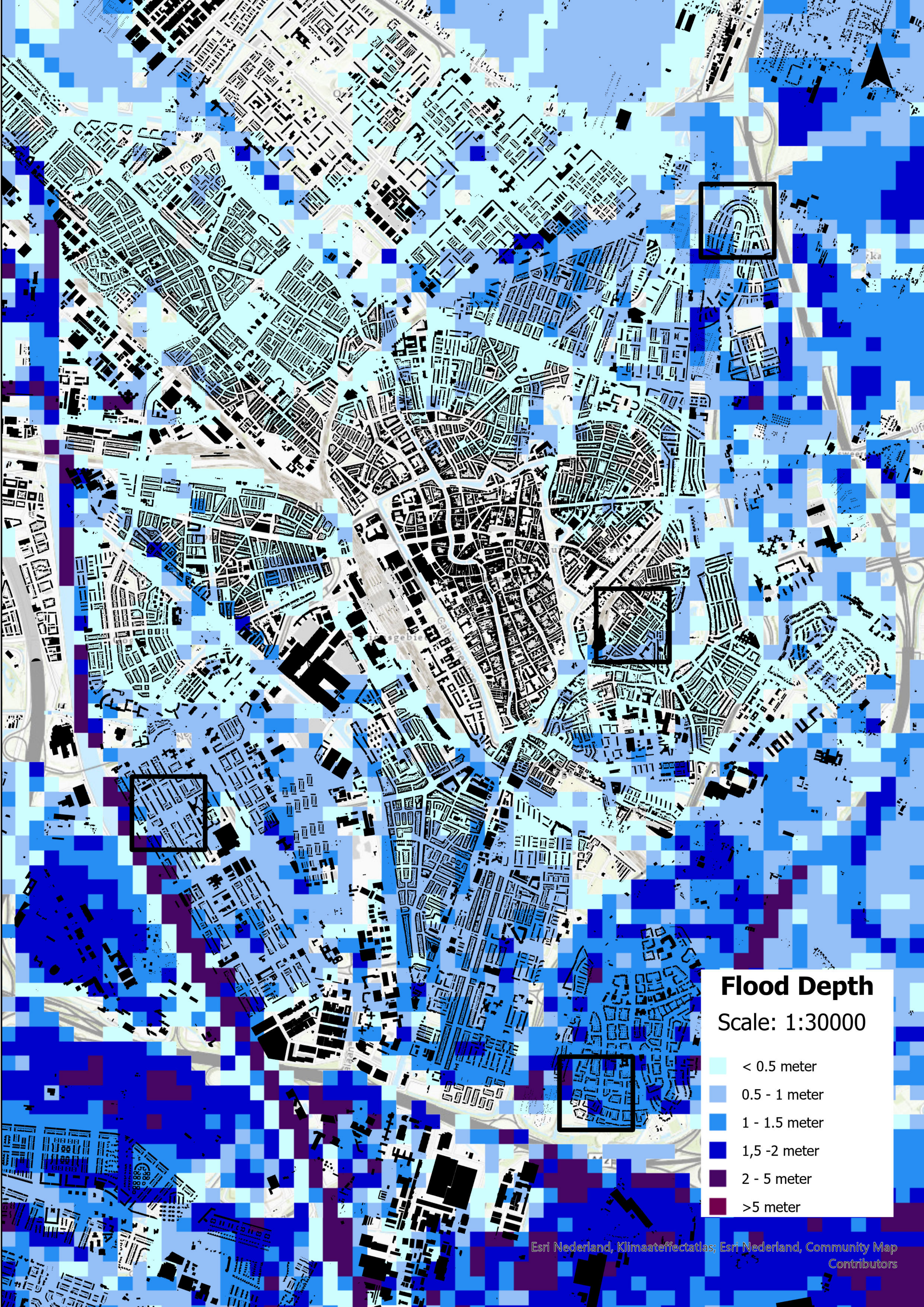


Figure 7.8: Lunetten Zuid and the presence of clay (green) soil

often used as a flood adaptation.

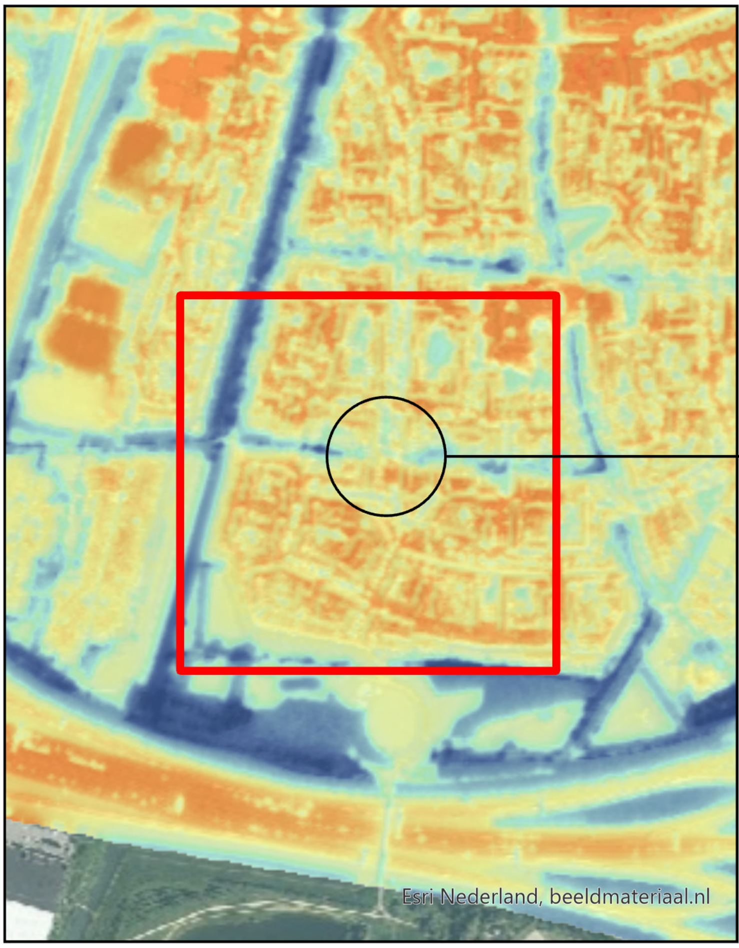
Thus the adaptation to flood must come from a water storage solution. However, the area presents an unequal distribution of geomechanics properties [17], thus different portions of the area require a different treatment. Overall, having the crossing at Simplonbaan as the divisor, requires a more compacted design solution on the left portion and it does not on the right portion of the design area.


Flood Depth
Scale: 1:30000
< 0.5 meter
0.5 - 1 meter
1 - 1.5 meter
1,5 -2 meter
2 - 5 meter
>5 meter
Esri Nederland, Klimaateffectatlas; Esri Nederland, Community Map Contributors

Climate Challenges: Location 2 Lunetten Zuid

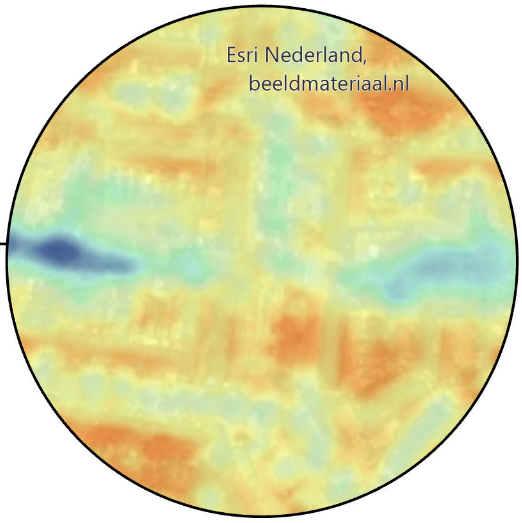
N

Heat: Air Temperature at 1.5 m on a heat wave (Scale 1:1000)



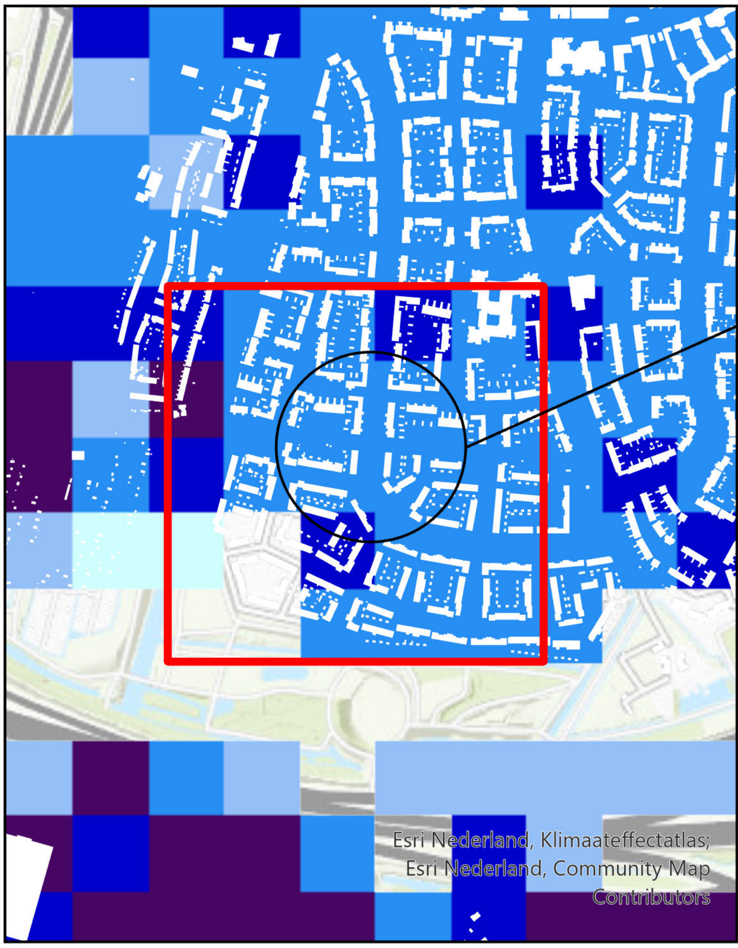
During a heat wave, the air temperature is low only where greenery is present: the main parks and roads with high number of trees.

Zoom Scale 1:3000

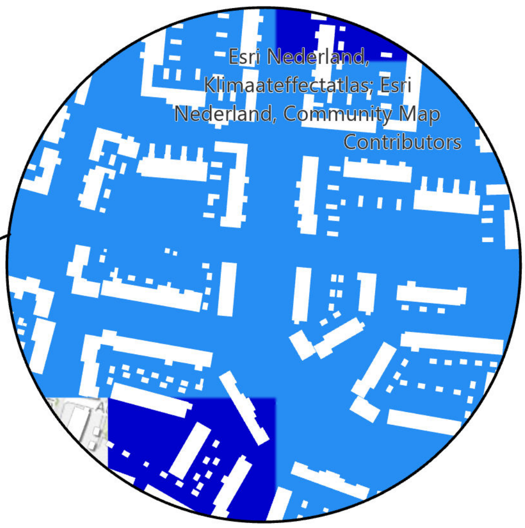


The selected project area includes an intersection with lower temperature horizontally, and higher temperatures vertically.

Flooding: Flood depth average probability (Scale 1:1000)



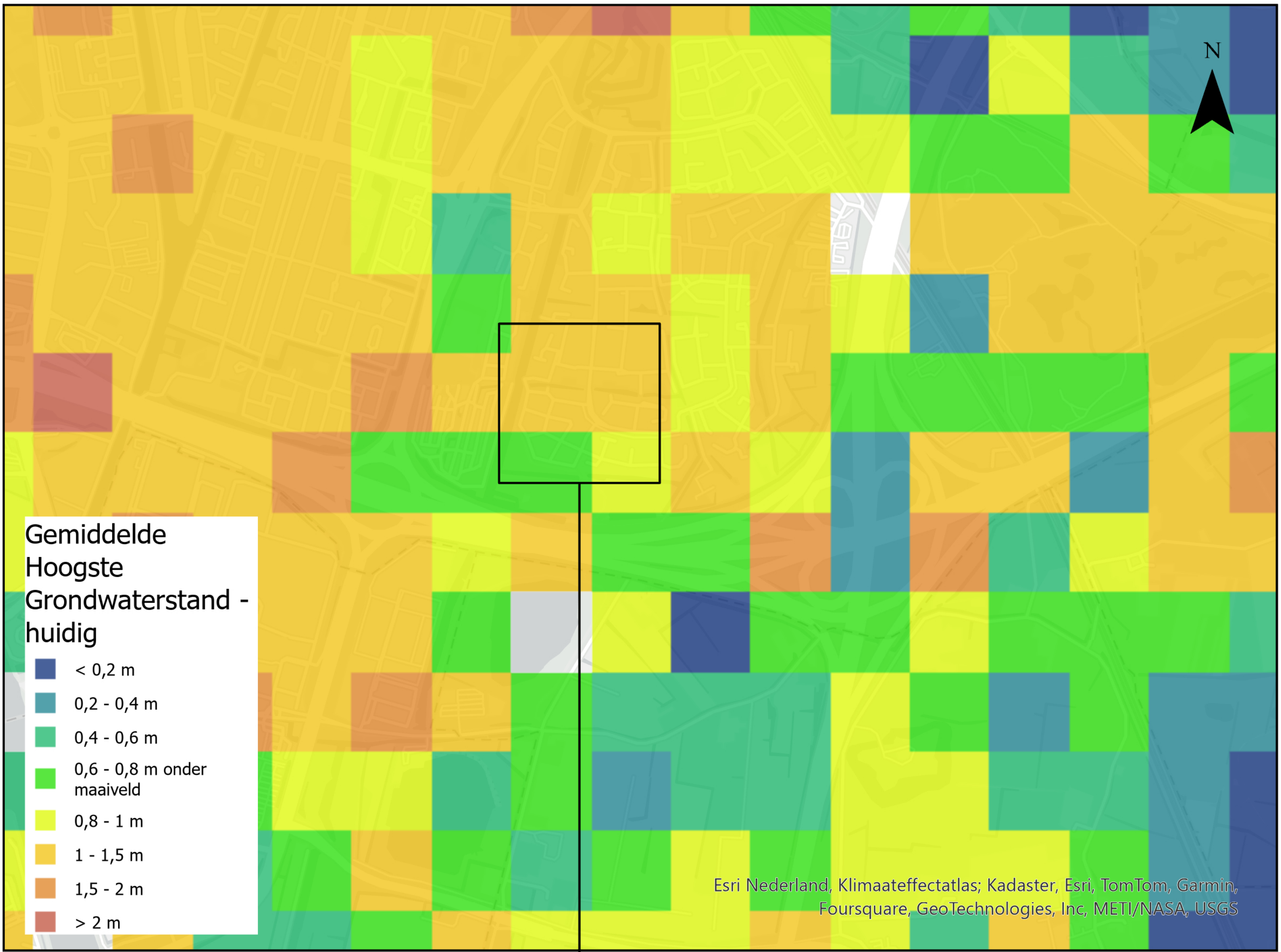
Zoom Scale 1:4500



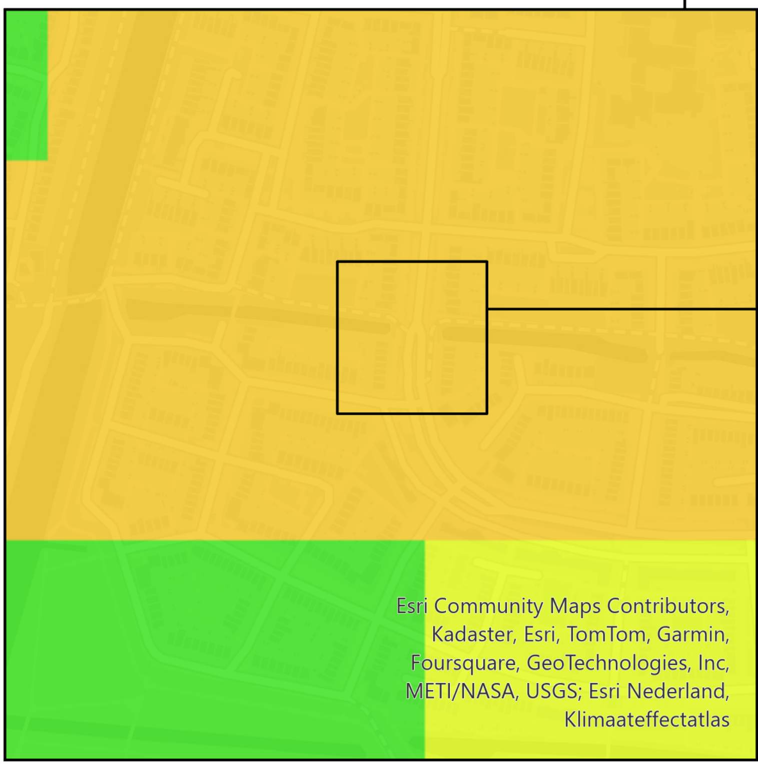
Moreover, the selected area is between spots where flood depth can get to up to 2 meters.

- < 0.5 meter
- 0.5 - 1 meter
- 1 - 1.5 meter
- 1,5 -2 meter
- 2 - 5 meter
- >5 meter

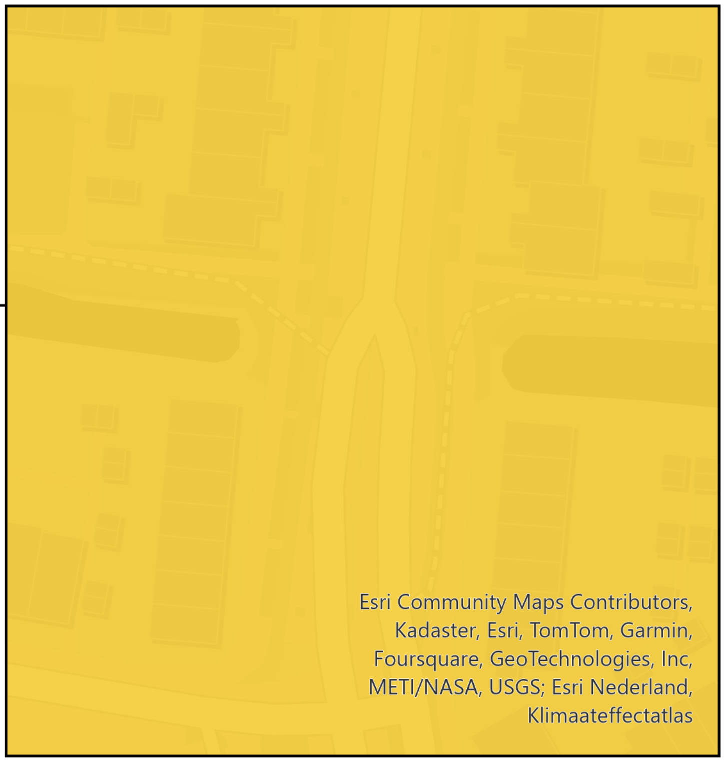
Mean Highest Groundwater Level - Current: Location 2 (Lunetten Zuid)



Mean Highest Groundwater Level Macro (Scale: 1:20000)



Mean Highest Groundwater Level 500x500m (Scale: 1:5000)



Mean Highest Groundwater Level design area (Scale: 1:1000)

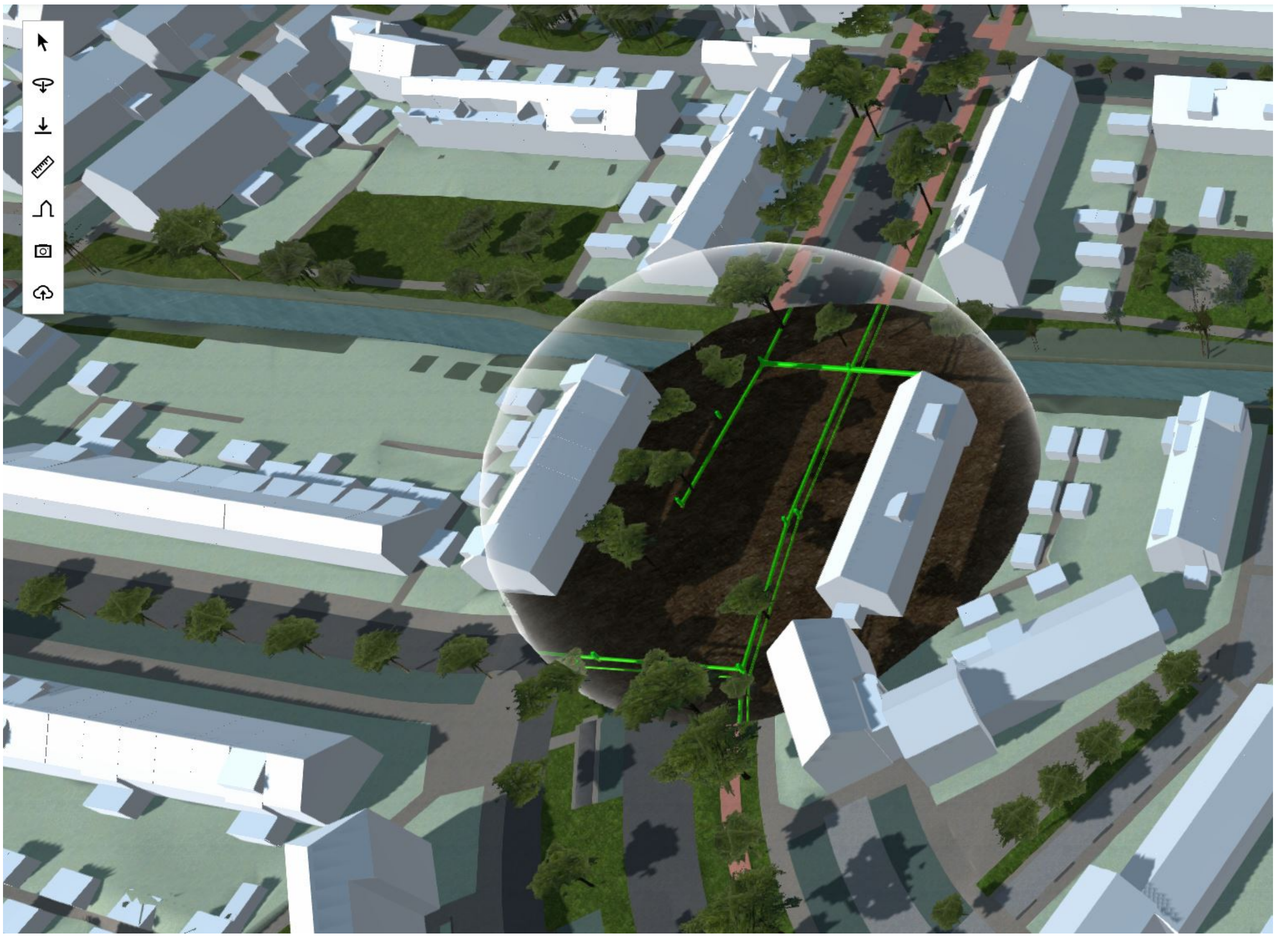


Figure 7.9: Lunetten Zuid is mostly clay (green) soil

From a social anaysis, the main age group living in Voordorp are citizens, more likely professionals, from 25 to 45 followed by 45 to 65 [68]. The major public space is the park in the bottom left of the studied 500 by 500 meter area. [18] The park is now not directly connected to the neighborhood. In addition, the closest sports area is inside of the park, being no other fitness public spaces in the area. The predominant age groups in Lunetten Zuid however would benefit from a fitness center closer to their homes for health reasons. The design thus proposes a fitness square combined with a covered public sports center. In the second one, a water roof is included, allowing rainwater to be collected.

Moreover, there is a predominance of paved surface instead of unpaved ones. However, due to the high groundwater level of the area and the presence of clay, infiltration is not interesting for the project.

There are also two playgrounds in the area. The existing playgrounds were converted into water squares with playground activities.

Where surface water already concentrates in the waterways the area was enlarged and the area of surface area extended. Where the surface water area was increased, the area around it was requalified as a public resting space with new urban furniture by the water body.

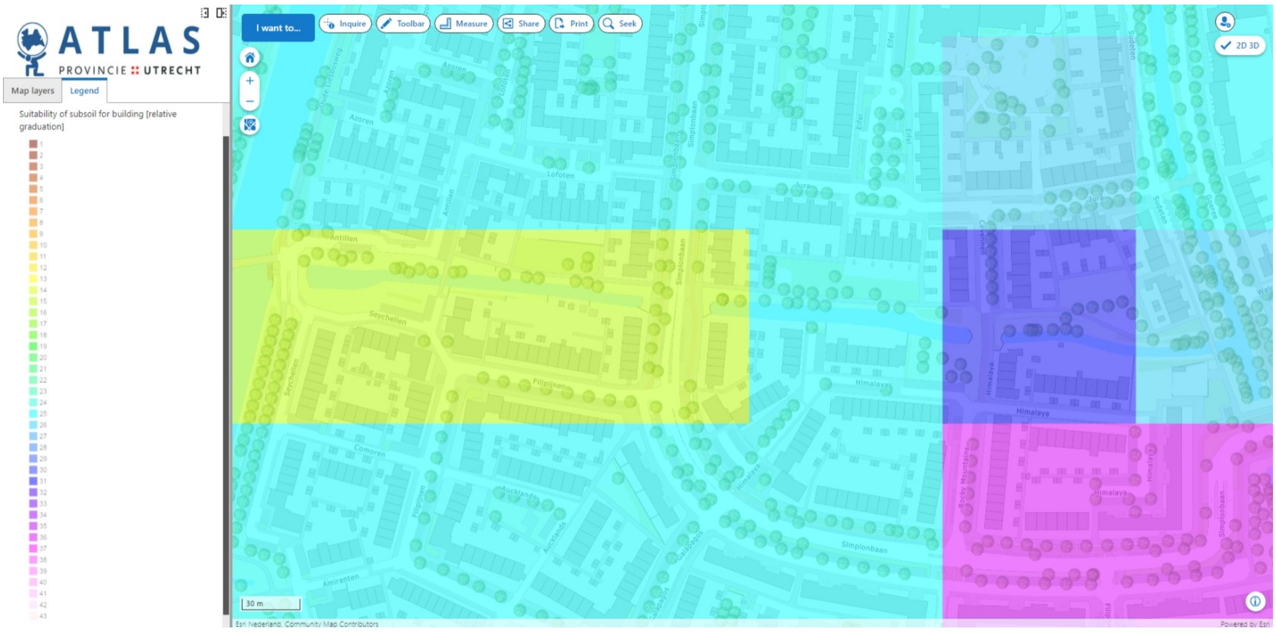
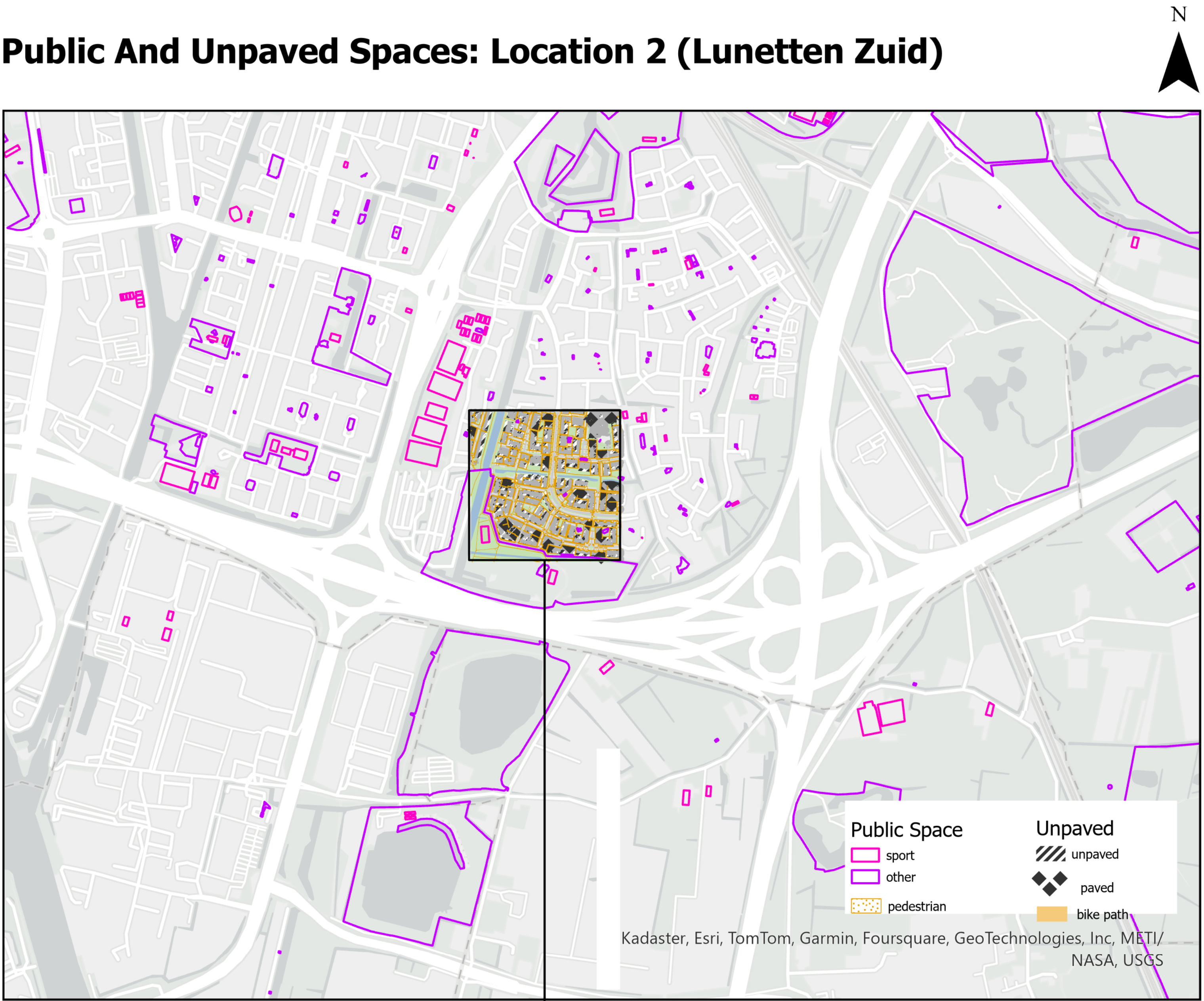


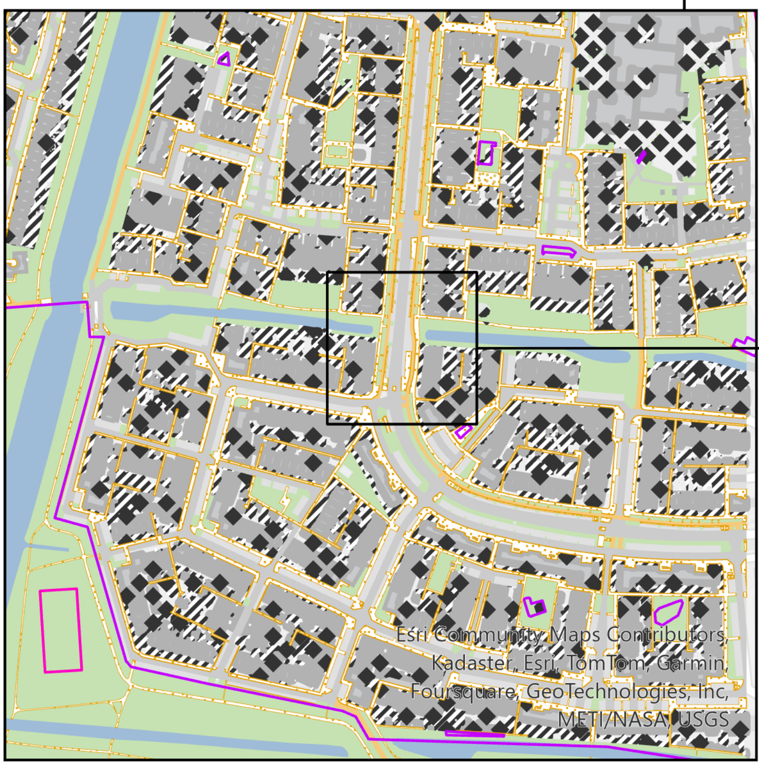
Figure 7.10: Lunetten Zuid is mostly clay (green) soil

The population in Lunetten Zuid is decreasing (7110 in 2019 vs 6980 in 2022) [68]. Requalifying public spaces can aid stopping the trend of a decrease in number of inhabitants by improving the surrounding for current and future population.

Public And Unpaved Spaces: Location 2 (Lunetten Zuid)



Public/Unpaved Spaces Level Macro (Scale: 1:20000)



Public/Unpaved Spaces 500x500m (Scale: 1:5000)

Public/Unpaved Spaces design area (Scale: 1:1000)

All these re-qualified or new public spaces are linked through a green corridor that connects the most inhabited part of the neighborhood portion of Lunetten Zuid [68] to the main public space (park) via a corridor that crosses Simplonbaan. This created corridor follows the main waterway and is already shadowed and cool compared to other areas in the neighborhood due to the existing presence of greenery. The corridor moreover connects and creates multiple public spaces which are now leftover spaces along the main waterway or small disconnected playgrounds. The design thus prioritizes existing adaptive aspects, such as natural shadowing and the presence of a water body, but improve it by adding urban and ecological qualities while strengthening climate adaptation.

Of major importance is to create a continuation for the pedestrian path in the main street Simplonbaan. This can be done through a new pedestrian crossing in that spot. In that same intersection two public spaces are visible, inviting those who take public transport to enter the corridor.

The three local interventions are all an adaptation to flood, the main climate challenge in the area, but are positioned in a road that is already adapting to heat stress, improving and adding more activities in this corridor.

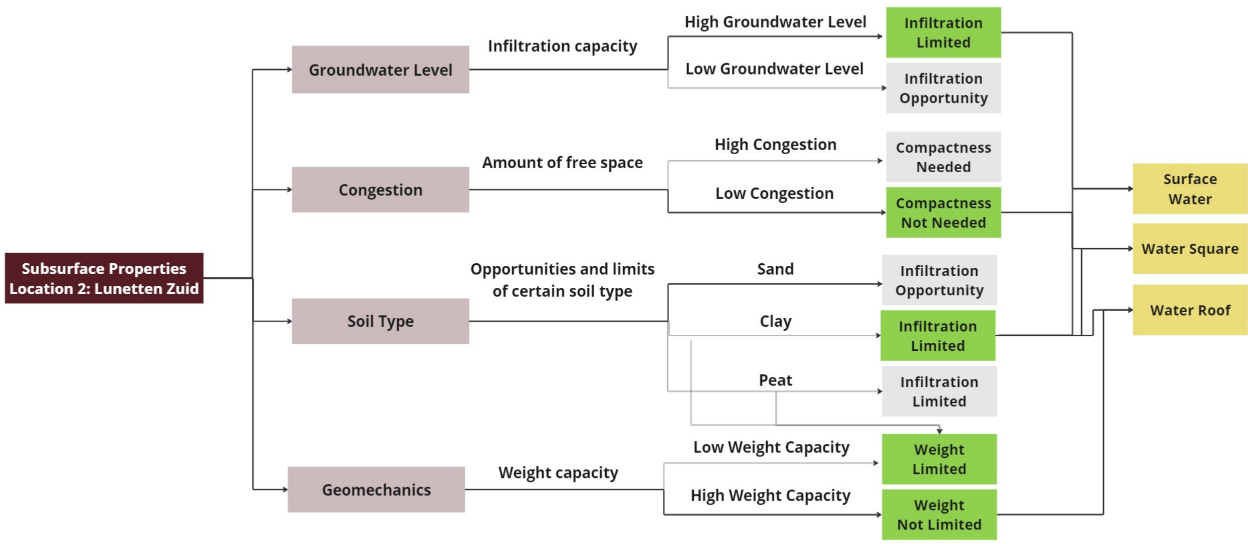
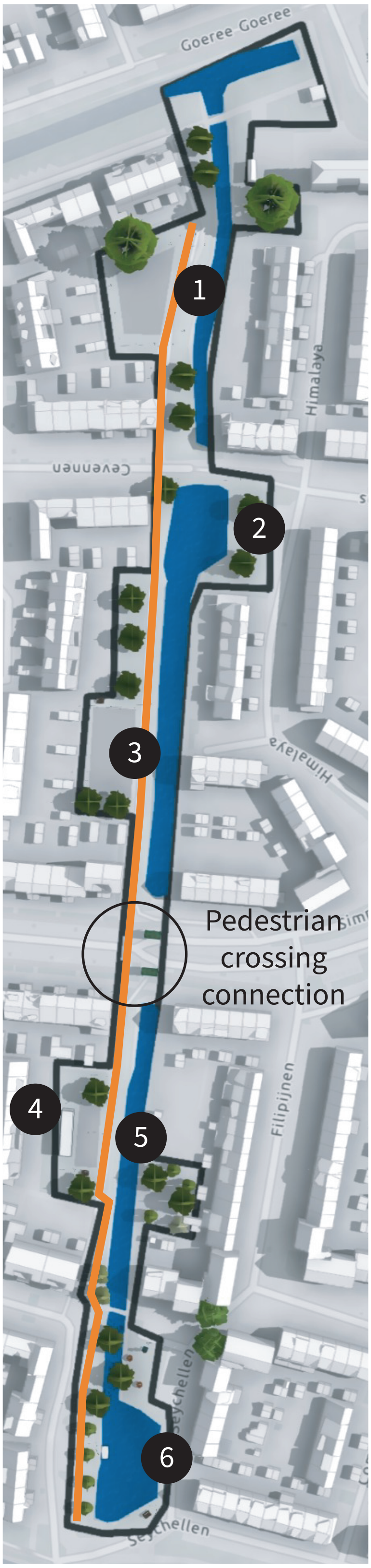
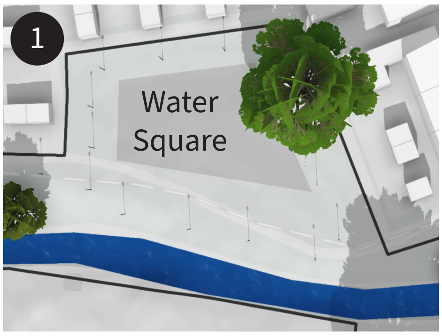


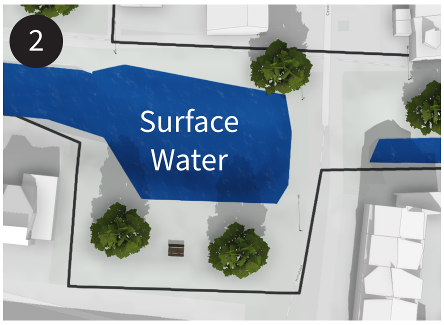
Figure 7.11: Lunetten Zuid Design Decision Tree

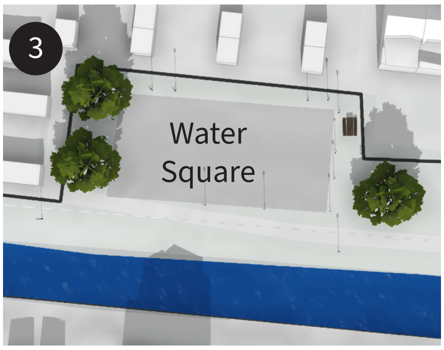
Regarding national guidelines, the national level document, Maatlat, states that no water damage on a shower that could happen every 100 years and at 0.2 m water depth at the street. [15] These are the same numbers that the climate scenarios were based upon. In addition, local standards regarding Utrecht indicates that local fauna should be preserved (B3), which it is by maintaining the existing greenery and enlarging the main water body. No water damage occurs during a 100-year shower, or 250-year for vital functions (N1), a large part of the precipitation (50 mm) on private land is infiltrated, retained and/or stored (N2), or/and at 0.2 m water depth at the street (V1), and the development is water-neutral and will not lead to additional water supply/drainage. (N3), all of thus are fulfilled through the design, and due to the limited opportunity for soil infiltration, the water is stored in the rooftop, in the enlarged water surface, and in the water squares.

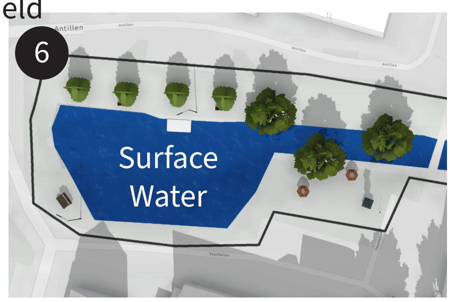
Area 2 (Lunetten-Zuid): Adaptation Design Plan











Water Square

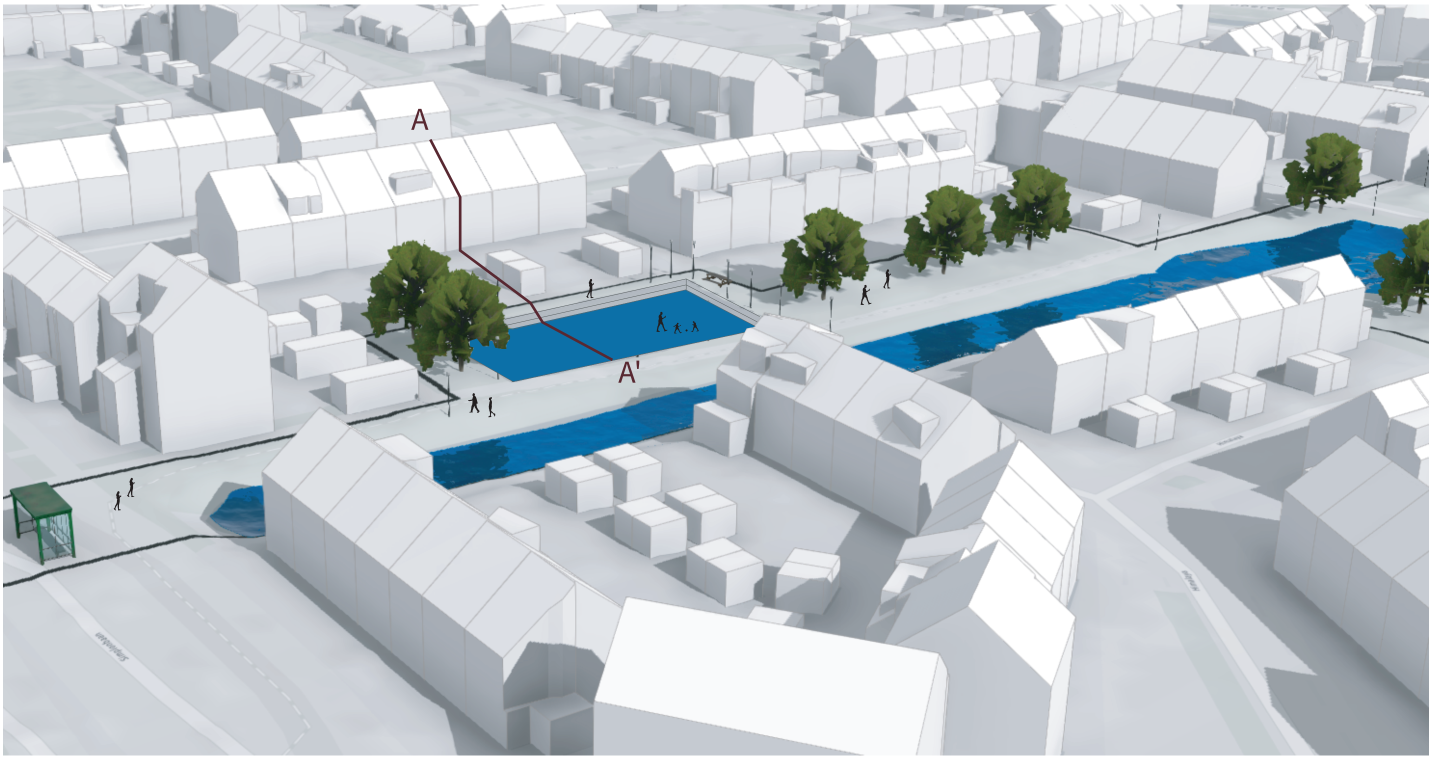
Surface Water

Water Square

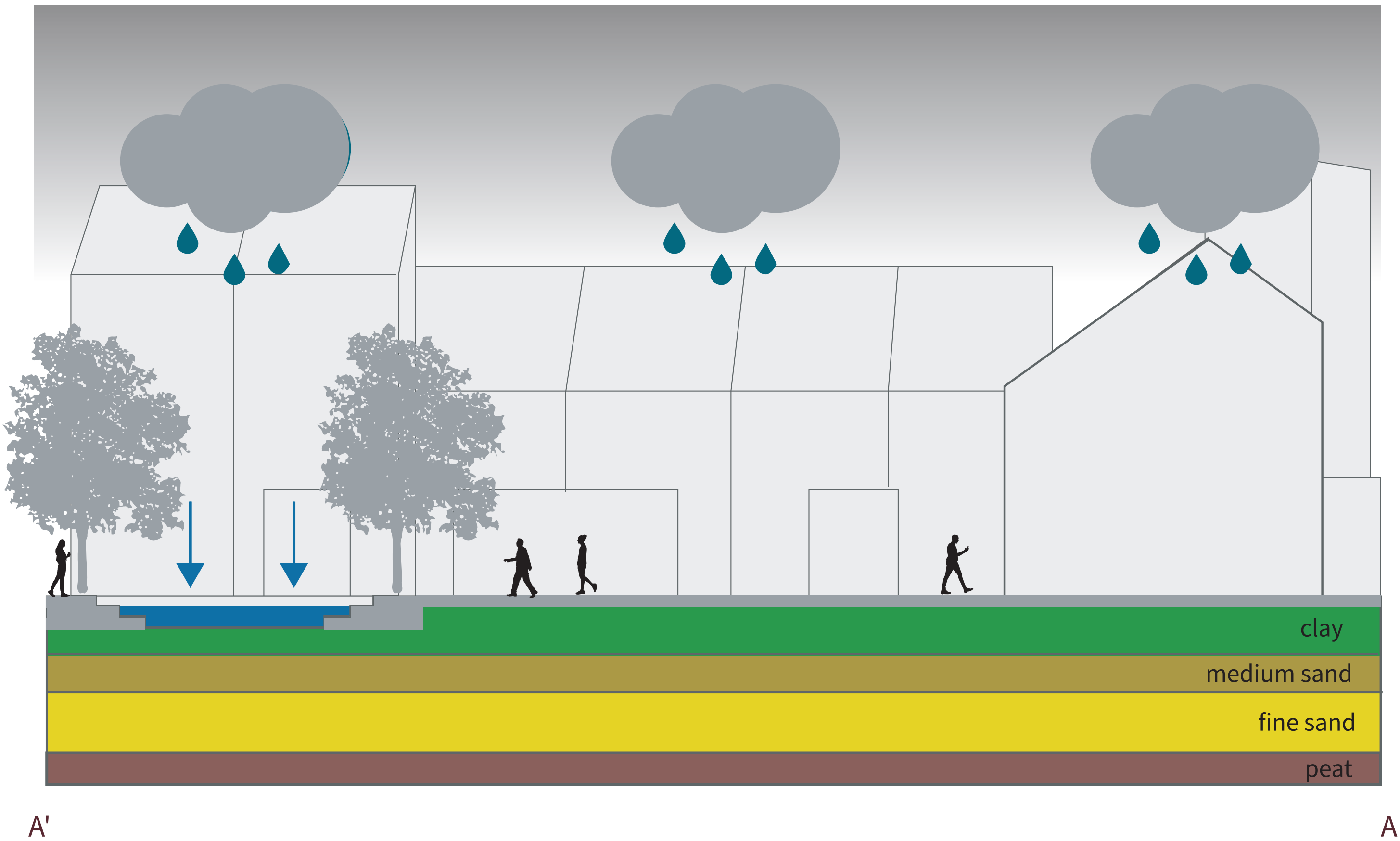
Water Roof

Surface Water

Area 2 (Lunetten Zuid): Adaptation to Flood (Water Square)



Area 2 (Lunetten Zuid): Adaptation to Flood (Water Square)



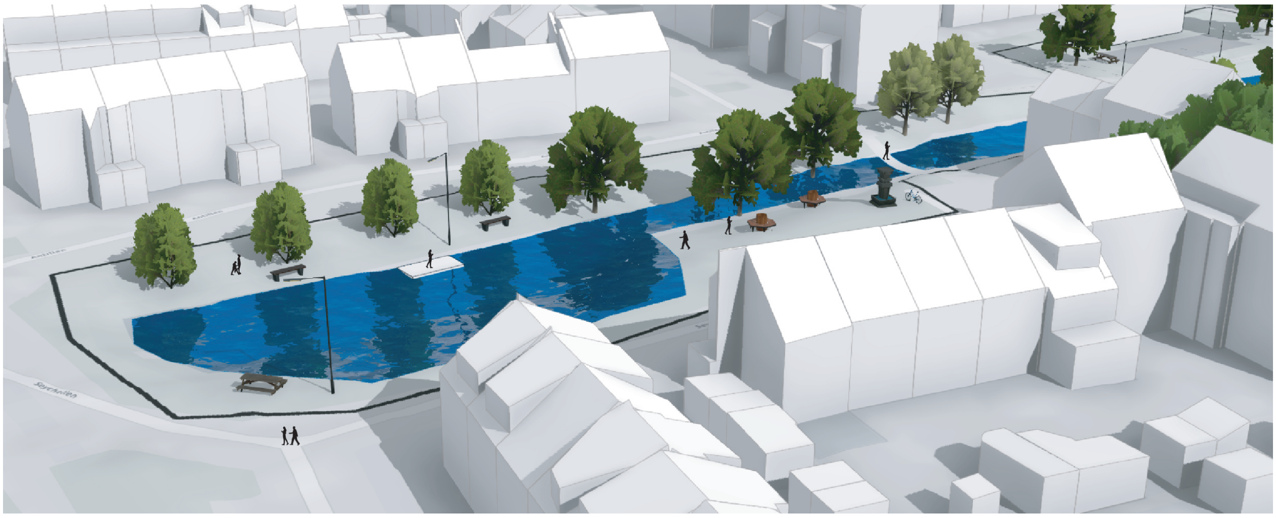


Figure 7.12: Surface Water Impression

In the case of Lunetten Zuid, the absence of horizontal detailed resolution was only felt regarding the water squares. The first clay layer is around 3 m deep and the water square goes deep 1.5 m. If the soil type information is accurate, this resolution is enough to guarantee a solid ground to place the water square. However more detailed data regarding the horizontal aspect would have been beneficial. For example, if instead of clay, part of the 100 m cell is made of a different type of soil, there might have been problems related to part of the water square being build in a soil type and part of another.

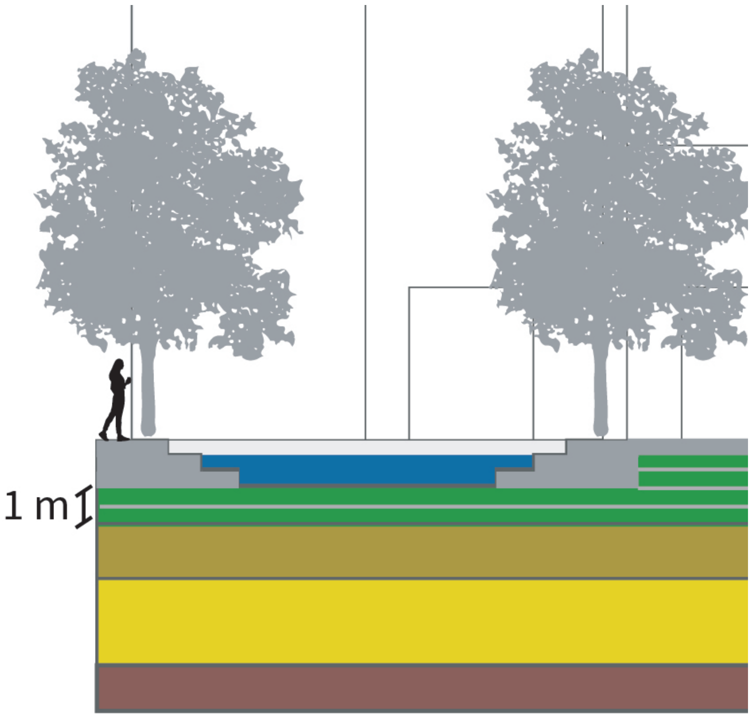


Figure 7.13: Detail Water Square

7.3. Area 3: Kanaleneiland Noord

Kanaleneiland Noord is one of the areas previuously identified that suffers from a lack of greenery, in particular horizontal greenery. This lack of greenery and infiltration does not improve the second main relevant climate challenge: waterlogging. From the climate scenarios used for the design proposals, i.e. one shower of 70 mm per hour and one of 140 mm per two hours, it is possible to identify areas where waterlogging is particular intense. A portion of the area where the water is concentrated was selected as the project area.

In addition, from the webservice of the BRO 3D, it was possible to identify that the most superficial layer of the subsurface are of clay soil, minimizing the capacity of the area for water infiltration. [12] The area also presents cables in part of the design areas on its subsurface citeutrecht3d, mainly in the Marshallaan street, meaning that attention should be paid when placing trees and introducing objects underground, and an average capacity to handle weight and suitability for building [19]. The area also presents a high mean highest groundwater level, reducing the infiltration capacity, which is very relevant for an area that suffers from waterlogging.

Figure 7.14: Kanaleneiland Noord and the prsence of clay (green)

Figure 7.15: Kanaleneiland Noord has partial subsurface congestion

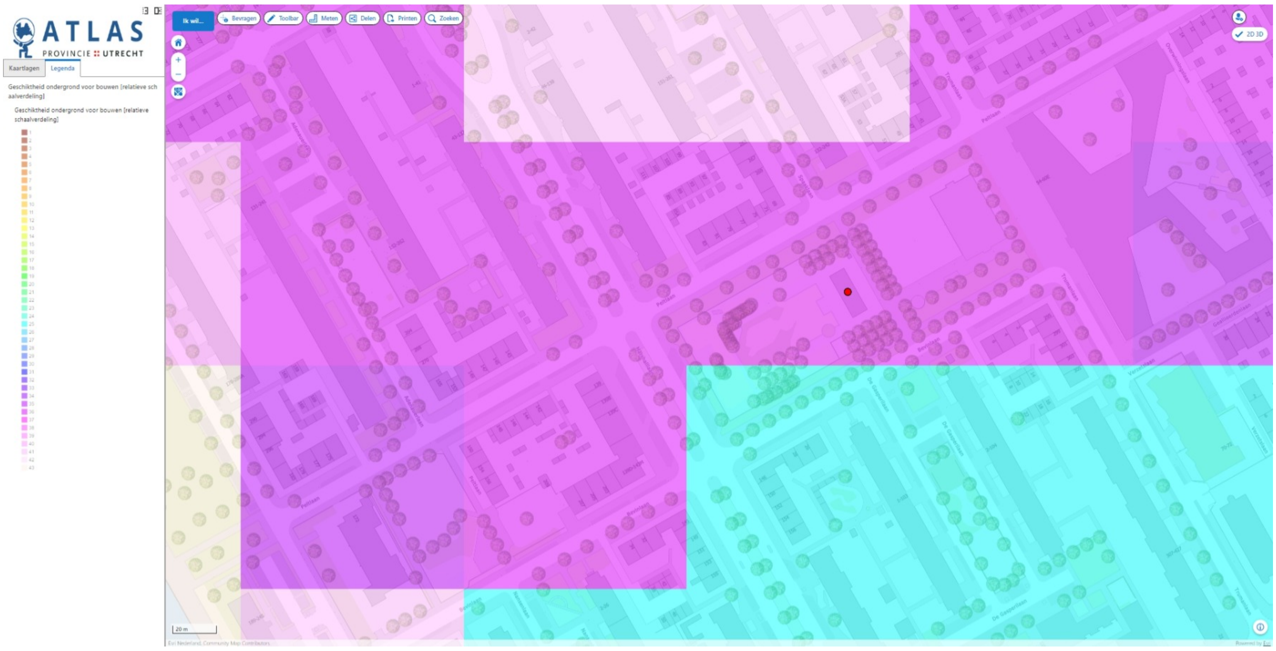


Figure 7.16: Kanaleneiland Noord has partial subsurface congestion

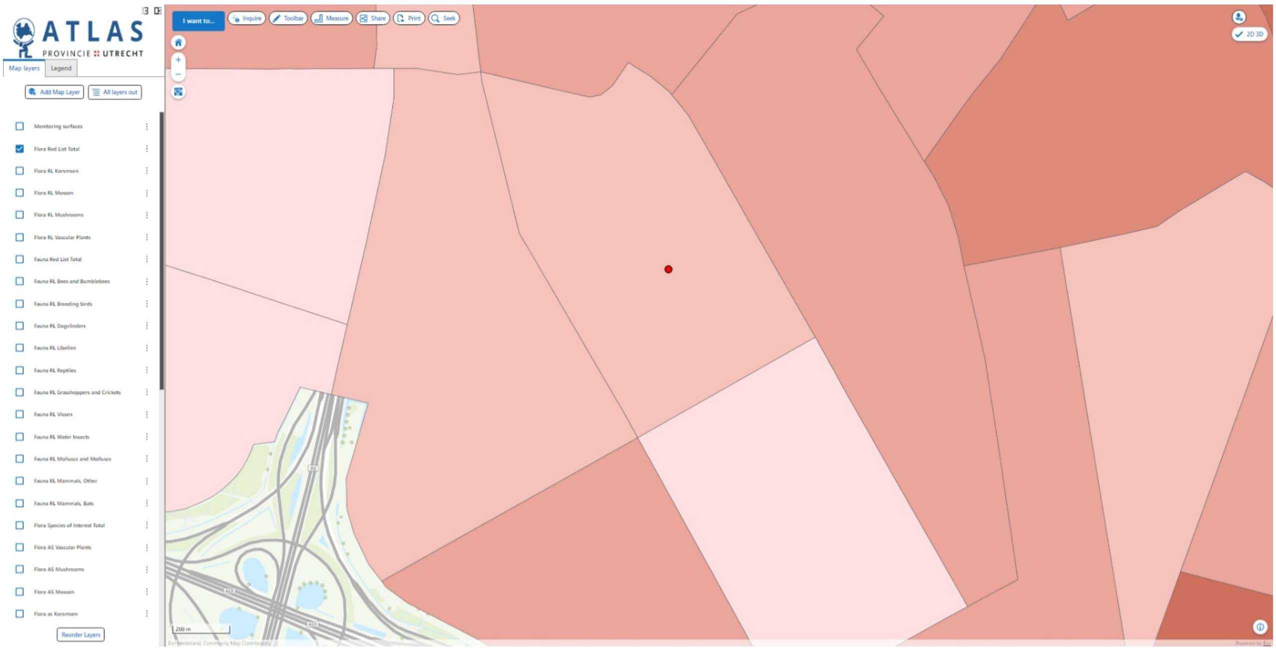


Figure 7.17: Kanaleneiland Noord flora redlist

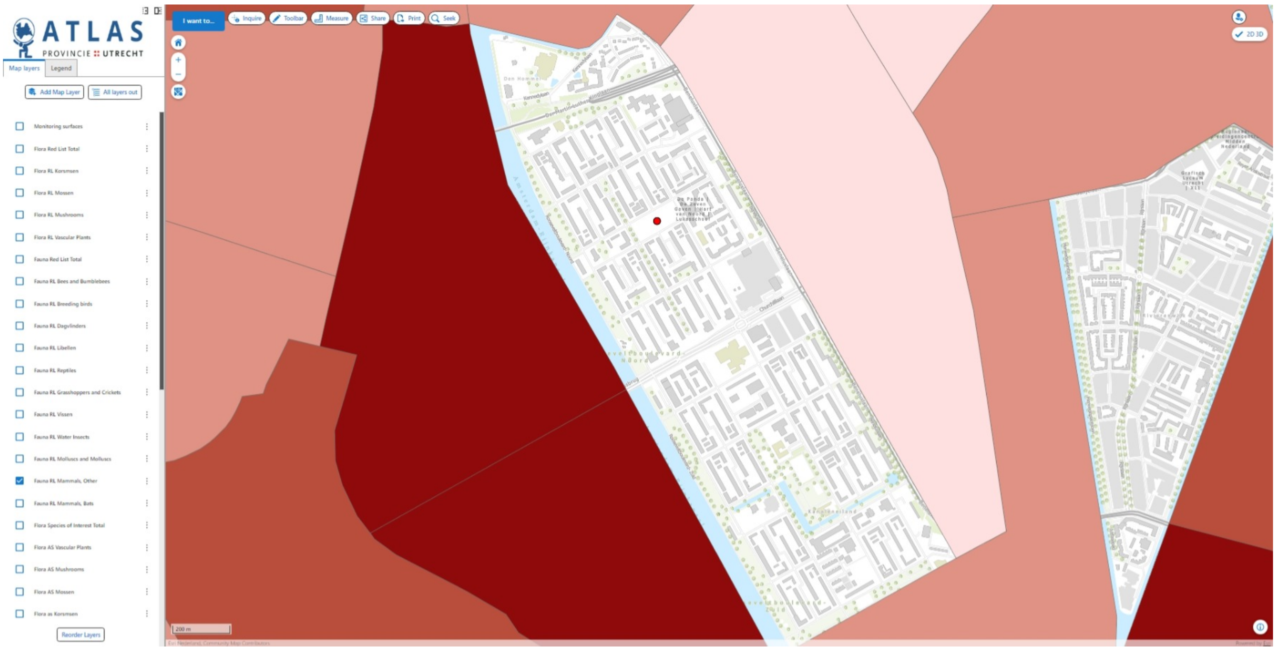


Figure 7.18: Kanaleneiland Noord and the presence of other mammals

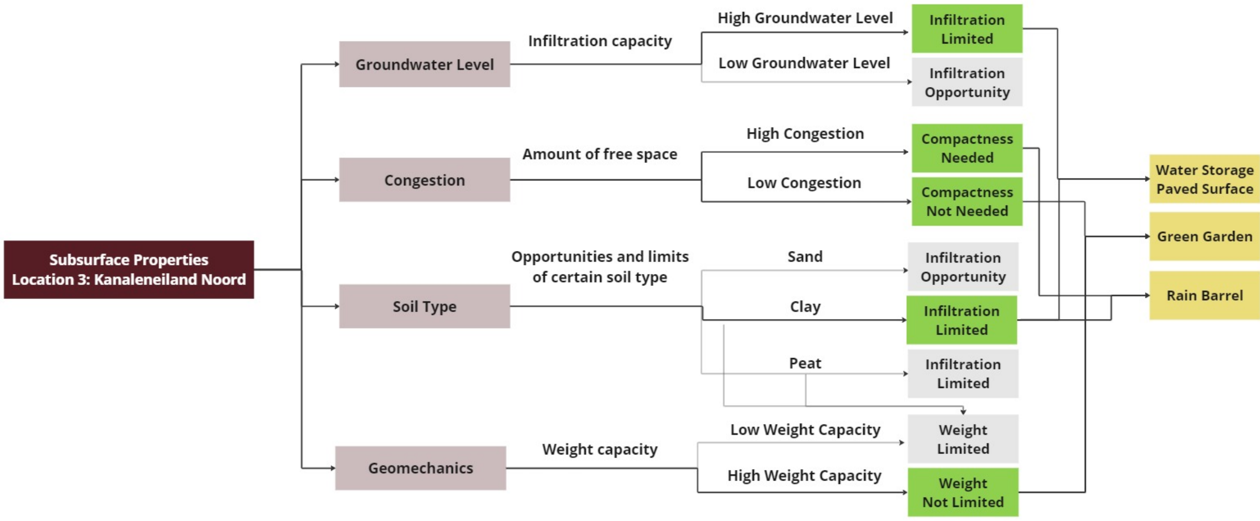


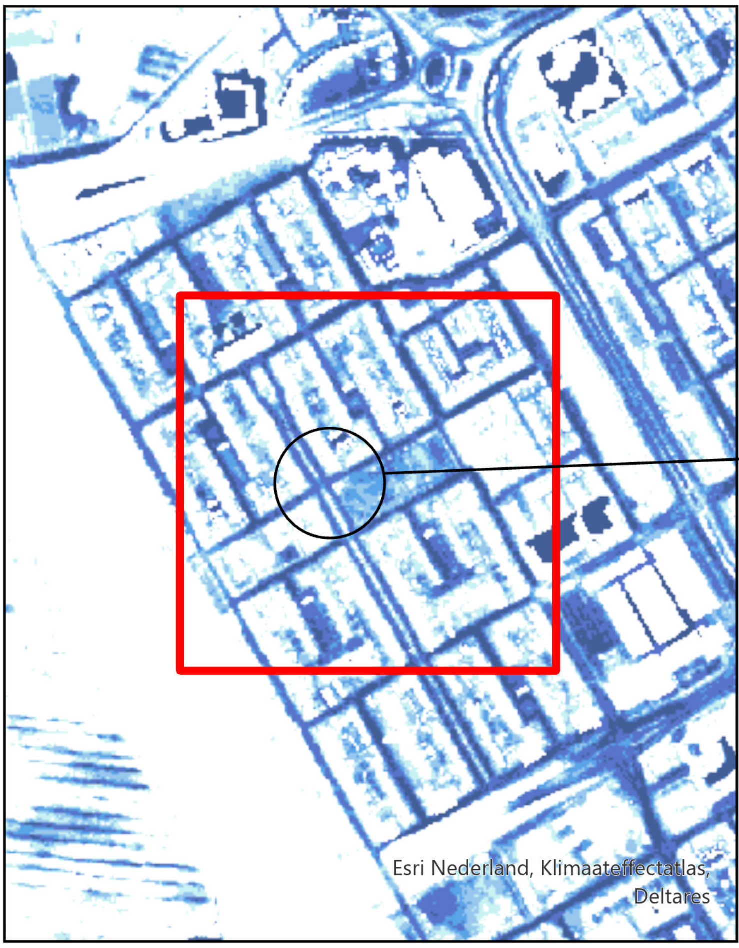
Figure 7.19: Kanaleneiland Noord Design Decision Tree

From an analysis of the public and green spaces, Kanaleneiland Noord features green spaces along its main canal, offering more than just grass with amenities like playgrounds and dog parks. Smaller greenery areas connect this main canal to and its greenery to Speeltuin Anansi, a large playground near a school. Essential for the connection of the southest and northest portion of the neighborhood to this greenery and play areas is the street Marshallaan, which already is highly arborized. The design proposal builds on top of this existing and important street, expanding it in direction to to the play area through a green garden, better connecting the vertical connection of that street to the play area and moreover to the greenery public area facing the canal.

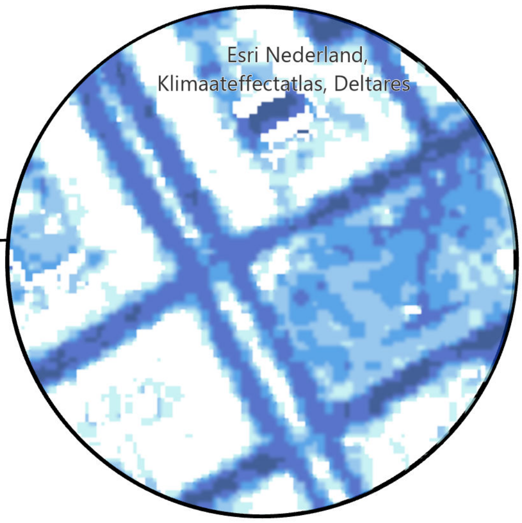
Climate Challenges: Location 3 Kanaleneiland Noord

N

Waterlogging: Shower of 140 mm/2 hours (Scale 1:1000)



Zoom Scale 1:3000

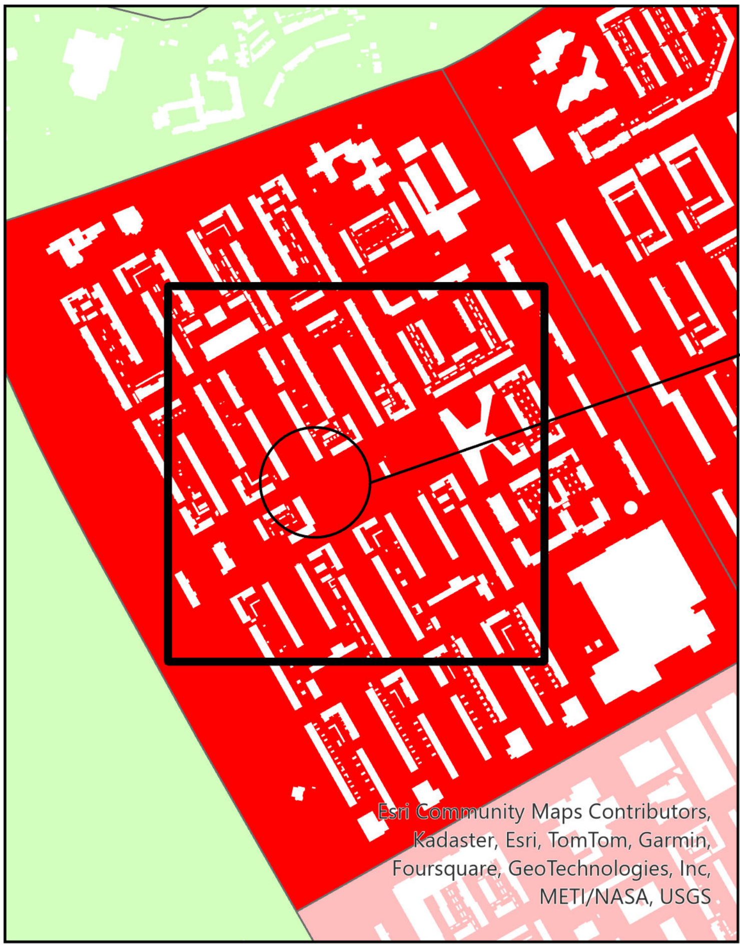


During a shower that occurs once every 1000 years, the play area suffers from waterlogging

Zoom Scale 1:3000

This area also suffers from a lack of greenery compared to surrounding neighborhoods

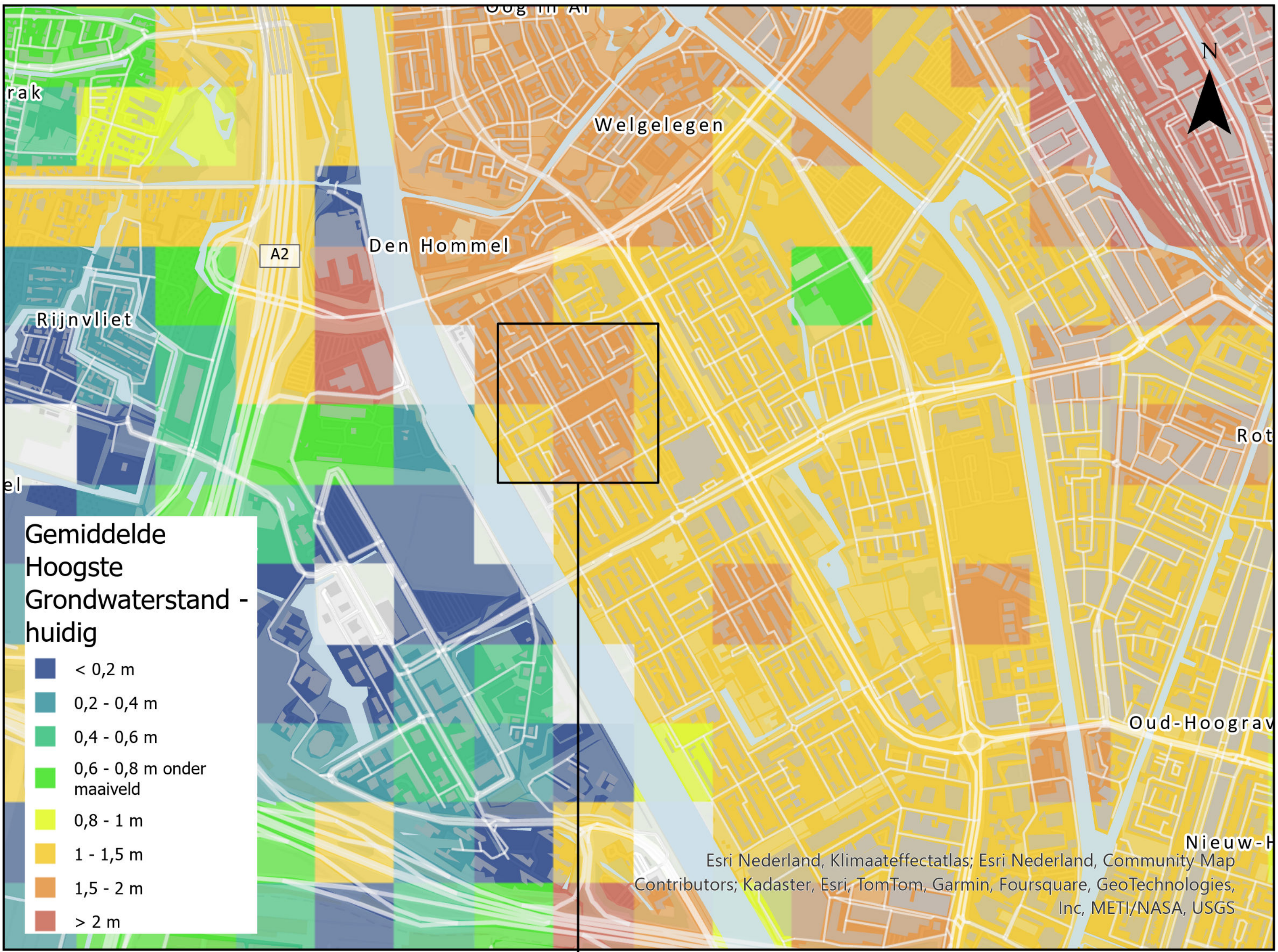
Biodiversity: Lack of greenery (Scale 1:1000)



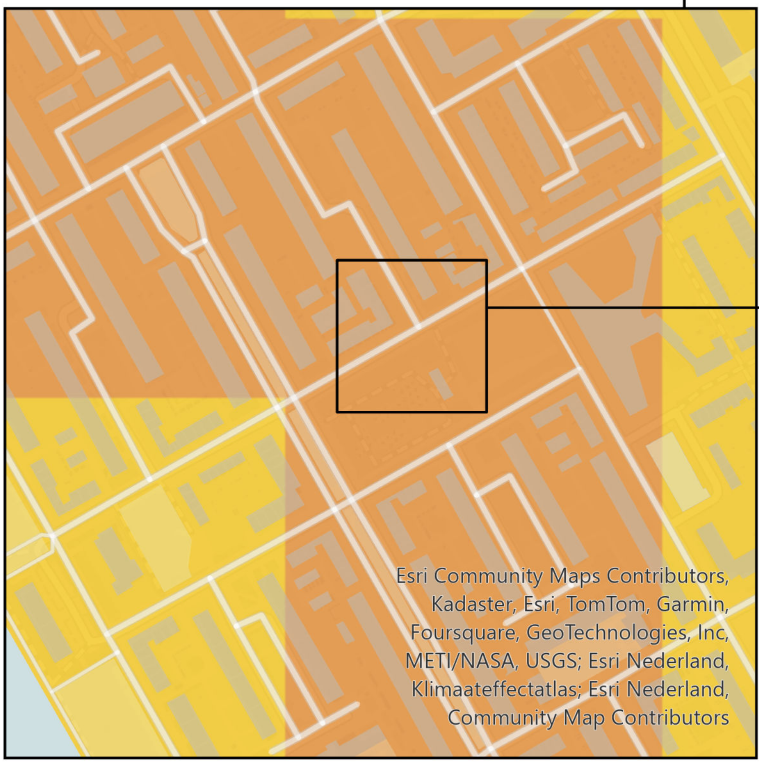
Percentage Greenery

- 0 - 10%
- 10 - 20%
- 20 - 30%
- 30 - 40%
- 40 - 50%
- 50 - 60%
- 60 - 70%
- 70 - 80%
- 80 - 90%
- 90 - 100%

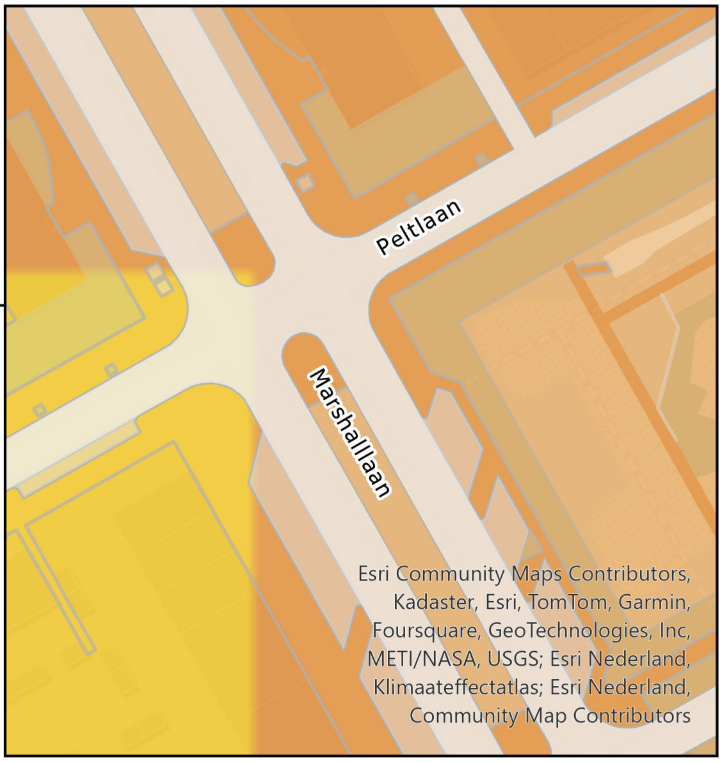
Mean Highest Groundwater Level - Current: Location 3 (Kanaleneiland)



Mean Highest Groundwater Level Macro (Scale: 1:20000)

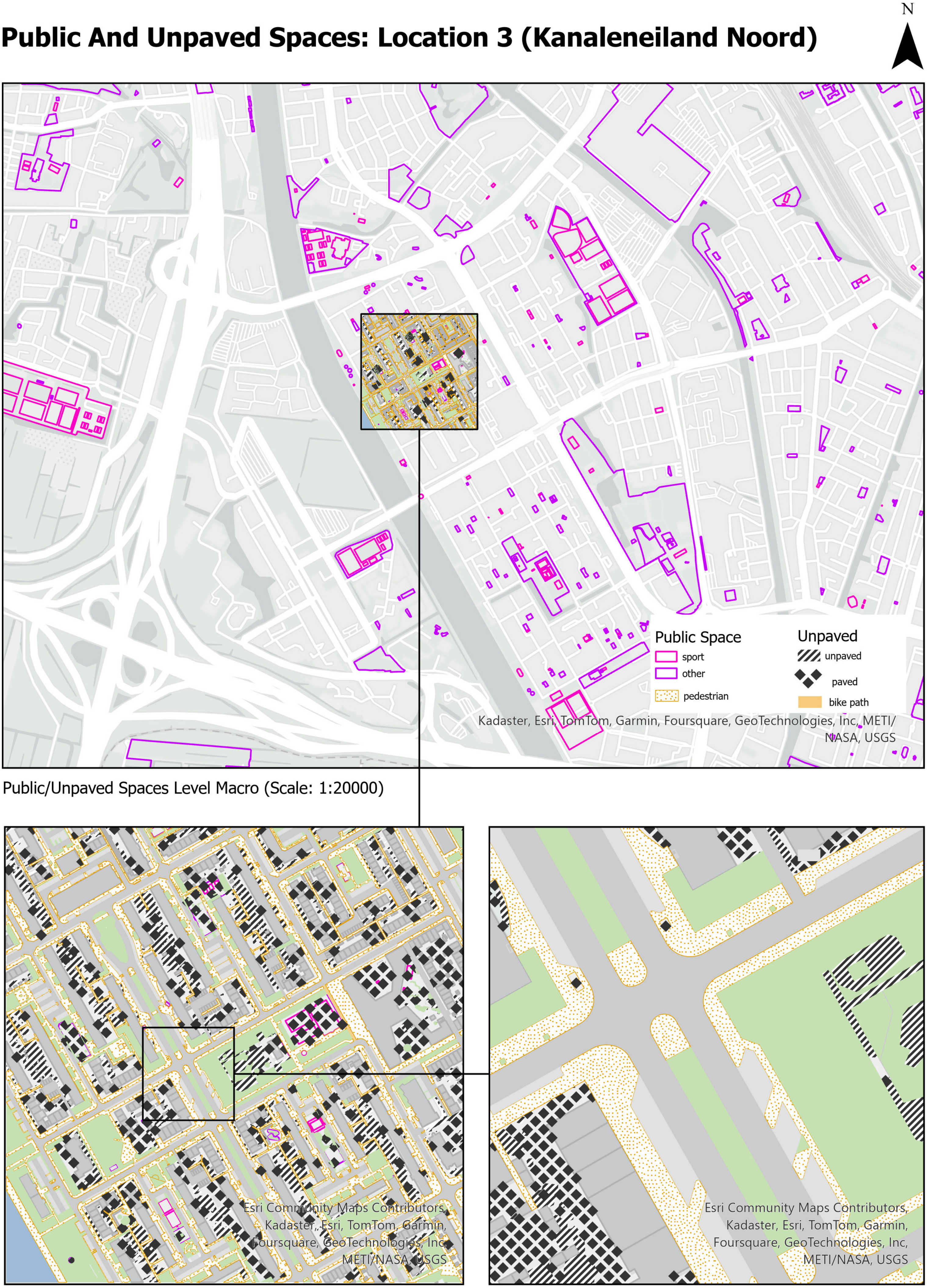


Mean Highest Groundwater Level 500x500m (Scale: 1:5000)



Mean Highest Groundwater Level design area (Scale: 1:1000)

Public And Unpaved Spaces: Location 3 (Kanaleneiland Noord)



Public/Unpaved Spaces 500x500m (Scale: 1:5000)

Public/Unpaved Spaces design area (Scale: 1:1000)

Regarding the local ecology, the design took into consideration the biodiversity improvement that could come with the additional greenery. From the geoportal of the province of Utrecht [17] it is possible to identify that the area contains a low level of biodiversity, with a low number of red list flora and a lack of mammals other than maps that are highly present in the green areas close to the canal.

Using a decision tree including all these mentioned characteristics, the design decided for the selection of the following standardized interventions: water storage under the paved existing parking spots at Marshallaan, a green garden facing the same street, expanding the fauna and flora of the canal parks towards the play area, and rain barrels that can collect and use the rain water to, for example, water the garden. These interventions consider the limitations and opportunities of the area, while adapting to the main identified climate challenges.

Local design standards for Utrecht states that ecological solutions should be prefered to ’grey’ solutions, (B1) where 30% of the surface is greenery (B2) and local fauna preserved (B3). [54] Regarding waterlogging, the Leidraad states that no water damage occurs during a 100-year shower, or 250-year for vital functions (N1), this numbers were used as basis for the rain scenarios and thus this requirement is fulfilled. In addition, a large part of the precipitation (50 mm) on private land is infiltrated, retained and/or stored (N2), and the development is water-neutral and will not lead to additional water supply/drainage (N3). [54] This is possible particularly due to the water storage under parking lots and the rain barrels. The use of numerical local standars ensure a quantitative way to measure the results of the climate adaptive design and the choice for interventions.

Moreover, the national guideline indicates that no water damage on a shower that could happen every 100 years and at 0.2 m water depth at the street and local habitats, green solutions over technical ones, and maintain a neighborhood level of greenery should be a priority. [15] All of these guidelines are followed through the choice of interventions.

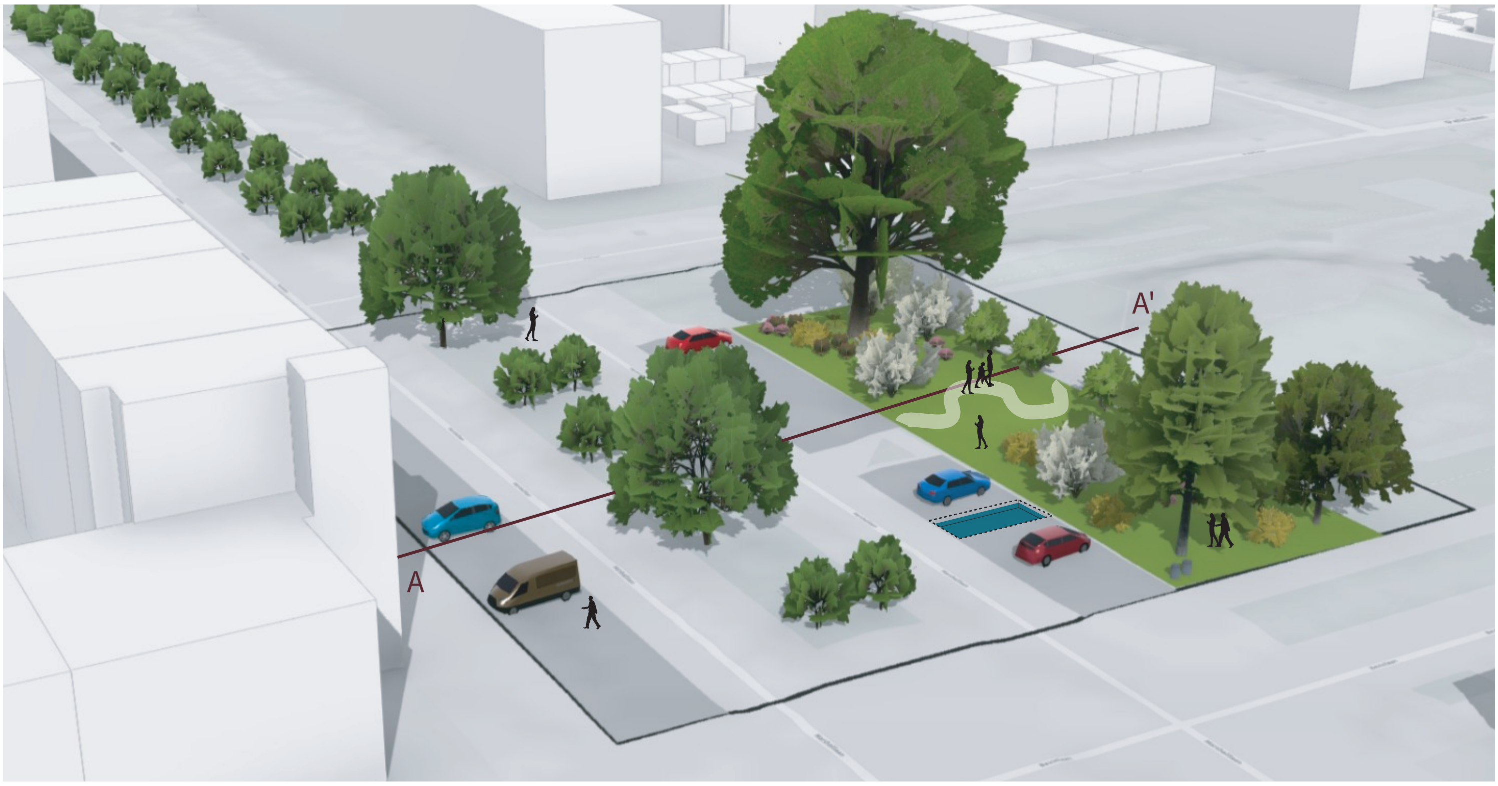
Area 3 (Kanaleneiland Noord): Adaptation Design Plan

Water Storage Under (Un)paved Surface

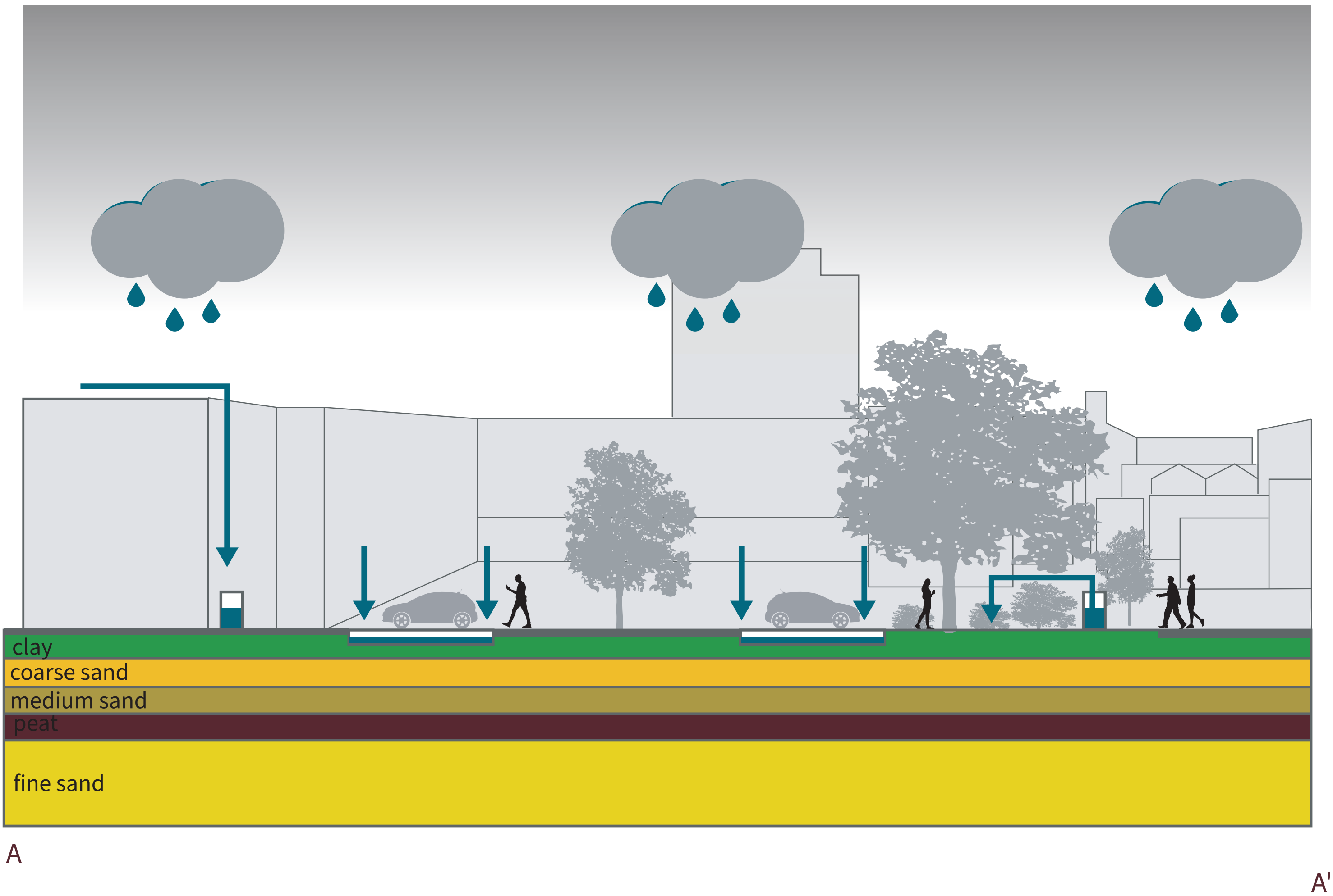
Green Garden

Rain Barrel

Area 3 (Kanaleneiland Noord): Adaptation Design Impression



Area 3 (Kanaleneiland Noord): Adaptation to Waterlogging and Lack of Biodiversity



Regarding the resolution requirements, similar issues to Area 1 arise regarding tree root sizing. In addition, the use of water storage under the parking spots require an horizontal resolution smaller than 100 m. This intervention also requires a high level accuracy regarding subsurface congestion as physical space is needed underground in the dimensions of the parking spot with a depth of minimum 50 cm.

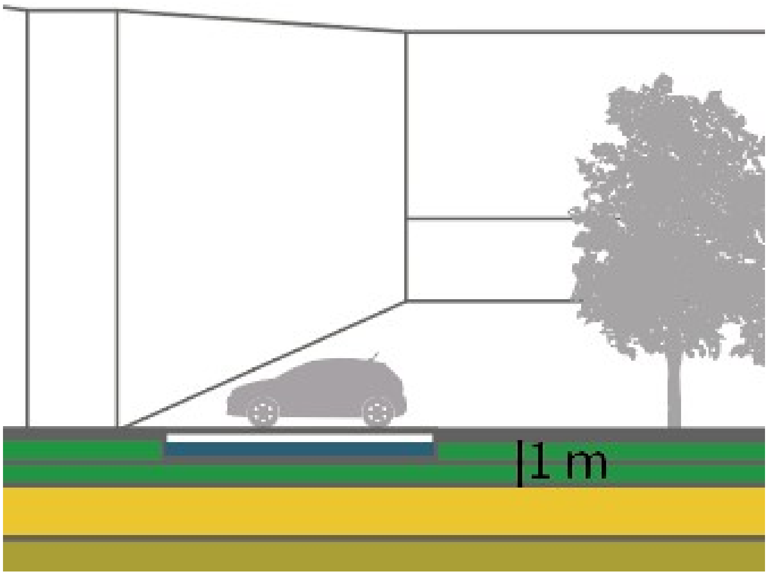


Figure 7.20: Water storage under pavement detail

7.4. Area 4: Voordop

In the Voordorp neighborhood, heat stress and waterlogging are the primary climate challenges in the 500 x 500 meter area. This determination was based on a municipality-provided map showing air temperature during a heat wave and one the two scenarios of rainfall, being one of them . The map revealed intense heat concentration in the playground and sports field near the local school. Additionally, extreme rainfall scenarios highlighted a propensity for waterlogging, particularly in the streets surrounding the same area, such as Aartsbisschop Romerostraat. Due to the public nature of this concentrated climate issue, this area was designated as the focus for design interventions.

A design proposal includes interventions that are related to the main climate themes, heat and waterlogging, for example interventions related to shadowing or to an increase of rainwater infiltration. However, for the purpose of testing the benefits of using subsurface information models while choosing local standardized design interventions, while also testing the information needs for the chosen interventions, the available knowledge on the subsurface was used.

Empirical knowledge, acquired through observation, experience, or experimentation, based on actual data, was also used for this design proposal. In this case, the analysis of the green spaces and unpaved areas in Voordorp indicates an unequal distribution of greenery and the composition of public spaces in the area.

The majority of green spaces in Voordorp originate from private gardens. A map highlighting unpaved areas reveals that these are predominantly situated within private properties. Apart from Chico Mendesstraat, characterized by trees and a canal, most public spaces exhibit a scarcity of greenery and unpaved surfaces. Playgrounds and sports fields, for instance, are frequently entirely paved. An exemplar of this is the playground adjacent to a school, delineated on a map. While this space holds potential to become one of the few green public areas or unpaved squares, it currently accommodates a fully paved playground and sports field.

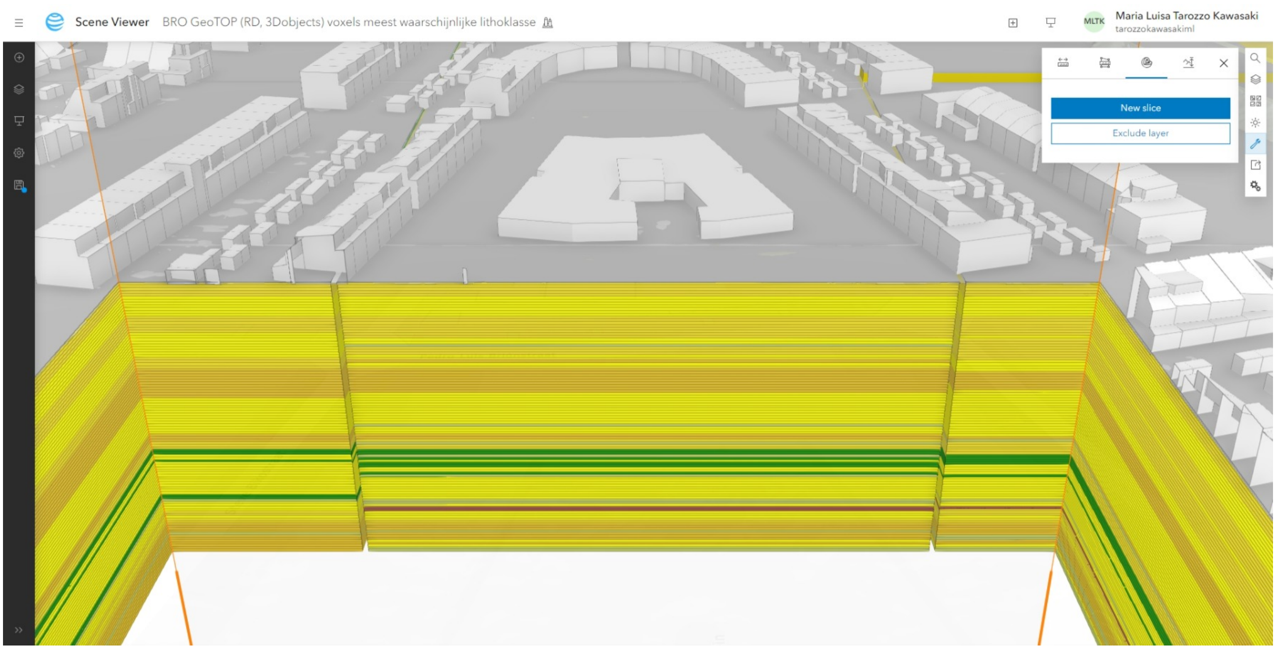


Figure 7.21: Voordorp is mostly composed of sandy (yellow) soil

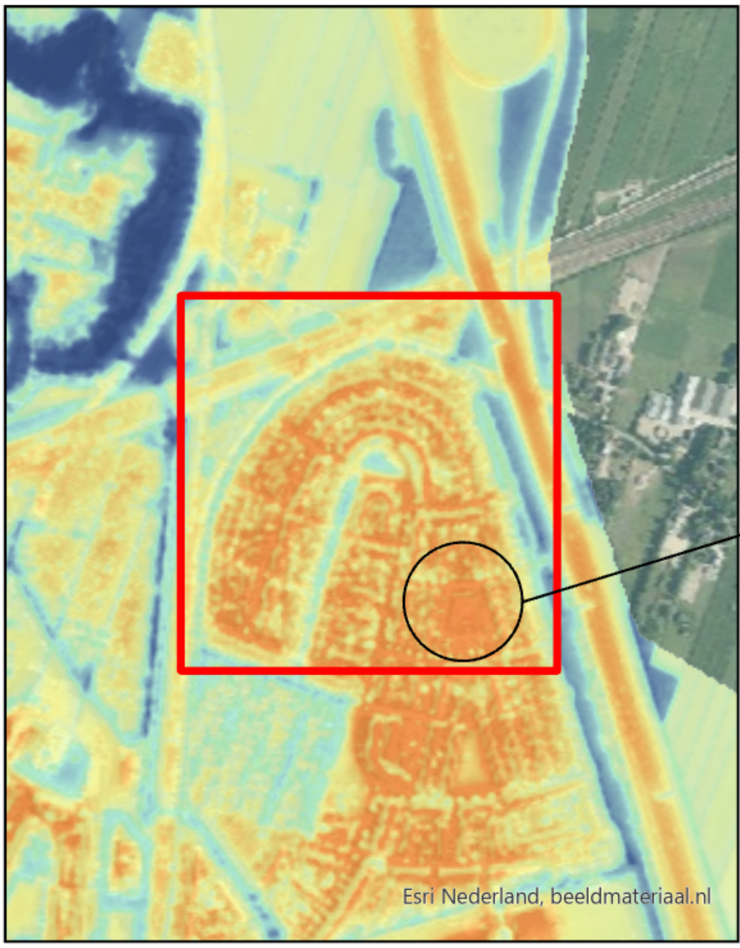
Unpaving the surface of this public space presents a compelling climate adaptation strategy for this spot, particularly considering its sandy soil composition, conducive to rapid rainwater absorption. To check the soil type of the area the BRO 3D webviewer was used. [12] This 3D viewer is publicly accessible, meaning that designer or other users could easily access for their projects. The yellow indicates sandy soil, green clay and brown peat.

In addition, the area present a mean highest groundwater level of 1.5 m, which is more than 0.7 m bellow surface level and thus do not present good water storage capacity, This value is the same one used in the infiltration opportunity score defined by Deltares. [22]

Climate Challenges: Location 4 Voordorp

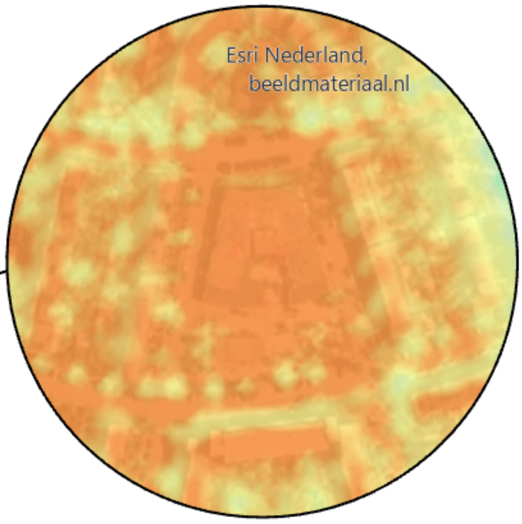
N

Heat: Air Temperature at 1.5 m on a heat wave (Scale 1:1000)



During a heat wave, the air temperature is higher on the public space around the local public school, the playground and the sports field.

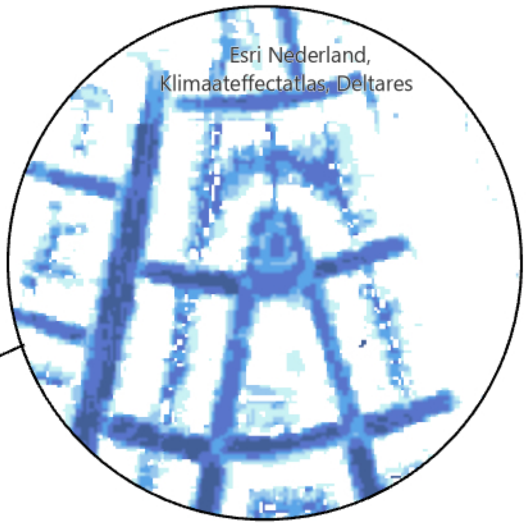
Zoom Scale 1:3000



This higher air temperature is due to a lack of greenery in the area compared to the greenery from private gardens in the surrounding.

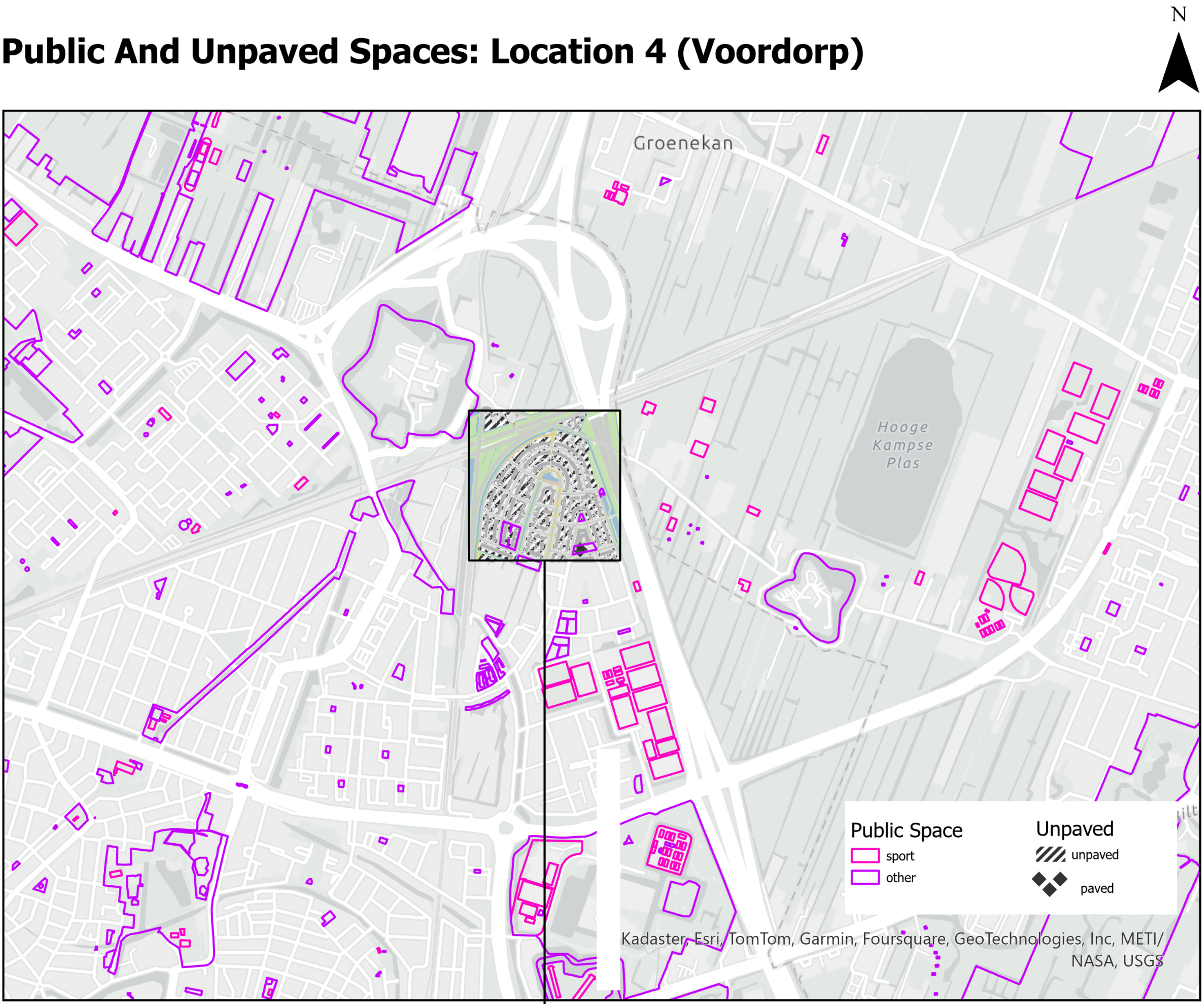
Waterlogging: Shower of 140 mm/2 hours (Scale 1:1000)

Zoom Scale 1:4500



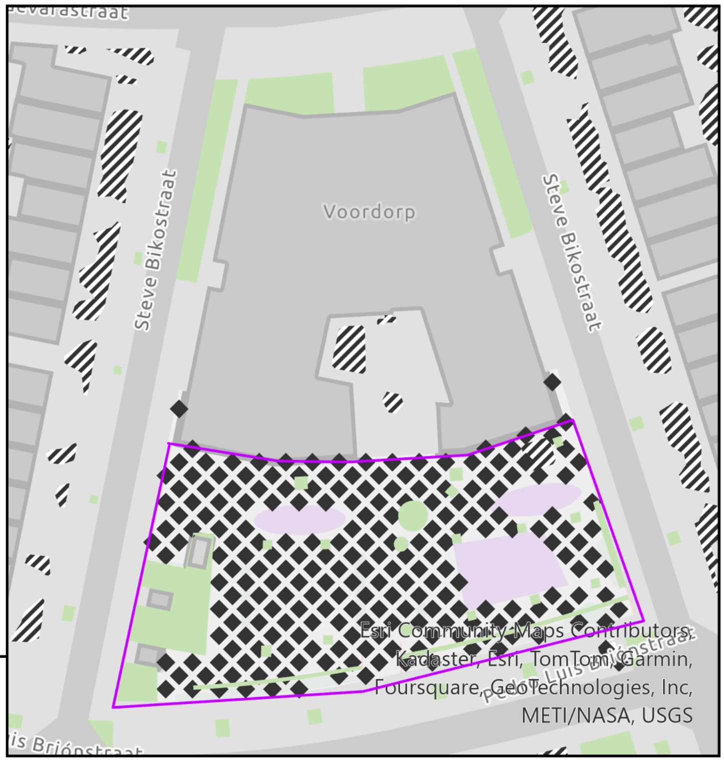
For the same reason, there is a waterlogging problem in the streets surrounding the local public school. This is aggravated by a tendency for waterlogging in the main street on the left.

Public And Unpaved Spaces: Location 4 (Voordorp)



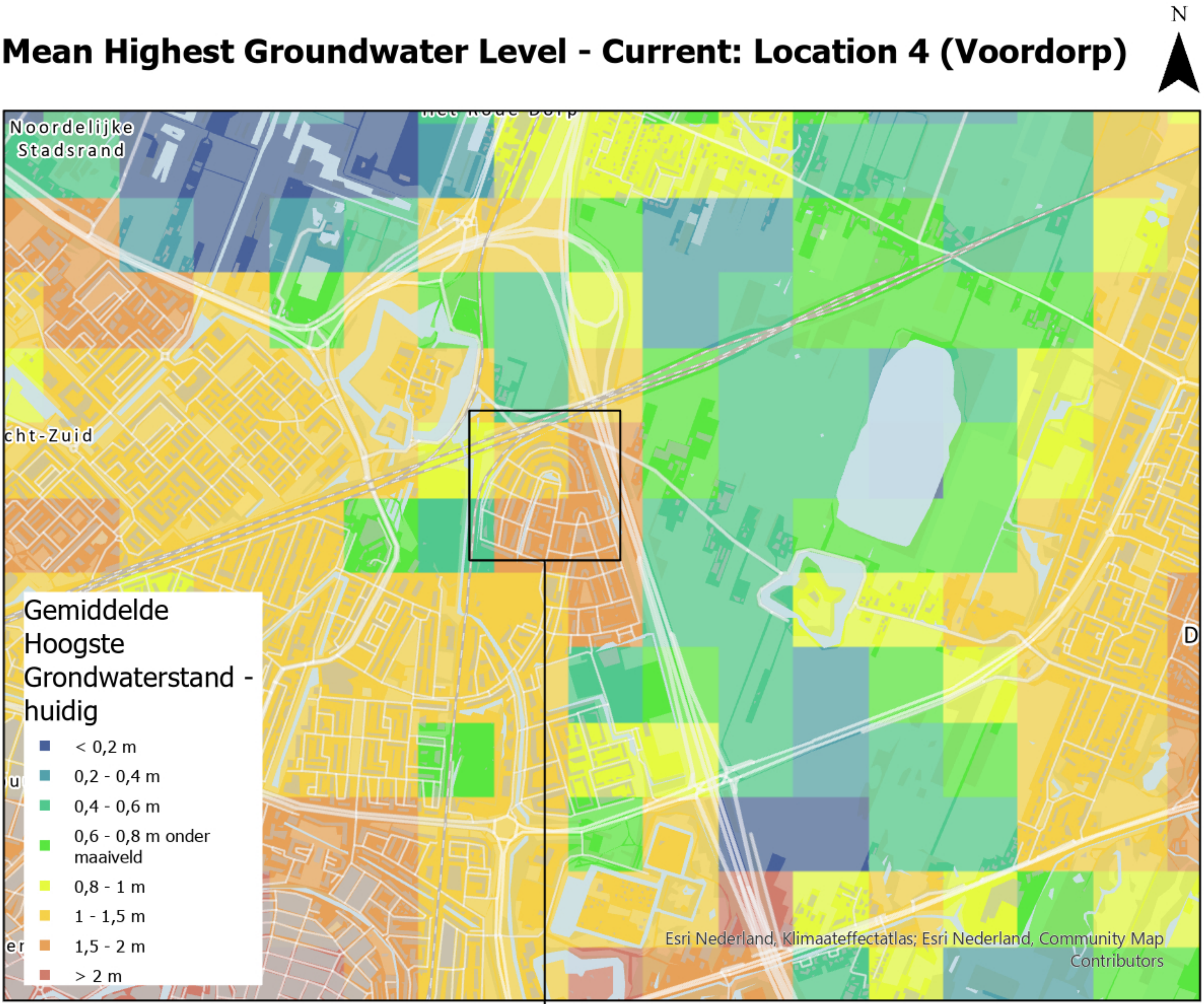
Public/Unpaved Spaces Level Macro (Scale: 1:20000)

Public/Unpaved Spaces 500x500m (Scale: 1:5000)

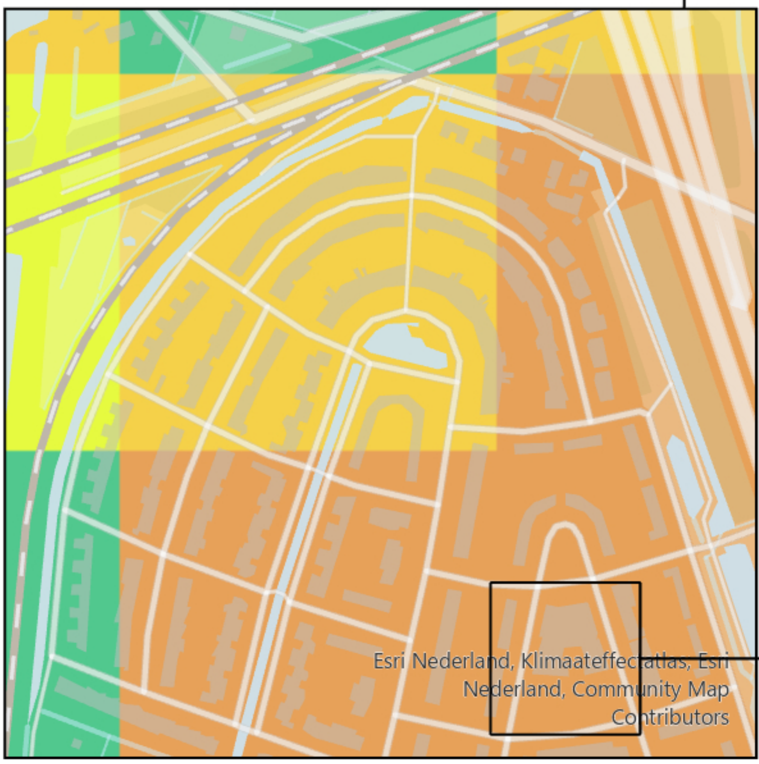


Public/Unpaved Spaces design area (Scale: 1:1000)

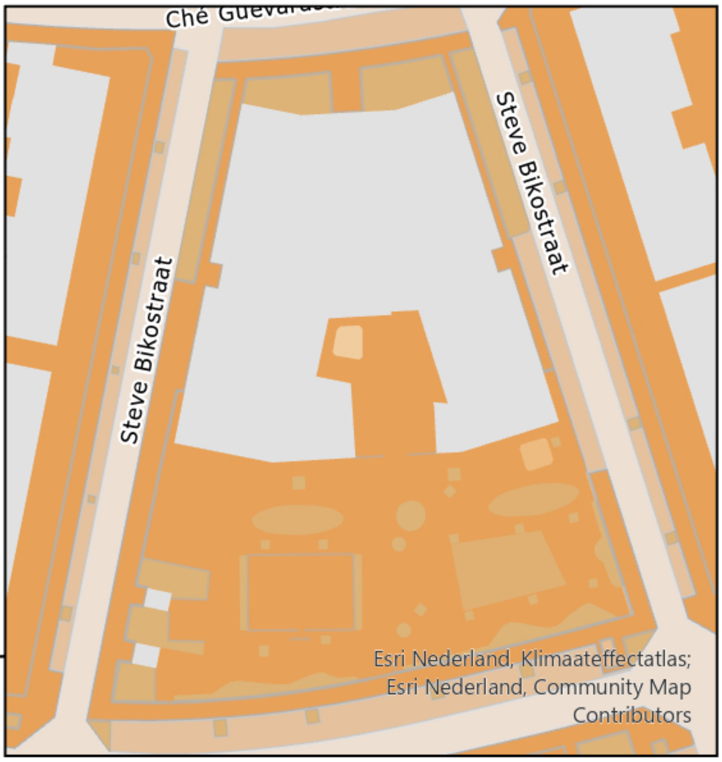
Mean Highest Groundwater Level - Current: Location 4 (Voordorp)



Mean Highest Groundwater Level Macro (Scale: 1:20000)



Mean Highest Groundwater Level 500x500m (Scale: 1:5000)



Mean Highest Groundwater Level design area (Scale: 1:1000)

Using the 3D Underground Viewer from the municipality of Utrecht, it is also possible to identify that there are no major underground structure under the playground, and thus there is no need for a limited space intervention. [20]. Finally, the map regarding geomechanics properties of the subsurface, indicating potential constraints weight-wise for interventions, indicate that there the subsurface can handle weight and thus is suitable for new building without significant weight constraint. [19]

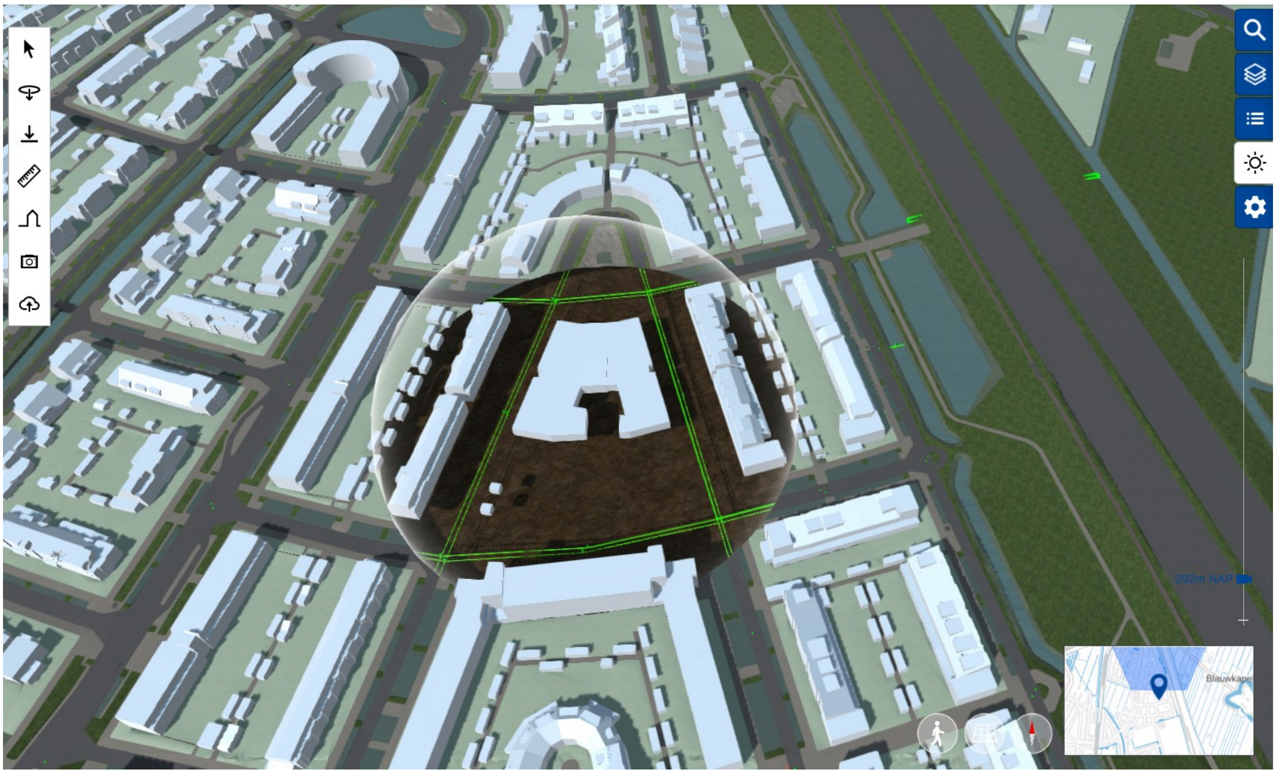


Figure 7.22: Voordorp Underground Objects

The area present some trees, which means that attention should be paid on not placing anything underground too close to their roots. As a conclusion from these observations, the area presents natural opportunities for water infiltration due to the sandy soil and lack of congestion but cannot store or infiltrate directly into the ground water because it presents a high groundwater level.

A design intervention that fits these particularities of the area is are infiltration crates. The the lack of congestion allows for the placements of new objects in the subsurface, such as the crates, which benefit from the highly infiltrating sandy soil. At the same time, a high average highest ground water level benefits from infiltrating crates because it allows storage of rainwater and infiltration into the groundwater in a delayed manner. [69] This solution also allows the current function of the sports field to remain in place, adding an extra hidden feature of rainwater absorption underneath.

For the heat challenge, the area would benefit from additional tree planting. Tree planting requires enough subsurface free room for the roots of the trees [3], this is known to be the case for the public area right in front of the school through the 3D underground viewer. Tree roots also increase the water infiltration of the area where it is planted [70], which is ideal in this case due to the presence of sandy soil. The area already present some trees, which will be kept, while attention should is paid on not placing the crates too close to their roots.

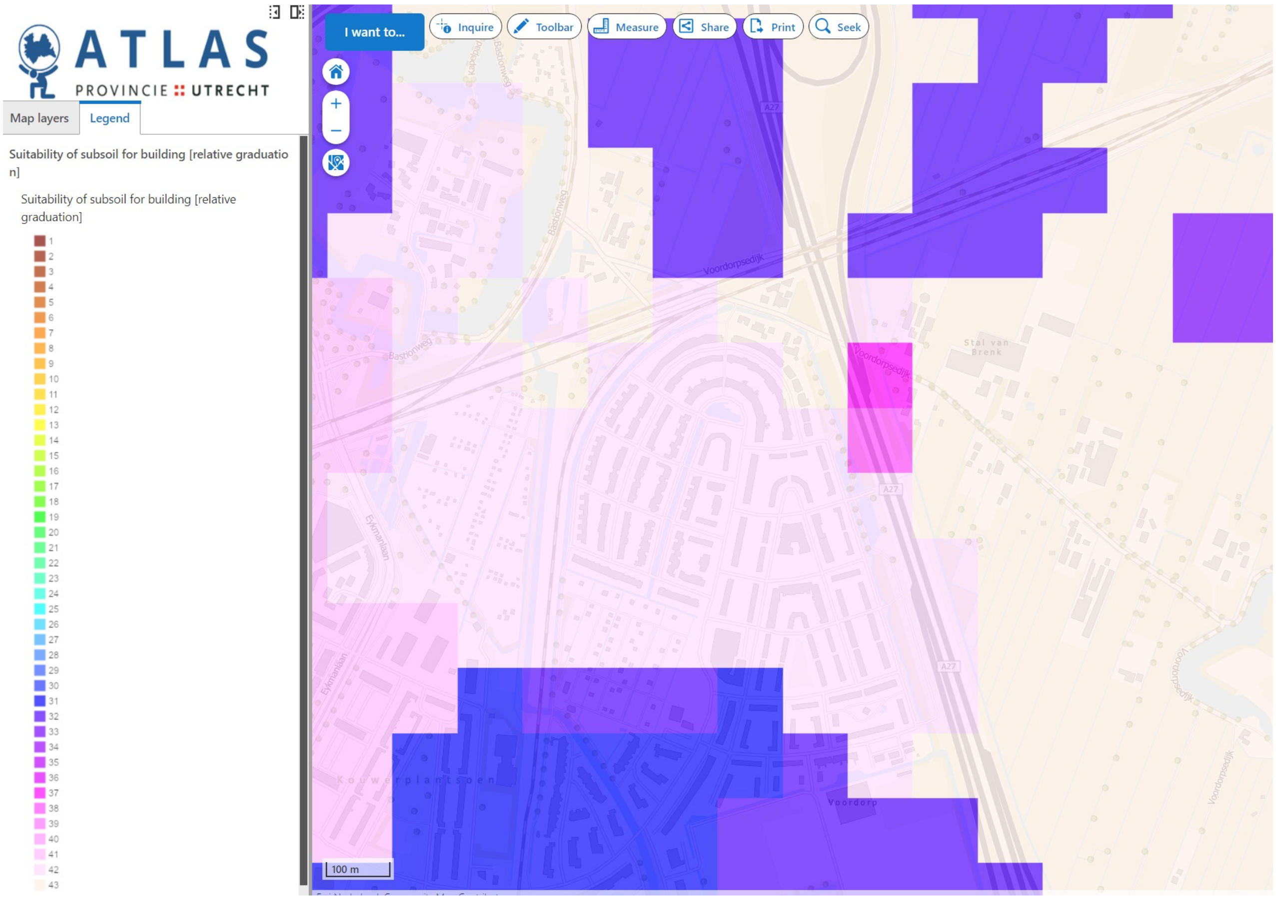


Figure 7.23: Voordorp Weight Suitability

Moreover, the design decision to unpave and add greenery to the sports field and playground in front of the school aims to add more urban qualities to one of the few public spaces in the neighborhood. With additional trees and greenery and natural urban furniture, the current playground could become a naural playground. Natural playground are green play areas with trees, sand, water, grassy terrain, and wooden climbing structures instead of traditional paved playgrounds [71], which not only aid climate adaptation, but also add quality to children's playtime. Playing in and with nature has many positive effects on children's motor, psychological, emotional and cognitive development. [72] In a 500 by 500 meter area where one of the few public spaces are playground, improving the qualities of these spaces is fundamental to local families, which is particularly interesting for Voordorp, a neighborhood where the majority of inhabitant are in the age group between twenty five and forty five years old and the third major group are children between the age of zero to fifteen. [73] Regarding the subsurface requirements for a natural playground, the area fits perfectly. The ground can be naturally present such as sand or added as an extra layer such as wood bark or grass [71]. Since the area present sandy soil, the added natural layer, if needed, could be placed directly on top of unpaved spots due to its sandy soil.

Regarding national guidelines, Maatlat states that no water damage on a shower that could happen every 100 years and at 0.2 m water depth at the street and it is necessary to prioritize

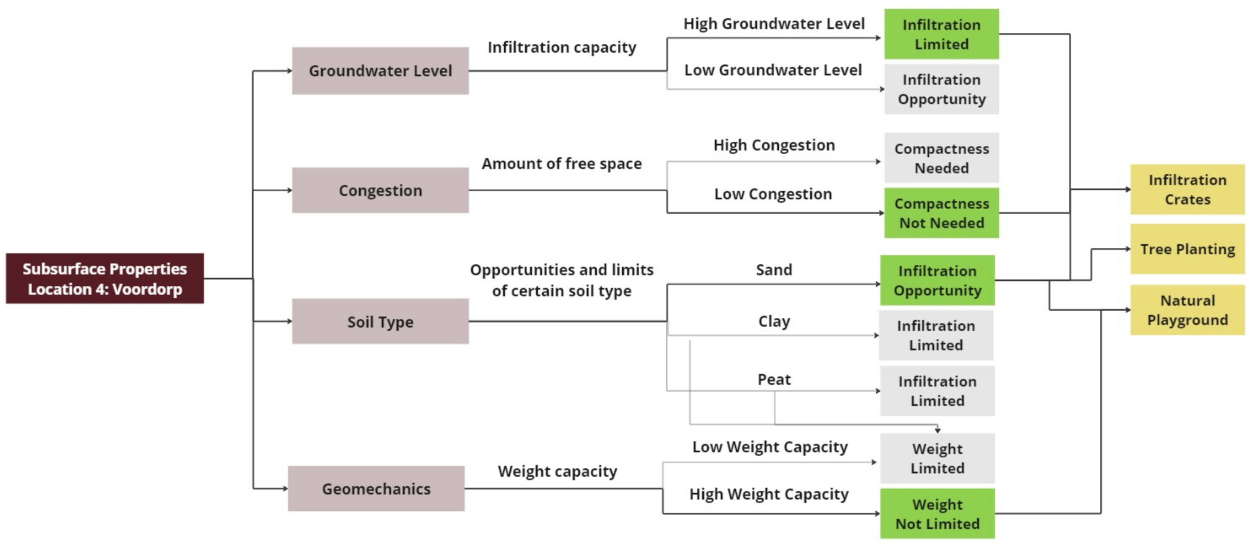


Figure 7.24: Voordorp Design Decision Tree

local habitats and green solutions over technical ones. It is clear that the water infiltration offered by the selected interventions and the choice to prioritize natural characteristics, such as soil type and existent trees, is aligned with this guideline. The Maatlat also requires that Allocate 40-50% of the area to be heat-resistant, which is possible with the depavementation of circa half of the surface of the design area through the selected interventions. In addition, local standards state that, regarding waterlogging and drought, no water damage occurs during a 100-year shower, or 250-year for vital functions (N1), a large part of the precipitation (50 mm) on private land is infiltrated, retained and/or stored (N2), and the development is water-neutral and will not lead to additional water supply/drainage. (N3). Groundwater levels and freshwater availability are guiding design factors (D1) and the area is infiltration-neutral (expansion) or infiltration-positive (redevelopment), 50% of the annual precipitation sum, depending on soil type (D2). All these are fullfilled by the interventions. For heat related local standards, a designer must ensure a minimum of 40% shade for rest areas and slow-moving traffic zones during peak sun exposure (21 June), and 30% shade coverage at the neighborhood level (H1), with cool shaded resting spots are available within a 300-meter walk and open to the public (H2). The positioning of trees was thought to fulfill this guideline. Finally for the playground and the new trees, local guidelines regarding biodiversity are relevant. These state that ecological solutions are preferable to 'grey' solutions (B1), where 30% of the surface is greenery (B2) and local fauna preserved (B3).

A plan, section and 3D impression of the design is provided in the following pages to illustrate the placement of the three selected interventions and the adaptation to heat and waterlogging through shadowing and rainwater infiltration.

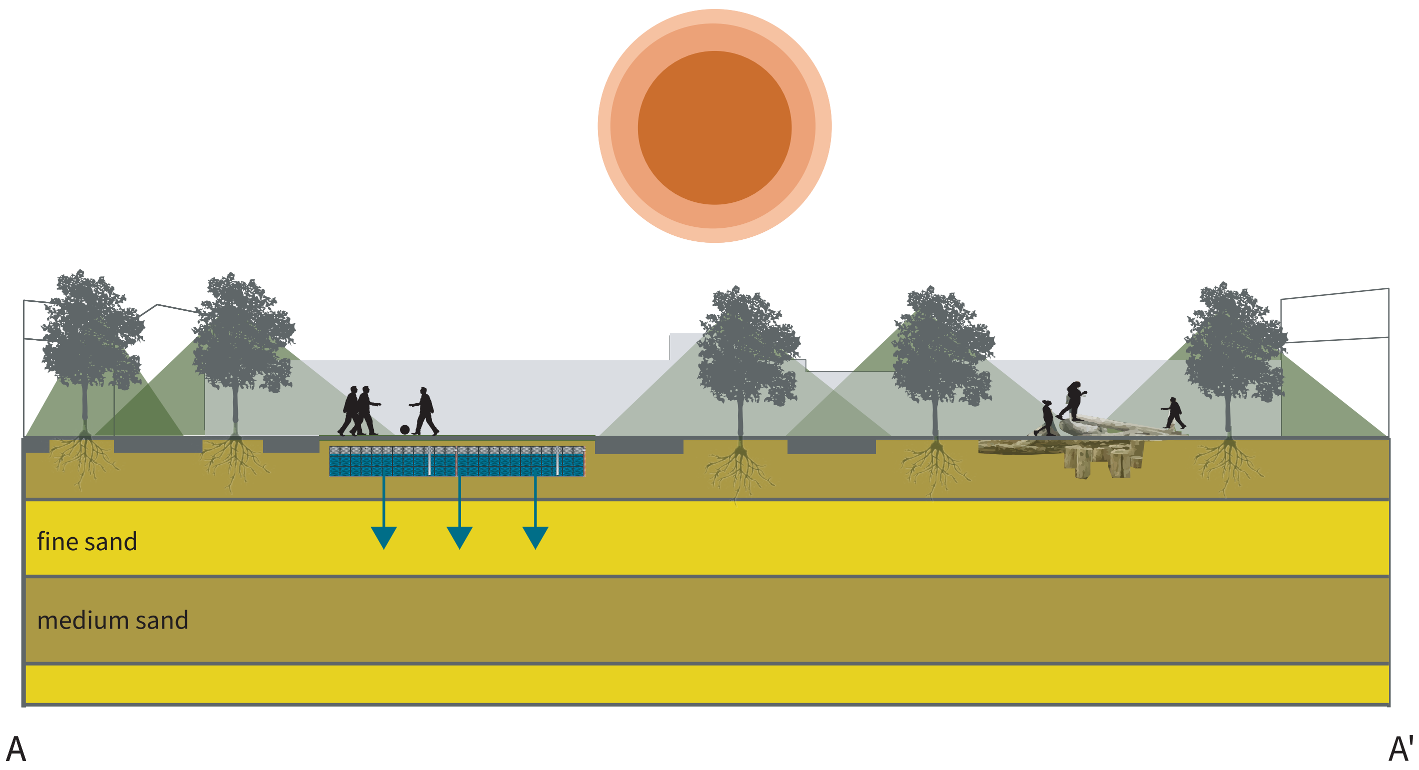
Area 4 (Voordorp): Adaptation Design Plan

Tree Planting

Natural Playground

Infiltration Crates

Area 4 (Voordorp): Adaptation to Heat Stress



Area 4 (Voordorp): Adaptation to Waterlogging

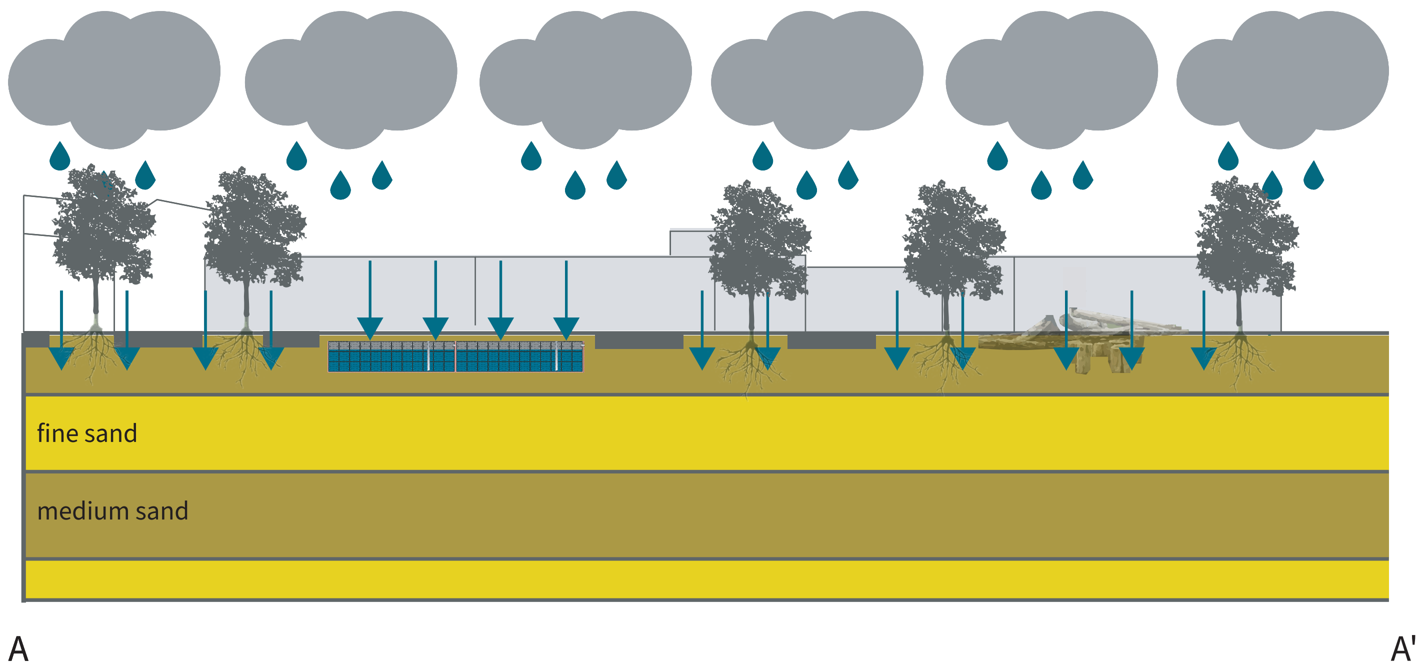


Figure 7.25: Voordorp Design 3D Impression

Voordorp would have benefited from an horizontal resolution ideally of 50 cm. The reasons behind this are similar to the ones for other design areas. Tree roots require a resolution and accuracy for their roots and infiltration/storage elements need accuracy similar to their unit size. The same is true for the infiltration in the playground. Natural infiltration usually concerns the shallow soil layer, or first 50 cm. This resolution is covered vertically but not horizontally. The design decision prioritize natural infiltration due to the presence of sandy soil. However, if a finer resolution would indicate a different soil type in the playground area, or if the data accuracy was low,this design decision would have been different.

8

Design Evaluation

Design was chosen as a methodology to better understand the information and resolution requirements regarding subsurface information models. The design choices exemplify the benefits of methodologies combining standardized climate adaptation intervention and access to subsurface information models during the design process. However, the intervention choices were all made by one single author. To avoid biases regarding the benefits of this method, an evaluation method is proposed.

Firstly, it was thought that an evaluation method should include design interventions that were proposed for each area (current situation) and compare them with the results from the design exploration. However, this method is only efficient to evaluate the climate adaptability of a neighborhood because all the interventions had the purpose to adapt an area to its main climate challenges. This is not what should be evaluated in from this methodology. The research question of this thesis is related to the benefits of using subsurface information models to aid climate adaptation change compared to not using the same models.

Therefore a methodology of evaluation was created using the same standardized climate adaptation interventions but without access to the subsurface information models. The idea behind this method is that designers could choose the interventions without knowledge of the subsurface, leading them to choose climate adaptation interventions from the standardized set that are not suitable for that subsurface.

The design of two of the same design areas as used in this thesis were compared with design proposal made by sixteen designers. From these, mostly were Architecture, Landscape or Urbanism students. Six of the surveyed designers were professionals.

The design proposals were created as an online survey. In the survey information regarding the climate challenges of two of the design areas, namely Lunetten Zuid and Kanaleneiland Noord, were described. In addition, the same climate themed maps were made available to the designers regarding the design area. The designers then had to select from the twenty five standardized interventions [3] the ones which they would like to include in their design proposal. The twenty-five options included a small image exemplifying the intervention.

The participants could opt to be part of a draw for a 20 euro Amazon gift card. Two types of questionnaires were created, changing the order of the design areas, to avoid more elaborated answers in the first neighborhood.

The participants after deciding for the interventions were asked to describe the reasoning behind their design and to identify potential datasets that would have facilitated their design choices. The designers knew this survey was being used for the purpose of design evaluation on a MSc thesis but were not aware of the contents in the thesis or in the design proposals. A copy of the survey can be find in the appendix.

The municipality of Utrecht was also contacted to evaluate the CLIMACAT tool but they did not respond on time for this thesis. Their eventual comments will be included in an improvement of the tool but this will not be documented in this thesis.

8.1. Survey Results

The majority of designers selected green garden, tree planting, natural routes and (natural) wadis as their main climate adaptation intervention for Lunetten Zuid, an area prone to heat stress and flooding.

When justifying the design choices, most designers said that they decided to increase the infiltration capacity of the area by adding more greenery. The choice for planting trees in particular is related to increasing water infiltration while creating more shadow. While this is a logical reasoning, Lunetten-zuid presents clay soil and high average highest groundwater level, meaning that the area has very limited infiltration capacity [22]. If designers had access to subsurface information, maybe they would have noticed the limited infiltration capacity and would have chosen an intervention that is linked to the limitations of the area but also potentials, such as the capacity for building and lack of subsurface congestion. In that case maybe they would have opted for water squares or water roofs. On the other hand, (artificial) shadow routes would have worked as a design intervention even without subsurface knowledge because this intervention do not always require to be bellow the surface. Natural wadis would also potentially work on this case because the area present low subsurface congestion and alredy contains a main canal and other water surfaces. This was visible in the map given to designers.

Kanaleneiland Noord is an area that is prone to the lack of biodiversity and waterlogging. For this area, the most selected interventions were green garden, natural playgrounds, (natural) wadis and soil structure improvement. In this case, designers justify their choices by choosing public green spaces to increase biodiversity and natural infiltration solutions to increase biodiversity and rainwater infiltration. Soil structure improvement was also chosen by the majority of designers for biodiversity improvement. This last intervention is heavily linked to soil type properties and it was interesting to see how it was chosen even though there was no previous knowledge on soil type.

The main design choices are logical due to the climate challenges, however rainwater infiltration in Kanaleneiland Noord through natural infiltration is very difficult. Using subsurface information models it is possible to see that the soil type is the area consists of mainly clay and high average highest groundwater level, making the infiltration capacity in the area very low. Thus the area would be more suitable to infiltration crates, artificial water storage, and rain barrels for rainwater infiltration and storage.

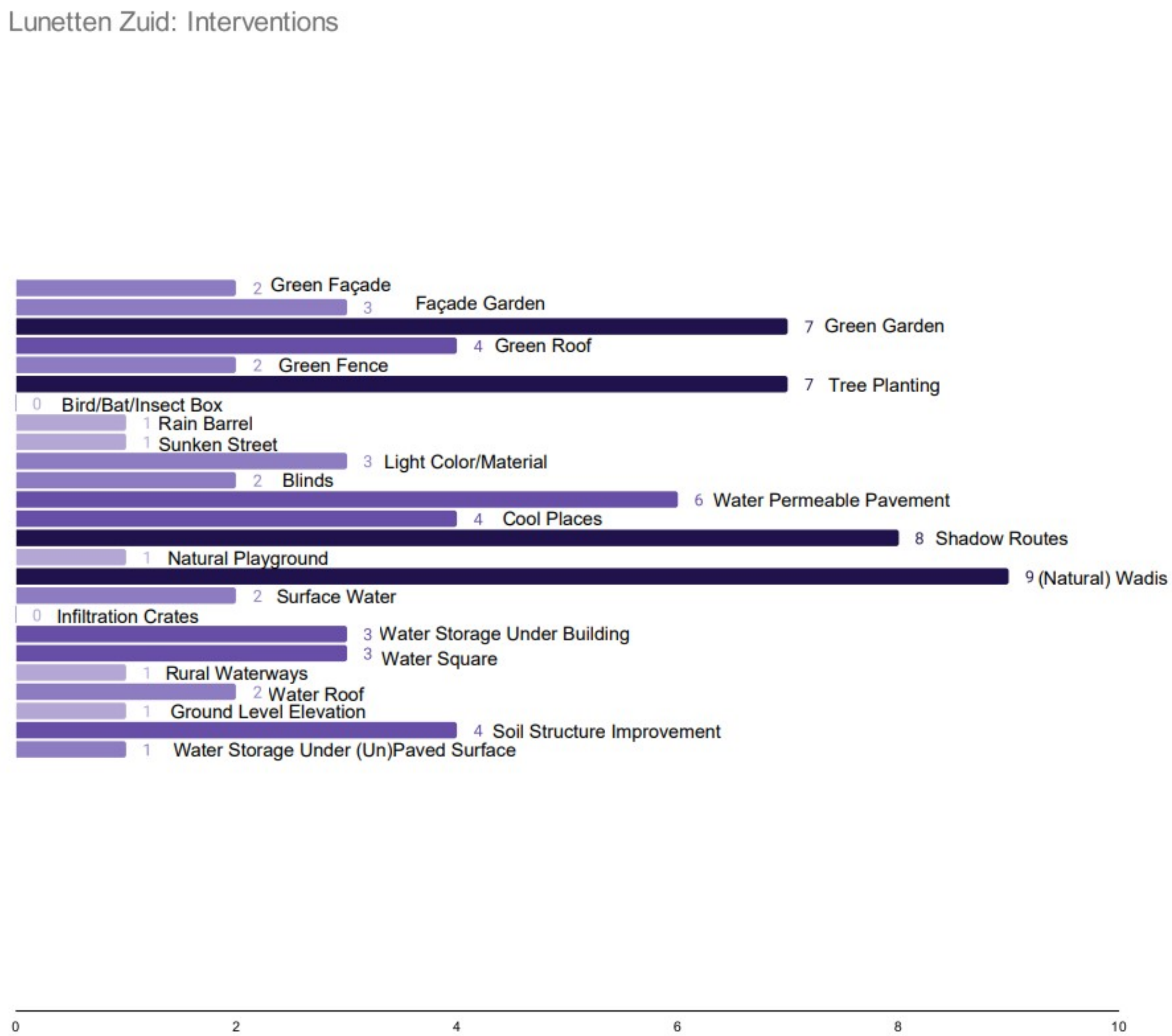


Figure 8.1: Results Survey Lunetten Zuid

When asked which additional information would have been helpful to aid the design decisions, most designers answered demographic data. Only 12.5% of designers answered that subsurface information would have aided there decision. From this percentage, half of them specifically requested information on soil types.

The results of this survey showcase how the lack of knowledge regarding subsurface information can lead to climate adaptation interventions that are not suitable for an area. The knowledge of soil type, subsurface congestion, average highest groundwater level, and geoemechanic properties during the design preliminary exploration can lead to design choices that are more sensible to the context and thus more effective for climate adaptation. In addition, the results of the survey also showcases how only a minority of designers believe it is relevant to have subsurface information during preliminary local climate adaptation design.

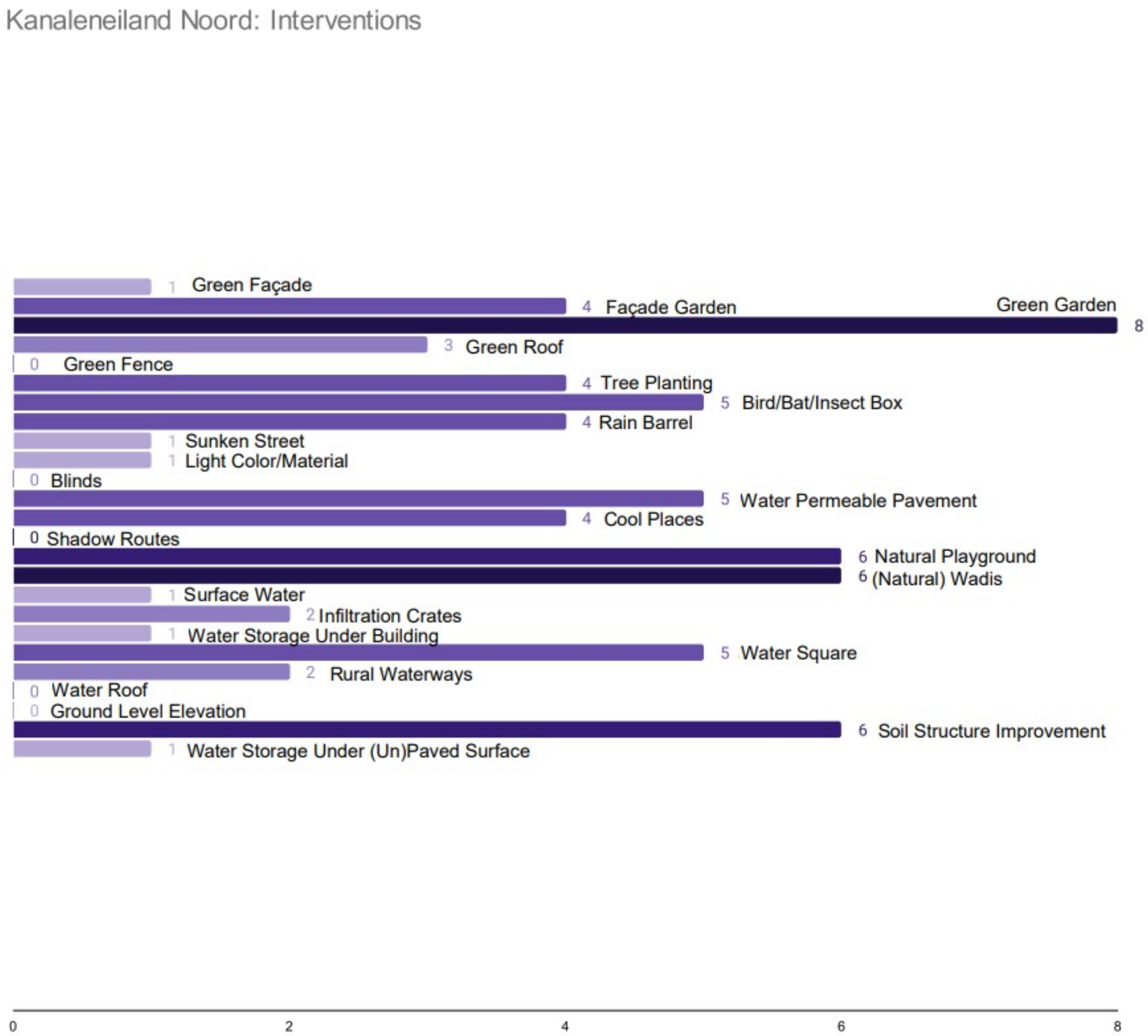


Figure 8.2: Results Survey Kanaleneiland Noord

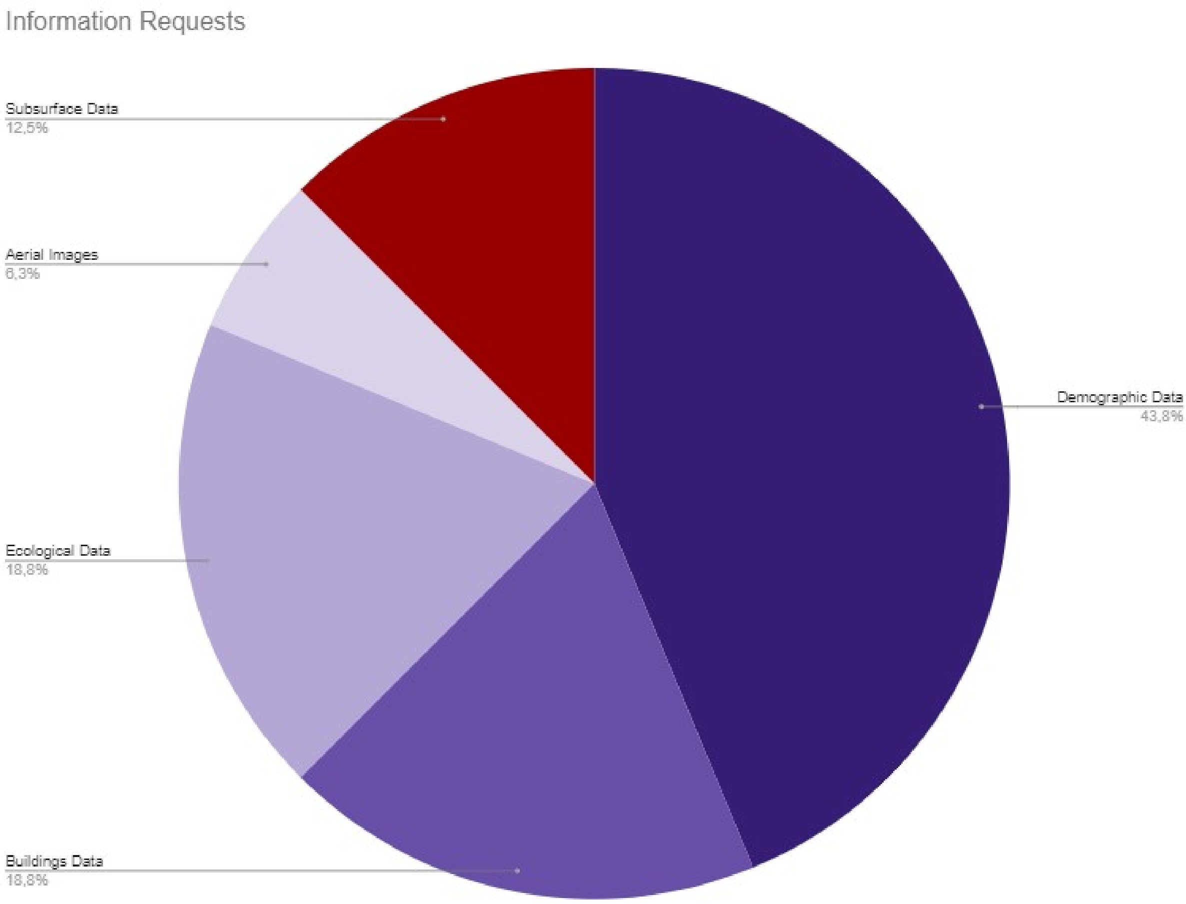


Figure 8.3: Additional Information Requests

9 Design LADM Standardization

As described in chapter 4.3, LADM Part 5 contain classes that can be useful for the standardization of urban planning and design information. The basic classes of the LADM Spatial Planning package are plan groups, plan blocks, plan units and plan permits. In chapter 4.3 these classes are explained and subclasses tailored for climate adaptation were created using existing attributes and adding new relevant ones to these classes.

Standardization plays a big role in sharing urban design information, and moreover, in sharing plans that contain climate adaptation information. The design proposal in Voordorp is used to expemplify this. Using the created subsclasses adapted from LADM Part 5 basic classes, the interventions and plan were stored in a database using the existing and new class attributes.

A new table was created using the attributes from the subclass CLIMA_PlanGroup, which uses the attributes from SP_PlanGroup but include additional attributes regarding the responsible and source of a plan. In this table information was stored regarding one of Utrecht's masterplan, namely the Utrecht 2040 plan. An ID was created for this plan and the resposible for it was defined as the municipality of Utrecht.

The SQL script used to populate the first table is as follows:

```sql
INSERT INTO clima_plangroup (pgid,hierarchylevel,label,referencepoint,
    responsible,source) VALUES (
  'MU2040',
  '1',
  'Utrecht2040',
  '',
  'Municipality Utrecht',
  'Utrecht 2040'
);
```

A second table was then crated to store information regarding local plans. Each local plan refers to a masterplan and therefore using PlanGroup and PlanBlock classes allows to store hierarchical relationships between different plans. It is partricularly interesting the use of attributes already existing in the Spatial Planning LADM package, such as attributes for storing the function of a local plan, for example Public Facility, and natural risks, such as a

pgid	hierarchylevel	label	referencepoint	responsible	source
MU2040	1	Utrecht2040		Municipality Utrecht	Utrecht 2040

Figure 9.1: Masterplan stored using CLIMA_PlanGroup subclass attributes

tendency for storms. Other than the attributes which are part of the PlanBlock class, the subclass CLIMA_PlanBlock included attributes tailored to store information regarding an area climate challenge, soil type, subsurface congestion, average highest groundwater level, and geomechanics. In this table, all these attributes were used to store information regarding the design proposal for Voordorp.

The SQL script used to populate the second table is as follows:

```sql
INSERT INTO clima_planblock (pbid,blockname,functiontype,protectedsite,
    naturalrisksafetyarea,restrictionzone,constraintname,constraintdescription,
    technologicalrisksafetyarea,miningriskssafetyarea,climatetheme,soiltype,
    subsurfacecongestion,groundwaterlevel,geomechanics,plangroup_id) VALUES (
  'UVoord001',
  'VoordorpPlan001',
  'cultivationPublicFacility',
  '',
  'stormRiskZone',
  '',
  '',
  '',
  '',
  '',
  'Waterlogging Heat',
  'Sand',
  'Low',
  'Above1m',
  'SuitableBuilding',
  'MU2040'
);
```

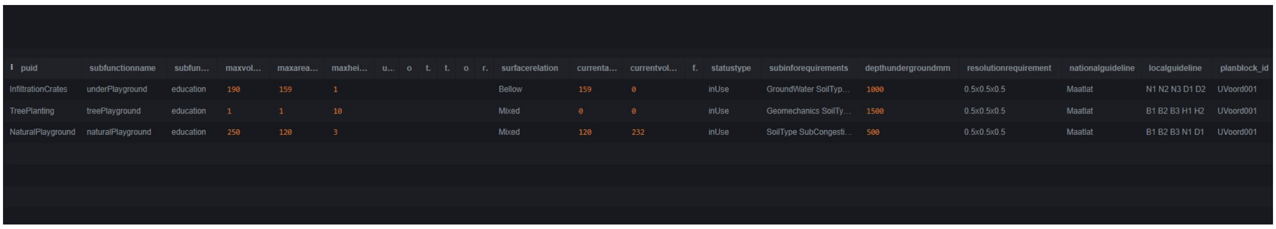
pbid	blockname	functiontype	p...	naturalrisk...	r...	c...	c...	t...	m..	climatetheme	soiltype	su...	ground...	geomechanics	plangr...
UVoord001	VoordorpPlan001	cultivationPublicFacility		stormRiskZone						Waterlogging Heat	Sand	Low	Above1m	SuitableBuilding	MU2040

Figure 9.2: Local plan stored using CLIMA_PlanBlock subclass attributes

Finally, a third table was created to store each one of the interventions that are part of the local plan proposed for Voordorp. In this table, each row corresponds to one of the three interventions. Each row refers to a plan, in this case the same Voordorp plan. That means that PlanBlocks can always contain zero or more PlanUnits. The subclass PlanUnit contains attributes regarding subfunction, the area, volume and height, which are all relevant and necessary for to store information regarding an intervention. In addition this class contains attributes regarding the status of an area (in use or not) and the surface relation (above, mixed, or bellow surface). The subclass CLIMA_PlanUnit is created using these attributes but contains additional attributes, such as resolution requirements, and national/local guidelines.

An example of one intervention (infiltration crates) stored in the table used the SQL script as follows:

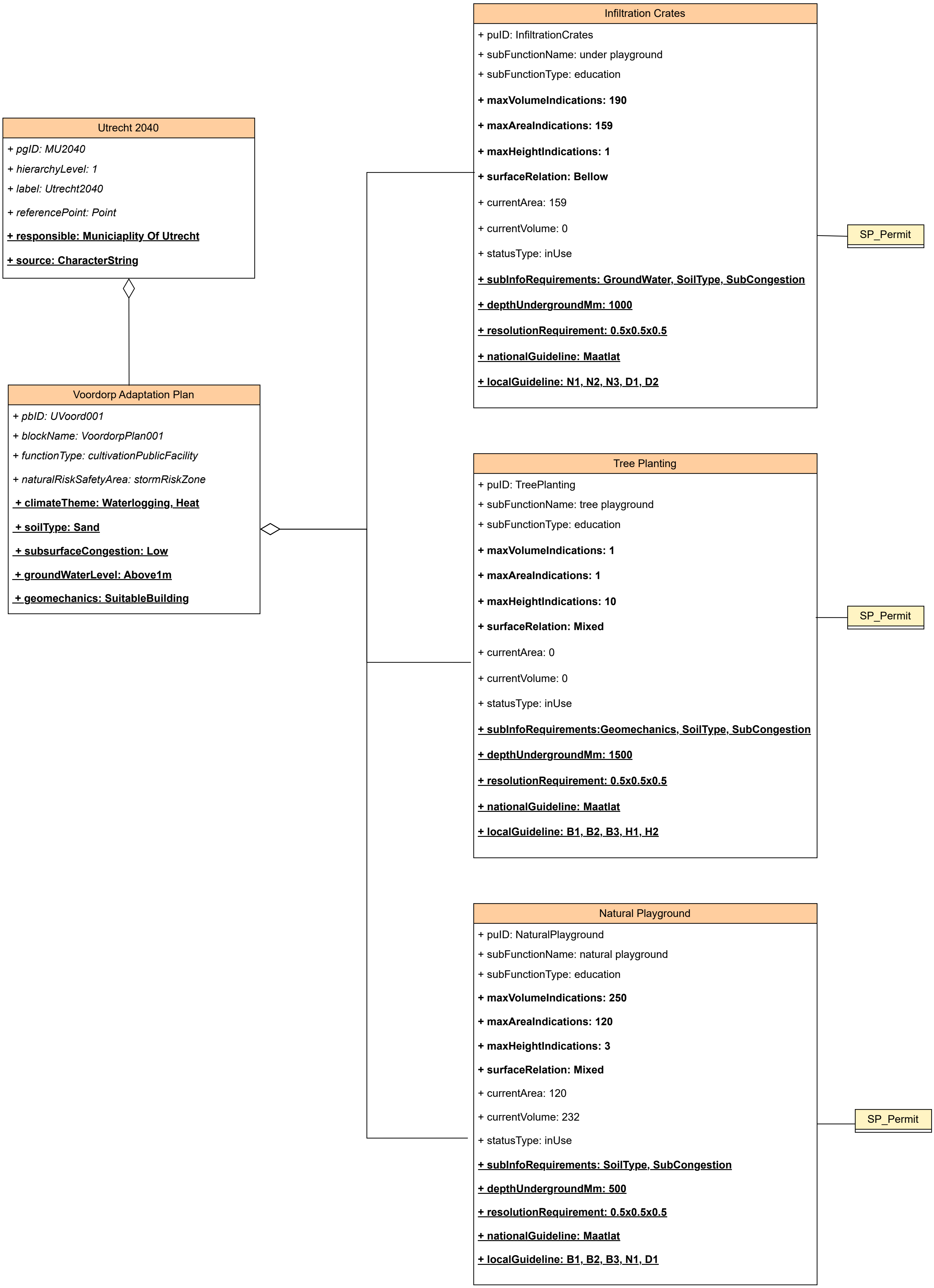
```

INSERT INTO clima_planunit (puid,subfunctionname,subfunctiontype,
    maxvolumeindications,maxareaindications,maxheightindications,unitindications
    ,otherindications,typeofbuildingindications,typeofshapeindications,
    otherconstructionindications,referencepoint,surfacerelation,currentarea,
    currentvolume,featureprotected,statustype,subinforequirements,
    depthundergroundmm,resolutionrequirement,nationalguideline,localguideline,
    planblock_id) VALUES (
  'InfiltrationCrates',
  'underPlayground',
  'education',
  '190',
  '159',
  '1',
  '',
  '',
  '',
  '',
  '',
  '',
  'Bellow',
  '159',
  '0',
  '',
  '',
  'GroundWater␣SoilType␣SubCongestion',
  '1000',
  '0,5x0.5x0.5',
  'Maatlat',
  'N1␣N2␣N3␣D1␣D2',
  '001'
);
```



puid	subfunctionname	subfun...	maxvol...	maxarea...	maxhei...	u...	o	t.	t.	o.	r.	surfacerelation	currenta...	currentvol...	f.	statustype	subinforequirements	depthundergroundmm	resolutionrequirement	nationalguideline	localguideline	planblock_id
InfiltrationCrates	underPlayground	education	190	159	1							Bellow	159	0		inUse	GroundWater SoilTyp...	1000	0.5x0.5x0.5	Maatlat	N1 N2 N3 D1 D2	UVoord001
TreePlanting	treePlayground	education	1	1	10							Mixed	0	0		inUse	Geomechanics SoilTy...	1500	0.5x0.5x0.5	Maatlat	B1 B2 B3 H1 H2	UVoord001
NaturalPlayground	naturalPlayground	education	250	120	3							Mixed	120	232		inUse	SoilType SubCongesti...	500	0.5x0.5x0.5	Maatlat	B1 B2 B3 N1 D1	UVoord001

Figure 9.3: Interventions stored using CLIMA_PlanUnit subclass attributes

In cases where CAD or other 3D geometry files are available, this data can be stored and loaded using tools such as FME. However, since the design proposals for Voordorp are preliminary and no specific files were created, this was not done. Instead, the plan information is stored in tables as demonstrated in this thesis. With more time and knowledge, these plans could have been prepared for loading with tools like FME.


Utrecht 2040
+ pgID: MU2040
+ hierarchyLevel: 1
+ label: Utrecht2040
+ referencePoint: Point
+ responsible: Municiaplity Of Utrecht
+ source: CharacterString
Voordorp Adaptation Plan
+ pbID: UVoord001
+ blockName: VoordorpPlan001
+ functionType: cultivationPublicFacility
+ naturalRiskSafetyArea: stormRiskZone
+ climateTheme: Waterlogging, Heat
+ soilType: Sand
+ subsurfaceCongestion: Low
+ groundWaterLevel: Above1m
+ geomechanics: SuitableBuilding
Infiltration Crates
+ puID: InfiltrationCrates
+ subFunctionName: under playground
+ subFunctionType: education
+ maxVolumeIndications: 190
+ maxArealndications: 159
+ maxHeightIndications: 1
+ surfaceRelation: Bellow
+ currentArea: 159
+ currentVolume: 0
+ statusType: inUse
+ subInfoRequirements: GroundWater, SoilType, SubCongestion
+ depthUndergroundMm: 1000
+ resolutionRequirement: 0.5x0.5x0.5
+ nationalGuideline: Maatlat
+ localGuideline: N1, N2, N3, D1, D2
SP_Permit
Tree Planting
+ puID: TreePlanting
+ subFunctionName: tree playground
+ subFunctionType: education
+ maxVolumeIndications: 1
+ maxArealndications: 1
+ maxHeightIndications: 10
+ surfaceRelation: Mixed
+ currentArea: 0
+ currentVolume: 0
+ statusType: inUse
+ subInfoRequirements:Geomechanics, SoilType, SubCongestion
+ depthUndergroundMm: 1500
+ resolutionRequirement: 0.5x0.5x0.5
+ nationalGuideline: Maatlat
+ localGuideline: B1, B2, B3, H1, H2
SP_Permit
Natural Playground
+ puID: NaturalPlayground
+ subFunctionName: natural playground
+ subFunctionType: education
+ maxVolumeIndications: 250
+ maxArealndications: 120
+ maxHeightIndications: 3
+ surfaceRelation: Mixed
+ currentArea: 120
+ currentVolume: 232
+ statusType: inUse
+ subInfoRequirements: SoilType, SubCongestion
+ depthUndergroundMm: 500
+ resolutionRequirement: 0.5x0.5x0.5
+ nationalGuideline: Maatlat
+ localGuideline: B1, B2, B3, N1, D1
SP_Permit

10

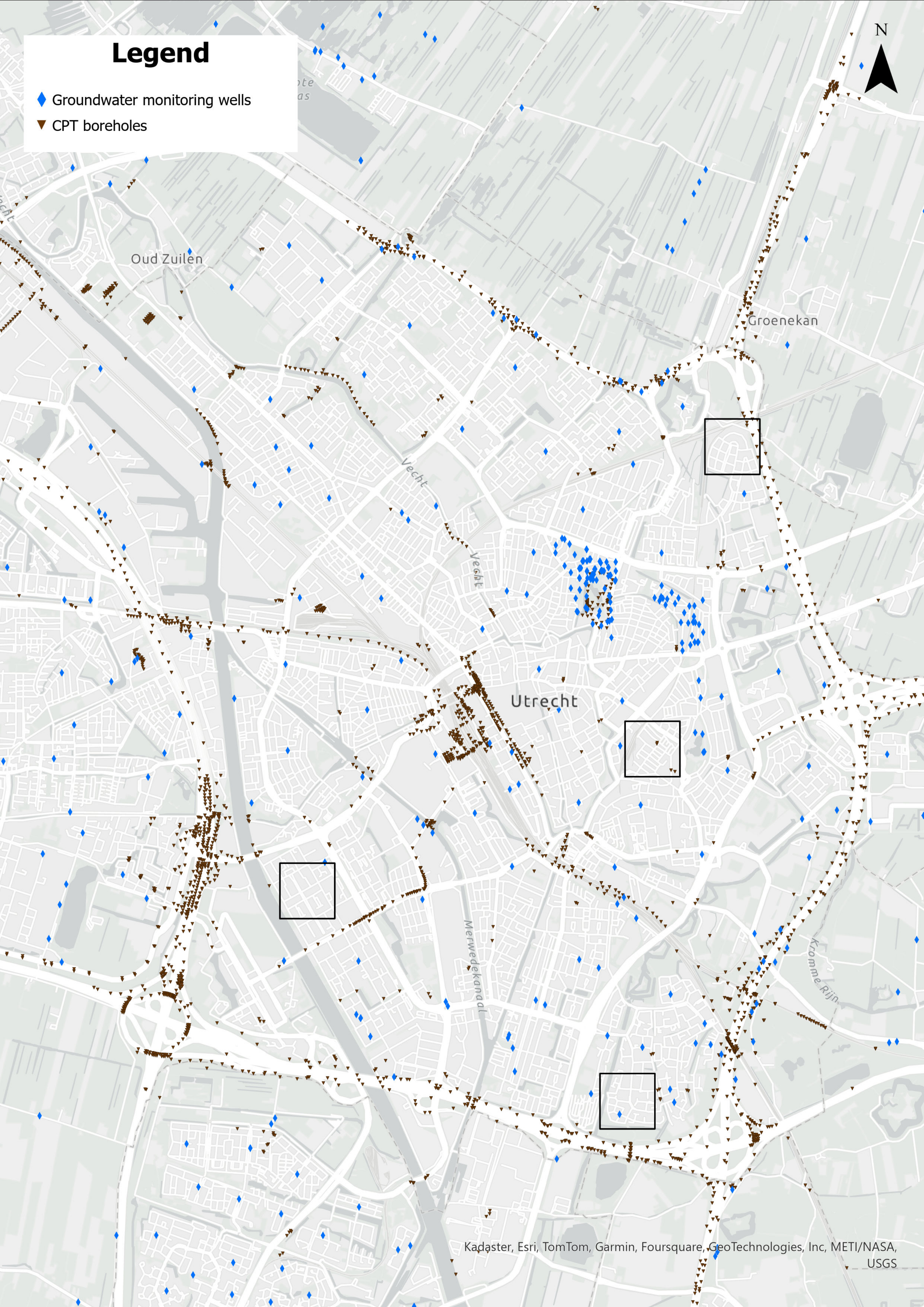
Increasing Data Resolution and Accuracy

Subsurface data always present a certain level of uncertainty due to the methods in which this data is collected and represented. This is because subsurface information models are usually created by interpolation, taking existing data points and generating new ones between them. In addition, subsurface information models are often not in the resolution defined as needed for local climate adaptation design.

One way to increase the data resolution and accuracy of existing subsurface information models is by adding new data points, ideally in the studied area. That means, in practice, digging a hole in the design area and confirming or refuting the data in the information model regarding certain subsurface properties. This would give the most certainty regarding the subsurface properties of an area for obvious reasons. However, this method is very impractical for preliminary design. Another way to add new data points is by integrating information from existing boreholes and groundwater monitoring wells close to the area, which may not have been taken into consideration during the interpolation process.

The location of existing CPT boreholes and groundwater monitoring wells is publicly available. A map was created using GIS software. This map contains layers from the Key Register imported via ArcGIS Living Atlas regarding the location of CPT boreholes and groundwater monitoring wells. In addition the map contains the four different design areas. Successively, four different maps were created zooming in each design area. These four areas are used as examples of four locations where boreholes and groundwater wells were not taken into account but could have. As seen in the zoomed in maps, the position of these elements vary largely even within the same city.

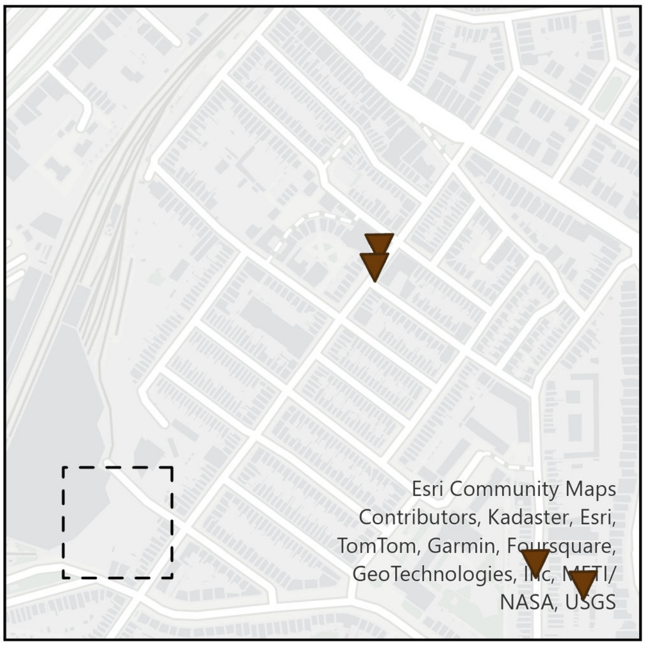
The information publicly available regarding CPTs and groundwater monitoring wells is ideally interpreted by an expert. However, there are other methods and software that could allow planners and designers to do it on their own. The following sections describe the different methods known by the authors to integrate data from boreholes and groundwater monitoring wells.


Legend
Groundwater monitoring wells
CPT boreholes
N
Oud Zuilen
Groenekan
Vecht
Vecht
Utrecht
Merwedekanaal
Kromme Rijn
Kadaster, Esri, TomTom, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

Design Areas: CPT Boreholes and Groundwater Monitoring Wells

Scale 1:6000

Area 1: Kop Voordop

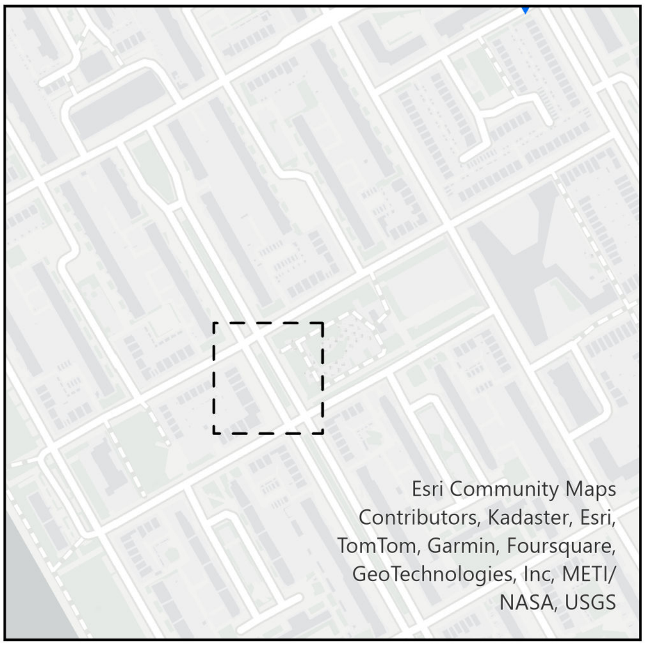


The design area has two close CPT boreholes that could have been included to increase data accuracy.

Area 2: Lunetten Zuid

The area has one groundwater monitoring well that could have been included to increase data accuracy.

Area 3: Kanaleneiland Noord



This design area does not have any close CPT borehole or groundwater monitoring well that could have been included to increase data accuracy.

Area 4: Voordop

This area has multiple close CPT boreholes that could have been included to increase data accuracy.

10.1. Integrating Groundwater Data

Groundwater levels are a type of subsurface requirements that is necessary for many design interventions. In particular, the average highest groundwater level is fundamental to better understand the (lack of) capacity of a soil to infiltrate water. A map regarding this property is available on a national level but on a resolution that is often not adequate for local climate adaptation design, covering an area that is too large.

A way in which this data accuracy and resolution could improve for the purpose of design is by integrating new data points, such as groundwater monitoring wells. The location of this wells is publicly available, however information regarding the average highest groundwater level is not available for each point.

For this reason, an integration method for this data is, mainly, to make available information regarding the average highest groundwater level. Once this information is made available, new methods can be done, such as a local interpolation, or integration of data for specific groundwater monitoring wells that are close to a design area.

10.2. Integrating CPT Data

Cone penetration tests (CPT) are procedures where a steel rod with a cone is pressed into the ground at a constant speed. During soil penetration, various measurements are taken at the cone of the rod.

Typically, two lines are drawn, representing the q_c and Fr values. These can be interpreted as follows:

- q_c: Resistance measured at the tip of the cone.
- F_s: Friction measured at the cone, which is normalized by $\frac{1}{q_c} \times 100$, resulting in R_f due to their strong correlation.

CPT data is typically presented by depth, while soil classification data like Soil Behaviour Type (SBT), which indicate subsurface properties such as soil types, is usually shown in graphs. This format complicates the assessment of SBT variations with depth and the analysis of soil behavior alongside conventional CPT data.

To address this issue, Jefferies and Davies proposed the Soil Behavior Type Index (Ic), enabling SBT to be displayed as a continuous profile alongside CPT data. This continuous profile is what is avaible on a national level on the BRO webservice. A geotechnical engineer's work often consist of interpreting CPT data such as this continuous profiles, deriving both the soil type and layer boundaries from it.

Robertson Classification Algorithm

The Robertson classification algorithm is used the standard for soil type classification using CPT data. It utilizes cone resistance (q_c) and sleeve friction (F_s) values from the CPT data. The normalized Cone Resistance (q_{c1N}) is calculated by normalizing q_c with respect to the effective vertical stress (σ_{vo}):

$$q_{c1N} = \frac{q_c}{\sigma_{vo}}$$

It relies on the Soil Behavior Type (SBT) chart, which categorizes soil behavior based on normalized q_{c1N} and the normalized sleeve friction ratio ($\frac{f_s}{q_c}$). Plotting q_{c1N} versus $\frac{f_s}{q_c}$ on the SBT chart categorizes soil behavior into various types like sands, clays, silts, and peats. Based on the plotted point, the algorithm assigns a soil type classification.

While this is the standard used by experts, there are different AI tools who are build using the same classification algorithm or similar ones. While these tools often had in mind geotechnical engineers, some of them are available as simple Python packages or webservices, and do not require the user do to the calculations. For this reason, some relevant AI methods are disucussed in the following subsection.

AI Classification Methods

Currently there are examples of AI tools that classify soil type and other subsurface properties based on the Robertson method among others. One such example is the CPT MODEL [74] by CEMS, which uses convolutional neural network to fully automatized soil type classification based on CPT data input.

The model was trained using about 49000 CPTs and 40000 boreholes. Among them, 1800 pairs satisfied the criteria of being within 6 meters of each other, serving as labeled data for the initial model training. Periodic retraining of the model occurs whenever fresh data meeting the 6-meter requirement emerges. For more information, the automated soil classification method is described in details in this article: `https://www.ritchievink.com/blog/2019/04/02/fully-automated-soil-classification-with-a-convolutional-neural-network-and-location-embeddings/`

To use this tool basic Python knowledge and Internet connection is required. The following code can be used:

```
from nuclei import call_endpoint, get_endpoints

# Get endpoints
APP = 'gef-model'
get_endpoints(APP)
# Output: ['/classify', '/default-version', '/model-versions', '/nen-table', '/plot']

# Define schema and call endpoint to get a plot
schema = {
    "aggregate_layers_penalty": 2,
    "cpt_content": content,
}
call_endpoint(APP, '/plot', schema)

# Use /classify endpoint to get detailed classification
schema = {
    "aggregate_layers_penalty": 5,
    "cpt_content": content,
    "merge_nen_table": True
}
result = call_endpoint(APP, '/classify', schema)
result["layer_table"][["depth_top", "G", "S", "L", "C", "P", "elevation_with_respect_to_NAP", "nen_row", "soil_code", "grain_pressure"]]
```

You can use the NEN description to identify the layer type or create your own description based on the components. Both methods have been successfully used in several projects [74]. However, this script does not cover all the functionalities that the tool has. The full tool is only available under request.

Other than Python tools, there are webservices that also automatized the classification of CPT data. One example is the BRO app created using VIKTOR web application [75]. Through it users can conveniently pinpoint Cone Penetration Tests (CPTs) from the BRO database on a map, visualize the data, and select up to ten CPTs for comparison. The soil structure from the selected CPT data is then classified using the Robertson method. The comparison results can be viewed within the app and also downloaded locally as a .xml file. Bellow is an image resulting from the webservice. The tool is also available as a Python package.

Figure 10.1: Visualization of CPT data classification using the webservice

11 Conclusion

The overall research question that this thesis aims to answer is: *How can 3D data subsurface information models support standardized local climate adaptation design?*

This question was then subdivided into seven subquestions that were answered in the three parts of this research. The first part focused on understanding why a common ground for climate adaptation design information was necessary.

The first subquestion this part aims to answer is: *1) How does climate adaptation relate to subsurface?*

While answering, it became apparent that climate adaptation strategies rely heavily on subsurface information, in particular when preference is given to nature-based adaptation approaches. Moreover, while trying to understand how local climate adaptation design relates to the subsurface, it became apparent the four main subsurface properties that are relevant for standardized local climate adaptation, namely groundwater level, subsurface congestion, soil type and geomechanics. These identified properties were used as the basis for analysing the suitability of existing subsurface information models for the purpose of local climate adaptation design.

This part also answered the subquestion: *2) What are the existing challenges for effective utilization of 3D subsurface information models in Dutch climate adaptation strategies?*

Several barries were identified while answering this question. In particular, institutional barriers, notably the lack of interdisciplinary collaboration between geoinformaticians and urban designers, present significant hurdles. Educational curricula often fail to equip professionals with the necessary breadth of expertise to bridge disciplinary divides, impeding effective communication and collaboration. Furthermore, technological barriers, particularly in data-rich environments, exacerbate integration challenges. Despite the promise of urban informatics in managing and analyzing urban data, standardization and integration hurdles persist. Finally, semantic barriers underscore the need for standardized frameworks and data models to facilitate seamless information exchange between subsurface models and national design guidelines. While initiatives such as the Key Registry for the Subsurface offer valuable data, the absence of integration with design guidelines limits its utility in climate adaptation design. The conclusion that comes from the answer of this research subquestion is that the challenges regarding an integrated geoinformatic design approach remain similar to the ones identified in existing literature. These identified challenges were considered when creating a tool that combines different relevant information, and preference was given to a public online catalog that was equally accessible for data providers and designers.

Part II presents all the relevant local climate adaptation design information models, including existing 2D and 3D subsurface models for each one of the identified relevant subsurface properties and standards or guidelines. This part is concluded with a relational diagram and a relational database that combine and represent visually all the relevant information relationships to the twenty five most relevant standardized local climate adaptation design interventions. This part of the thesis aimed to answer the following research questions:

3) What specific design interventions are commonly employed in Dutch climate adaptation? How do they relate to the subsurface?

To answer this question, a document published by the Dutch government is used. This document indicates the twenty five most commonly used climate adaptation design interventions in the Netherlands. [3] This document indicates that these interventions do not relate to soil type, however, different sources indicate that they do relate to different subsurface properties. This information relationship, often a dependency, was made more clear through a table. This table describes the information requirements for each one of the twenty five interventions. One of the conclusions from this table is that interventions related to water infiltration almost always require information regarding the soil type. This is because different soil types will have a higher or lower infiltration capacity. Thus for these interventions, information must be available for the infiltrating layers and potentially in high resolution. Another conclusion is that interventions that consist of a 3D element, such as an infiltration crate, would benefit from a model with underground pipes and cables, in 3D and real size, to simulate the new designed 3D object when placed in a congested 3D subsurface system.

Additionally, a catalog was made to describe resolution requirements for each intervention. This evaluation was made based on design guidelines such as the Bouwadaptied, the scale of representation of the intervention, its (unit) dimensions above and bellow the surface, and the purpose of the intervention, e.g. natural infiltration solutions are usually related to the first 50 cm of the subsurface. A matrix was also created evaluating how sensitive each intervention was to data accuracy and resolution for each one of the four subsurface properties.

To make the relationships on subsurface information properties visually apparent, along with other information dependencies, a relational diagram and databases were created. These models are better explained when answering the subquestion:

4) How comprehensive and accurate are the current national-level 3D subsurface information models in the Netherlands? Can we improve them?

To answer this subquestion an overview was given of all the existing subsurface information models for each one of the identified subsurface properties. The main conclusion regarding potential improvement of the existing information models is related to the data resolution of the models, for example the size of the voxels being too big, and the necessity of interpretation by an expert to some of the public data. This is particularly true for the usability of the soil type 3D model GeoTOP, which is proved to be useful on a national and municipal level but might request a different resolution for projects on the building or street scale. The current resolution of GeoTOP is 50 cm vertically, which suffices resolution requirements for most climate adaptation design interventions, and 100 m vertically, which is a number way superior to what desired in terms of horizontal resolution for local design. Subsurface models are also based on a probability due to the interpolation way in which they are created. This would be facilitated by the integration of more specific data, such as the groundwater wells graphs and CPTs data. At the moment, this information is public but requires the interpretation of an expert. This is a potential improvement for the models.

Another main conclusion from this assessment, further confirmed by the design exploration, is that some subsurface properties benefit more than others regarding the use of 3D models instead of 2D. The benefits of a 3D for properties such as soil type and subsurface congestion were clear due to the dependency of sections to study these properties. However, the lack of an existing 3D model for the average highest groundwater level or the building suitability of an area was not that significant. This is probably due to the fact that this properties are associated with a singular numerical value or percentage, and thus do not request multiple layers of information to be visible at once as other models do.

Finally Part III present practical solutions to the main research question. It presents practical examples of ways in which 3D (and 2D) data subsurface information models can support standardized local climate adaptation design.

The subquestion *5) What methodologies can be established for integrating subsurface information models into urban design?* is answered through the creation of an online catalog, or a tool for the combination of all the relevant information regarding Dutch climate adaptation design. This online catalog was named CLIMACAT and it is publicly available: `https://arcg.is/4jPvG`

A proposed standardization method using LADM Part 5 is also presented as a potential methodology to integrate information models but also to facilitate the sharing of planning information that contain climate adaptation interventions. Using the basic classes of the LADM Spatial Planning package, subclasses were created with additional attributes tailored for the storage of climate adapatation design information.

This question is also answered through a design exploration that test, in practice, the identified information needs and their sources, along with the new created method and tool. The design exploration answered the subquestions:

6) What data resolution or scale is necessary for diverse climate adaptation interventions? and *To what degree must models be precise to meet design requirements?*

The existing information models suffice the information needs for the design exploration. The models were sufficient to give an overview of the subsurface characteristics of a certain area and be used as the basis for the design design decision. However, it is important to note that this is a preliminary design. In the case in which these interventions were to be build, it would be necessary to study the subsurface characteristics locally, through a local test and with the help of an expert. This is highly linked to the limitation posed by the uncertainty of subsurface models and the resolution of the existing models. The main conclusion is thus that while the existing information models suffice the needs for a preliminary local climate adaptation design and the selection of the standardized interventions, the actual building of the interventions would request local investigation. In addition, the design exploration confirmed the hypothesis regarding data resolution presented in the resolution catalog. The soil type model sufficed the needs for vertical resolution for all the interventions but did not suffice the horizontal resolution requirement for most.

The different resolution vertically and horizontally is particularly relevant for subsurface models based on interpolation such as GeoTOP more than it is for the 3D digital twins, such as a 3D underground model of cables. This is because one is based on interporlation, while the other is probably based on an existing 3D elements.

This part also includes a discussion on potential methodologies for the integration of CPT and groundwater monitoring well data. For groundwater monitoring wells, it was concluded that information regarding the average highest groundwater level should be made publicly available along with other groundwater measurements. Public CPT data, on the other hand, can already be integrated without the help of experts with AI tools that often use well-known CPT data interpretation methods, such as the Robertson classification algorithm.

Finally, the subquestion *7) What is the additional value of integrating information models into climate adaptation design? Can this value be quantified?* was answered firstly through the demonstrated methodology in the design exploration and secondly through a design evaluation. The evaluation consisted of an online survey where sixteen designers were asked to create a design proposal using the same set of twenty five standardized climate adaptation interventions but without prior knowledge regarding the subsurface. As a result, many designers selected interventions that were not suitable for the area, such as natural infiltration where the infiltration capacity of the subsurface was low. Additionally, a quantitative measure that came from the survey is that, from the sixteen designers, only 12.5% considered that subsurface information would have aided their design.

12

Reccomendations

The results from this research can point to further research on how to model subsurface properties and on the creation of new design tailored tools. The tools and models were sufficient for the design and assessment aspect of this thesis but could have been further studied. For example, groundwater level could be recommended to be modelled as a continuous 3D layer that could be added to the soil types (GeoTOP) model. Using the different punctual highest average numerical values interpolated, this data could be represented in an integrated 3D model instead of a separated 2D map. This is particularly relevant for interventions, or other topics, related to water infiltration, where both groundwater level and soil types are needed.

In addition, the use of 3D building as an additional layer to the soil type 3D model or the subsurface congestion 3D model has proven to be immensely useful when designing for a better understanding of scale and size. A tool with designing purposes should thus take this into consideration.

There are many (AI) tools being created for the interpretation of CPT data. A potential research would include these tools to evaluate their usefulness in adding accuracy and resolution for local design.

Regarding the use of planning information standards, this thesis presents subclasses that utilizes LADM Part 5 basic classes attributes but with additional attributes tailored for storing climate adaptation interventions. In this thesis the UML diagram is presented along with instructions for storing planning information in a database. Future research could include testing this methodology using a real climate adaptation plan instead of a preliminary design exploration. The former should contain additional information and geometrical properties, allowing it to be loaded using a tool like FME and having its (3D) geometry made visible.

Finally, this thesis recommend the use of webviewers for interdisciplinary interactions, especially in urban design. Webviewers were incorporated into the virtual catalog CLIMACAT but also used throughout the entire design process. These were proven to be an accessible way for those with few to no GIS experience, being a a great way to deal with institutional and technological barriers regarding the integration of subsurface models in climate adaptation design.

13 Reflection

This thesis explores how can integrating information models aid well-informed design decisions, focusing on standardized climate adaptation interventions. These interventions, encompassing aspects like water storage, soil infiltration, and subterranean spatial management, necessitate a comprehensive understanding of subsurface properties. This requirement is highly significant in the context of pressing concerns surrounding climate change, as emphasized in documents like the Delta Programme, which mandates the Netherlands to achieve climate resilience and water robustness by 2050. Ensuring the availability of climate adaptation information across all sectors is paramount, and overcoming practical and theoretical obstacles necessitates fostering a shared understanding. Thus, this thesis coins the term ”common ground” to denote the pivotal intersection between information models, the subsurface, and design.

However, the search for a common ground between Geomatics and Urbanism was a personal journey that started three years ago, drawing heavily upon both prior experiences and informal dialogues. Within this narrative, while emphasizing the academic and practical significance of integrating subsurface information into design processes in the context of climate adaptation, this thesis frequently diverged from conventional methodologies, opting instead for unconventional approaches that defy the norms of both Geomatics and Urbanism theses.

Consequently, the primary constraint of this study is intricately intertwined with its greatest potential: its interdisciplinary nature. While the dual-degree framework facilitated the adoption of unconventional methodologies, such as utilizing relational databases to represent design interdependencies or assessing existing information models through a design proposal, it also complicates the evaluation of whether the author’s decisions would align with those of a purely design-oriented or geoinformatics-focused individual.

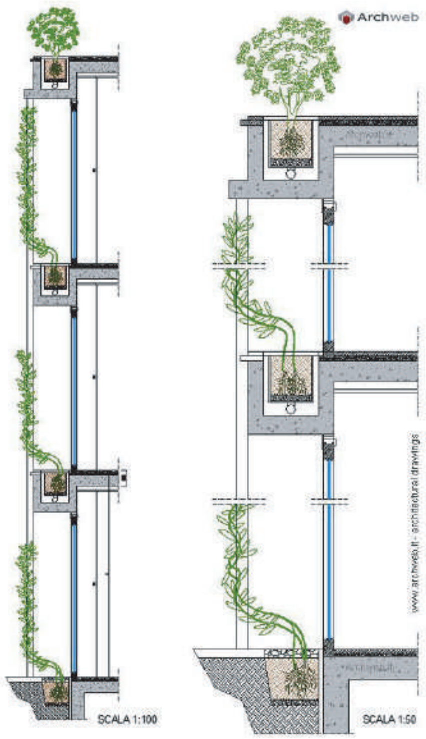
Thus, while adeptly addressing the research question and its subquestions, this thesis not only showcases the advantages and drawbacks of an interdisciplinary approach within standardized local climate adaptation design but also within the distinctive framework of a double degree thesis.

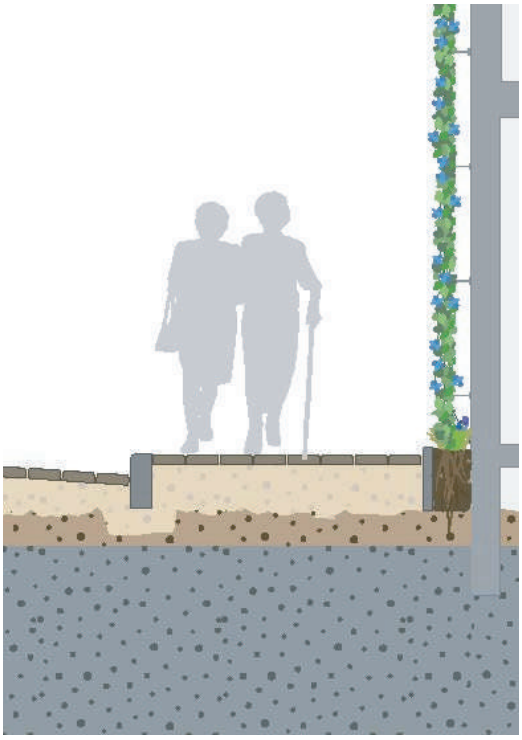
14

Annex A: Climate Adaptation Design Resolution Requirements Catalog

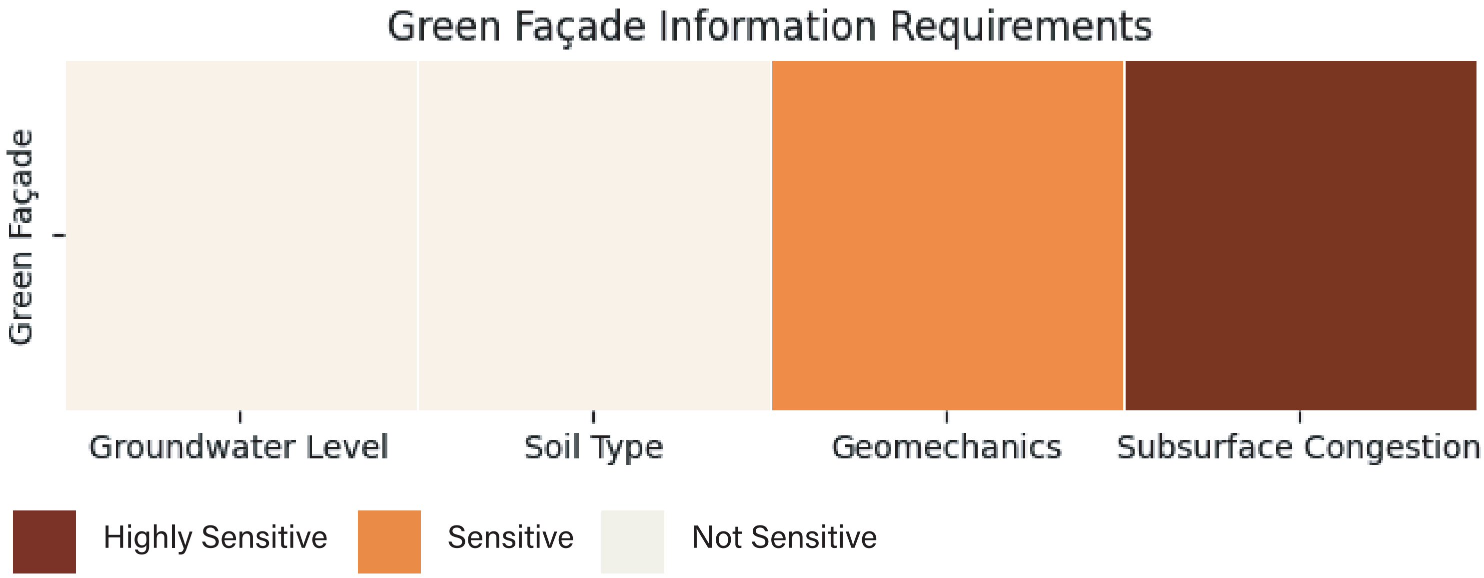
Green Façade

Adaptation: Biodiversity, Heat





Source (left to right): Archweb, Groenblauwenetwerken, Groenblauwenetwerken (Arhem)



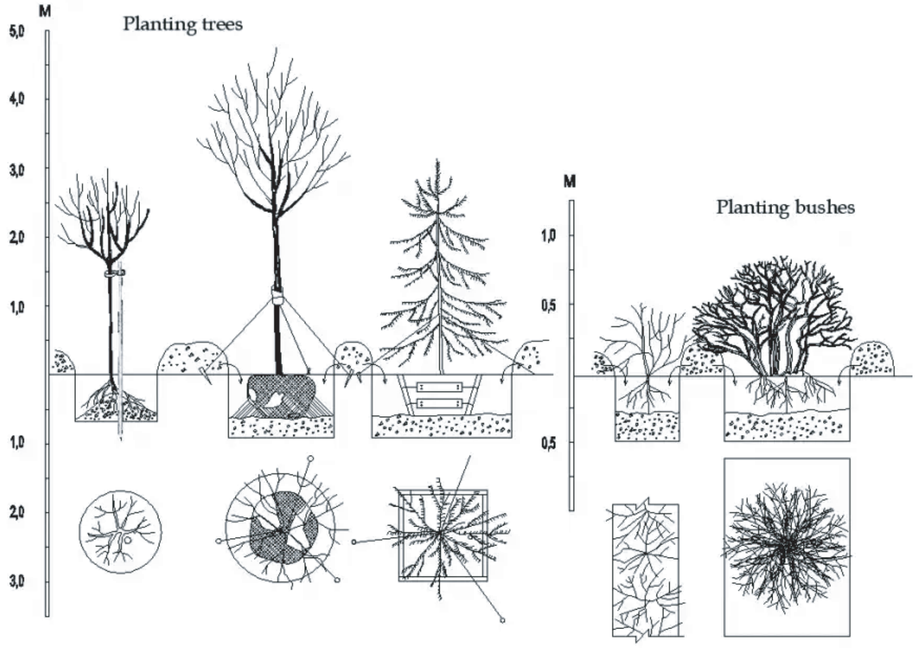
Subsurface Congestion: Solutions that include greenery that has its roots directly on the subsurface require enogh space for roots. (Bouwadaptief) Thus this intervention is highly sensitive to the accuracy of subsurface congestion information.

Geomechanics: A solid ground is necessary for this solution (Bouwadaptief), which means it is impacted by Geomechanics information but not as directly dependent as with subsurface congestion.

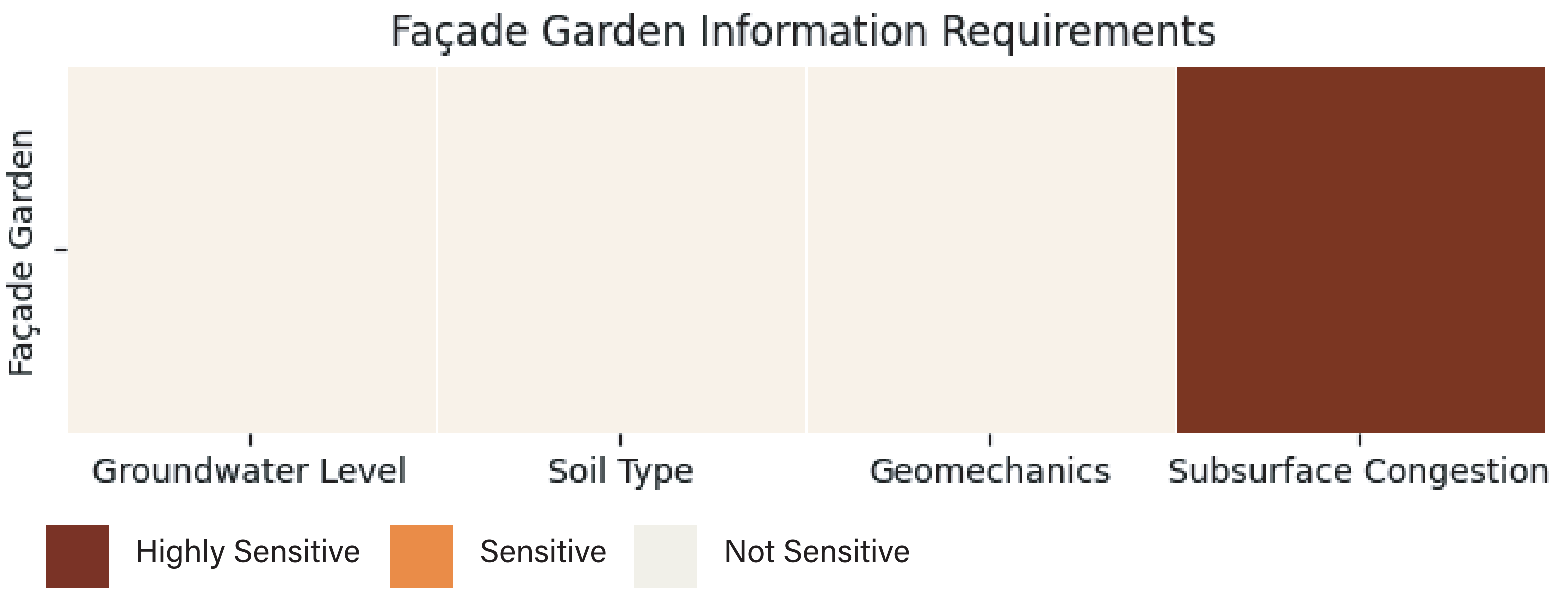
Resolution Requirement: Plant roots are 3D objects and might benefit from a 3D model of the subsurface congestion. The geomecahnics (suitability to build) can be available in 2D. Resolution is defined based on the size of the intervention and the root. In architectural drawings, this intervention is usually represented in 1:100 or 1:50 scale. Subsurface congestion is ideally represented in scale and level of detail. If trees are planted the root size need to be considered.

Façade Garden

Adaptation: Biodiversity, Heat, Waterlogging



Source (left to right): Cadbull, REDscapes (Bankastraat, Amsterdam)

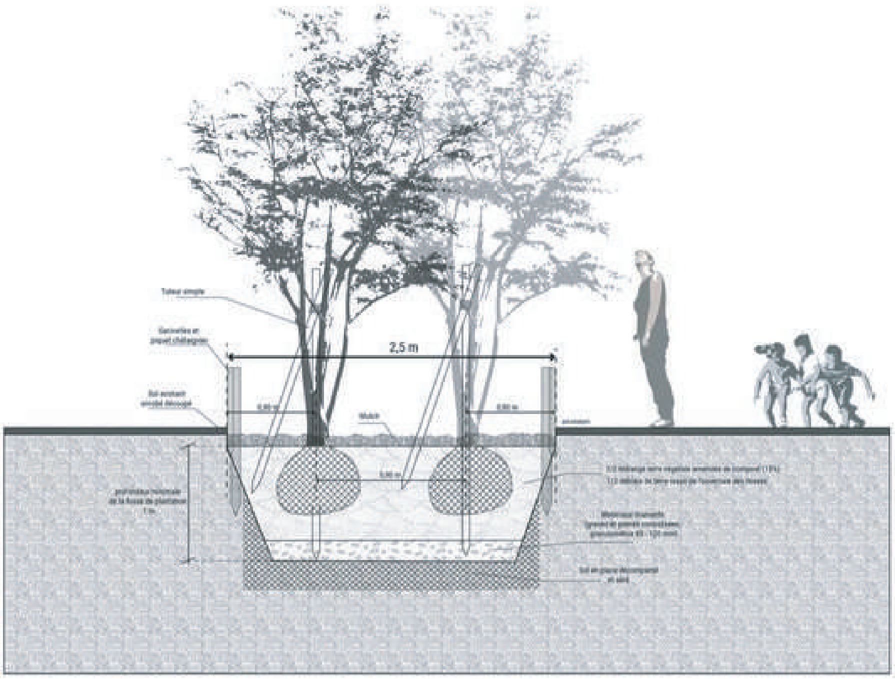


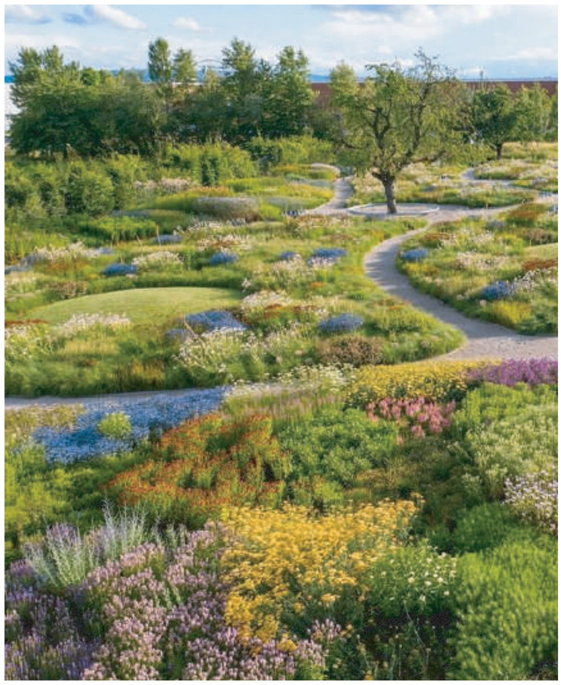
Subsurface Congestion: Ground-planted vegetation demands more root space and a stable substrate (Bouwadaptief). Therefore, when diretly planting on the soil instead of pots, this intervention is highly senstive to accuracy of subsurface congestion information.

Resolution Requirement: Plant roots are 3D objects and might benefit from a 3D model of the subsurface congestion. The geomecahnics (suitability to build) can be available in 2D. Resolution is defined based on the size of the intervention and the root. In architectural drawings, this intervention is usually represented in 1:100 or 1:50 scale. Subsurface congestion is ideally represented in scale and in this level of detail. This solution more often than not include smaller greenery and not big trees. However, if trees are planted, the dimensions for tree root growth must be taken into consideration as a resolution requirement.

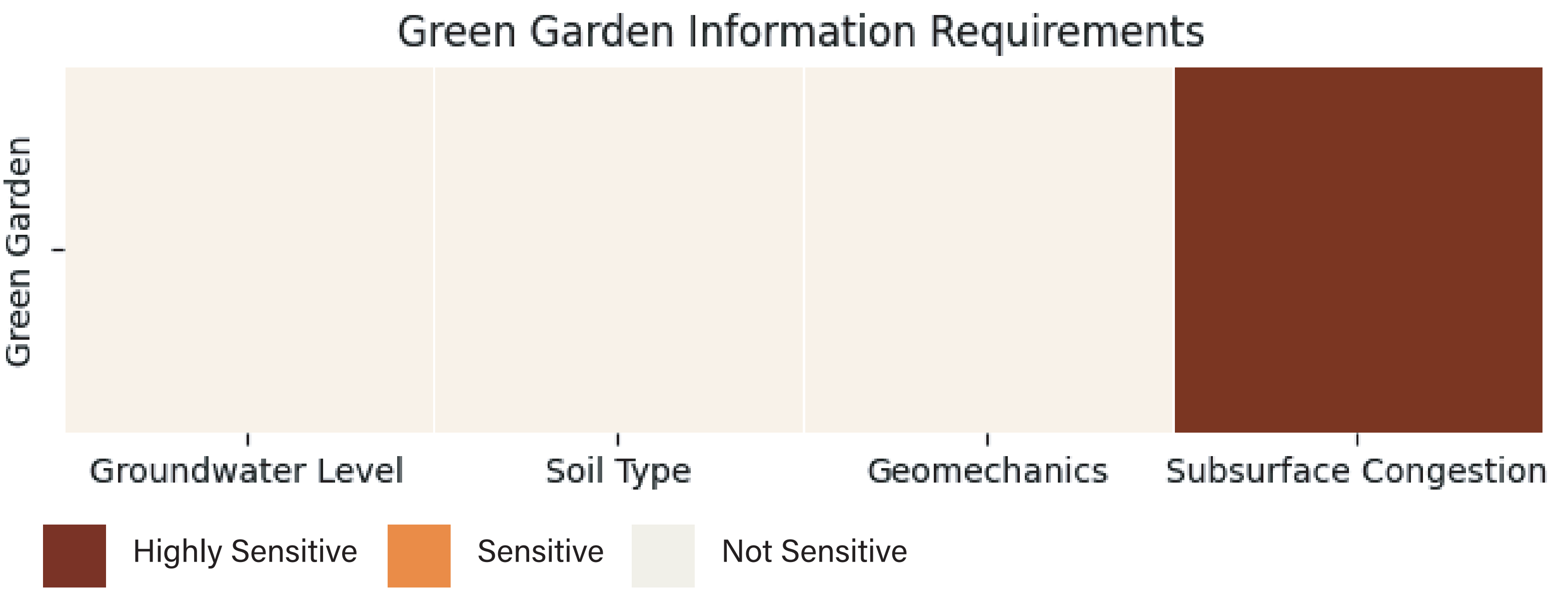
Green Garden

Adaptation: Biodiversity, Heat, Waterlogging, Drought





Source (left to right): CLAP Landscapes, Vitra Campus by Piet Oudolf

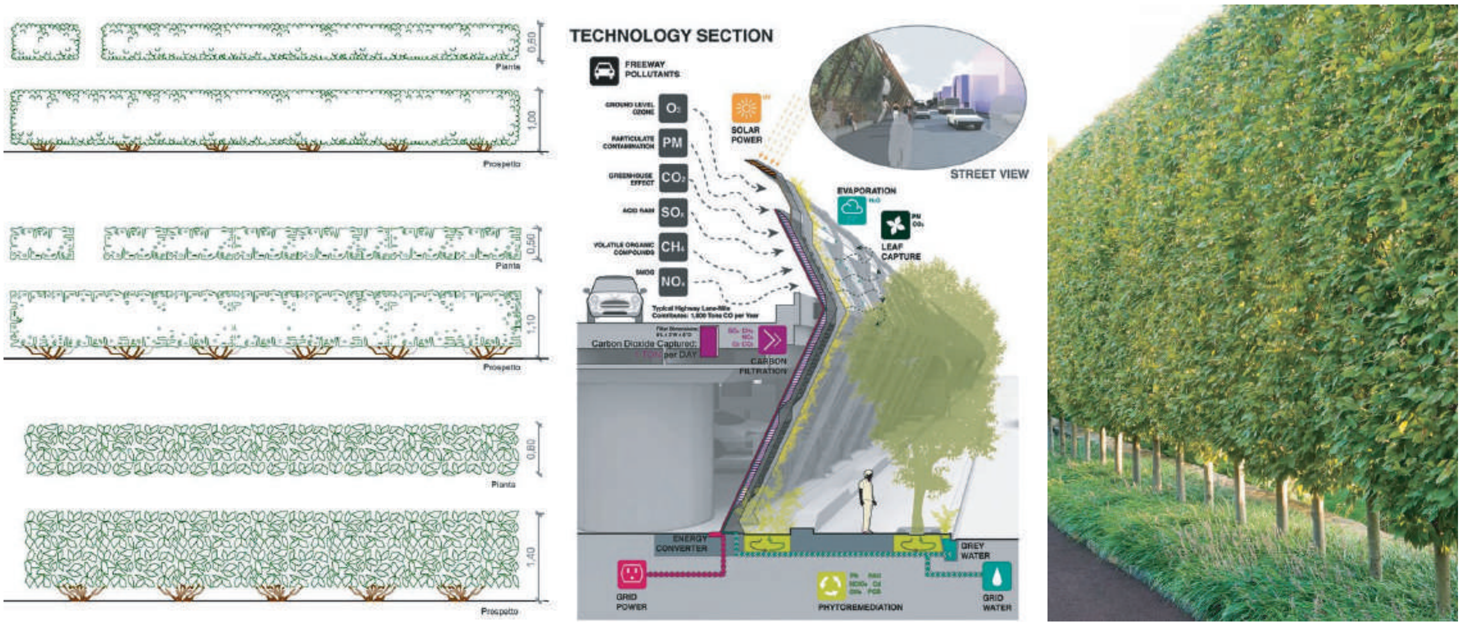


Subsurface Congestion: Ground-planted vegetation demands more root space and a stable substrate (Bouwadaptief). Therefore, when diretly planting on the soil instead of pots, this intervention is highly senstive to accuracy of subsurface congestion information.

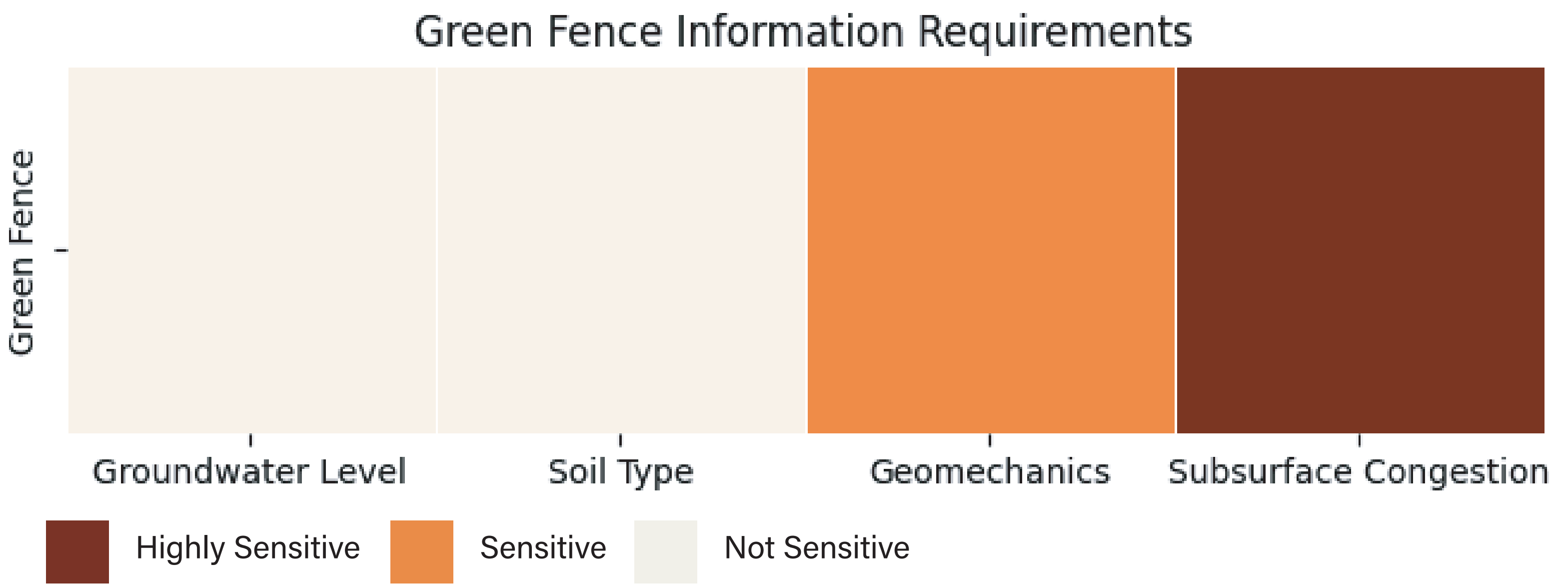
Resolution Requirement: Plant roots are 3D objects and might benefit from a 3D model of the subsurface congestion. The geomecahnics (suitability to build) can be available in 2D. Resolution is defined based on the size of the intervention and the root. In architectural drawings, this intervention is usually represented in different scales, mainly in 1:100 to 1:50. Subsurface congestion requires to be represented at a similar level of detail. In case trees are planted, the size of the roots must be considered. This vary based on tree specie but as a rule of thumb the space needed is 0.5 to 2 meters vertically and a radius of 1/2 x tree height around the tree horizontally.

Green Fence

Adaptation: Biodiversity, Heat



Source: Archweb, Oziio, GardenDesign



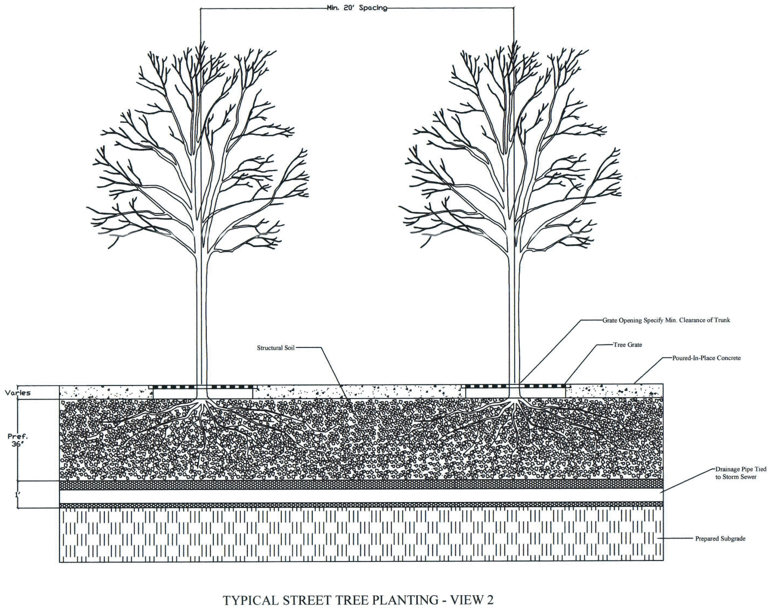
Subsurface Congestion: This intervention can be directly in contact with the subsurface or not. When directly planting on the soil instead of attaching greenery to an above surface structure, this intervention is highly senstive to accuracy of subsurface congestion information.

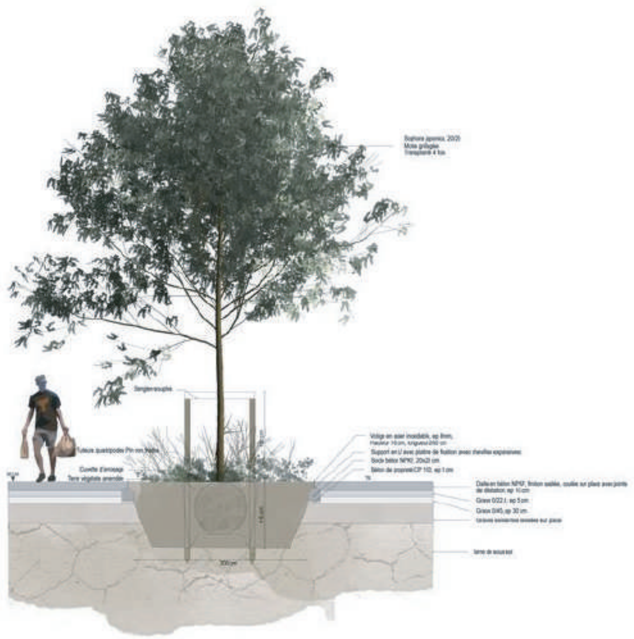
Geomechanics: A solid ground is necessary for this solution (Bouwadaptief), which means it is impacted by Geomechanics information but not as directly dependent as with subsurface congestion. This is particularly important if the solcution includes heavy new structures.

Resolution Requirement: Plant roots are 3D objects and might benefit from a 3D model of the subsurface congestion. The geomecahnics (suitability to build) can be available in 2D. Resolution is defined based on the size of the intervention and the root. In architectural drawings, this intervention is usually represented in different scales, mainly in 1:100 to 1:50. Subsurface congestion requires to be represented at a similar level of detail and take into account tree root size.

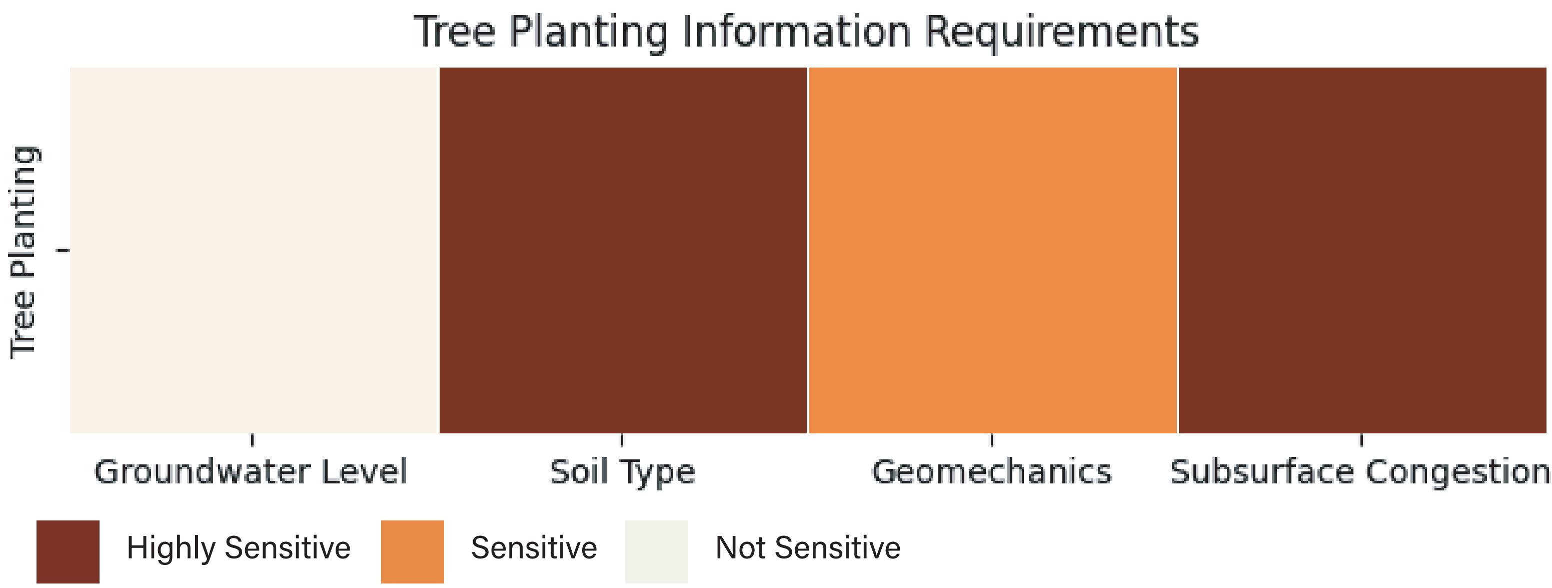
Tree Planting

Adaptation: Biodiversity, Heat





Source (left to right): Cornell University, Atelier PAP



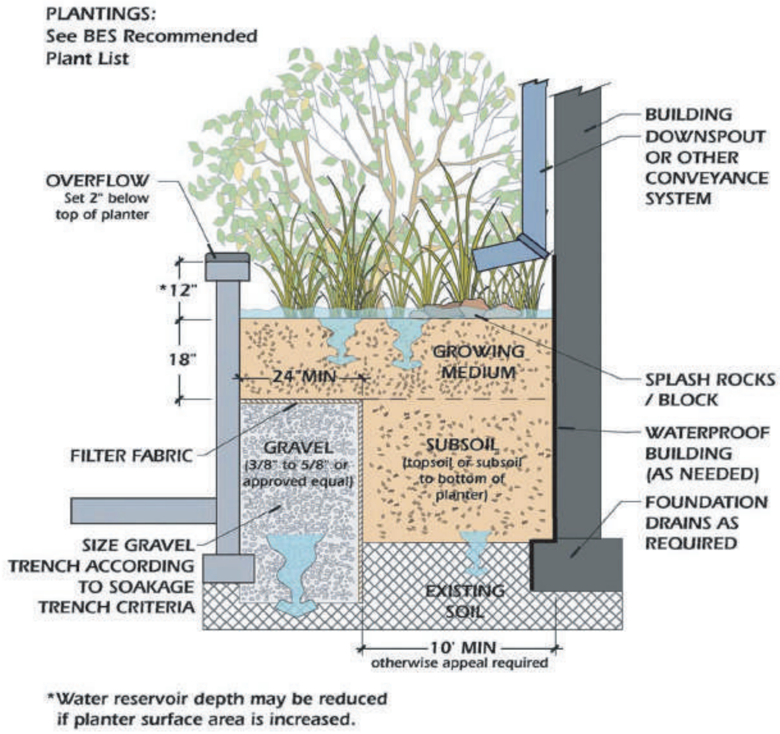
Subsurface Congestion: Tree roots require more subsurface space than other plant species. Thus this intervetion requires accurate subsurface congestion information . Particularly attention should be given to tree planting near roads (Bouwadaptief).

Soil Type: It is necessary to select trees that match the soil profile, for example wet vs. dry (Bouwadaptief). Accuracy on the soil type is required on the shallow portion of the subsurface where tree roots grow (first 0.5 meters but up to 2 meters for some tree species).

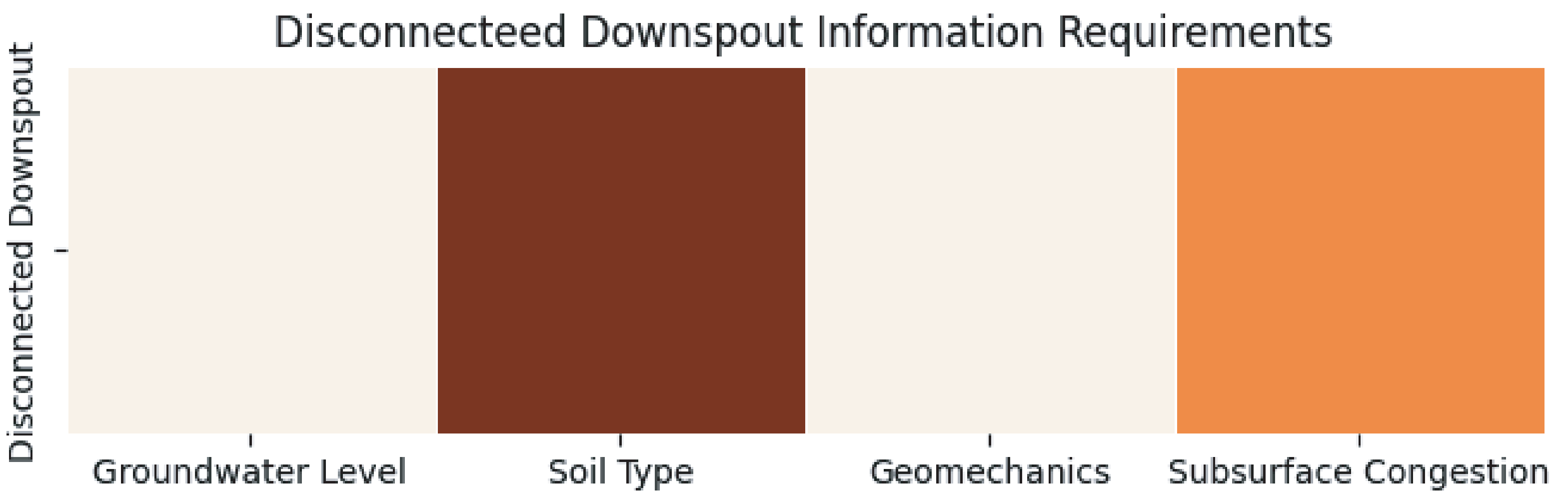
Geomechanics: A solid ground is necessary for this solution (Bouwadaptief), which means it is impacted by Geomechanics information but not as directly dependent as with subsurface congestion.

Resolution Requirement: Plant roots are 3D objects and might benefit from a 3D model of the subsurface congestion and soil type. As a rule of thumb, tree roots usually reach the first 0.5 to 2 meter depth and spread widely in a radius that is half of its height. However, 90% of the roots are on the upper 60 cm of the subsurface. Information ideally will have this level of accuracy.

Disconnected Downspout **Adaptation: Waterloggin, Drought**



Source (left to right): Deborah Silver, Wendy Allen Design



Highly Sensitive Sensitive Not Sensitive

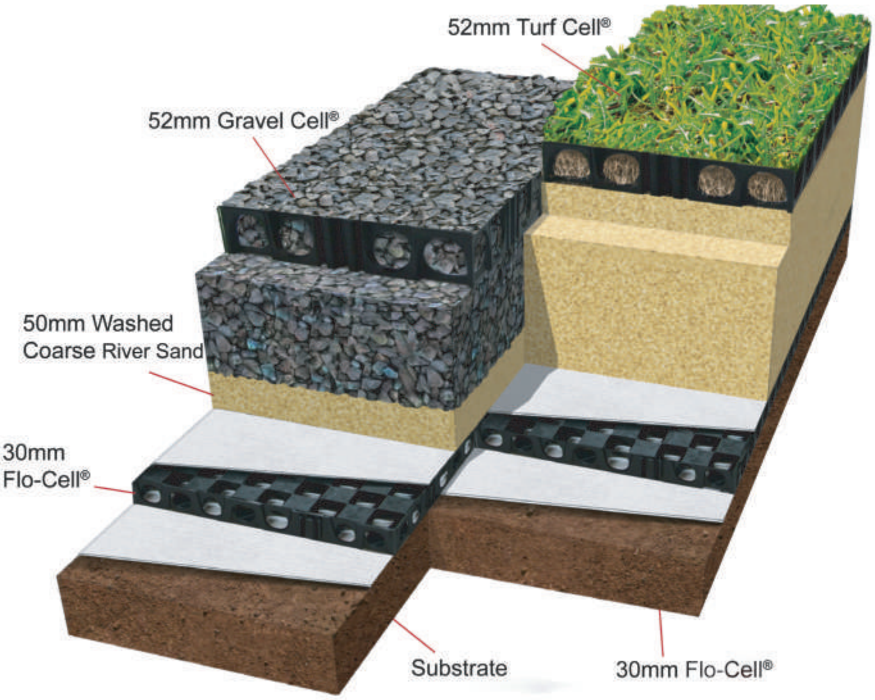
Soil Type: When disconnecting the downspout it is necessary to know with acuracy the infiltration capacity of the soil. The presence of the wrong soil type (less infiltrating) could lead to issues.

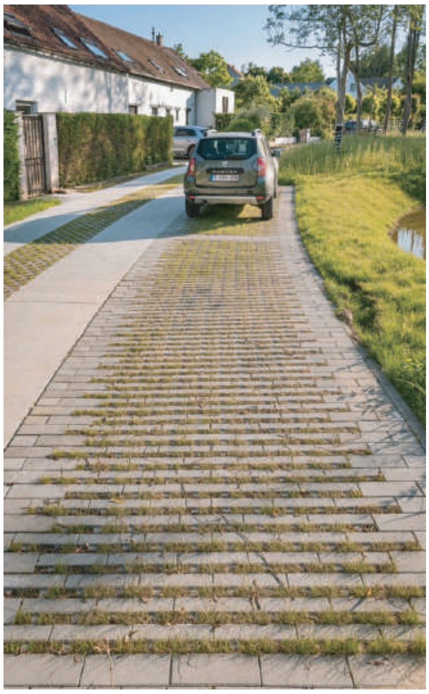
Subsurface Congestion: When disconnecting the downspout, it is necessary to consider the space available underneath to some degree (no presence of major obstacles).

Resolution Requirement: Subsurface congestion should ideally be on scale. Soil types need accurcy and the first half meter (shallow subsurface) is particularly important in terms of accuracy and resolution.

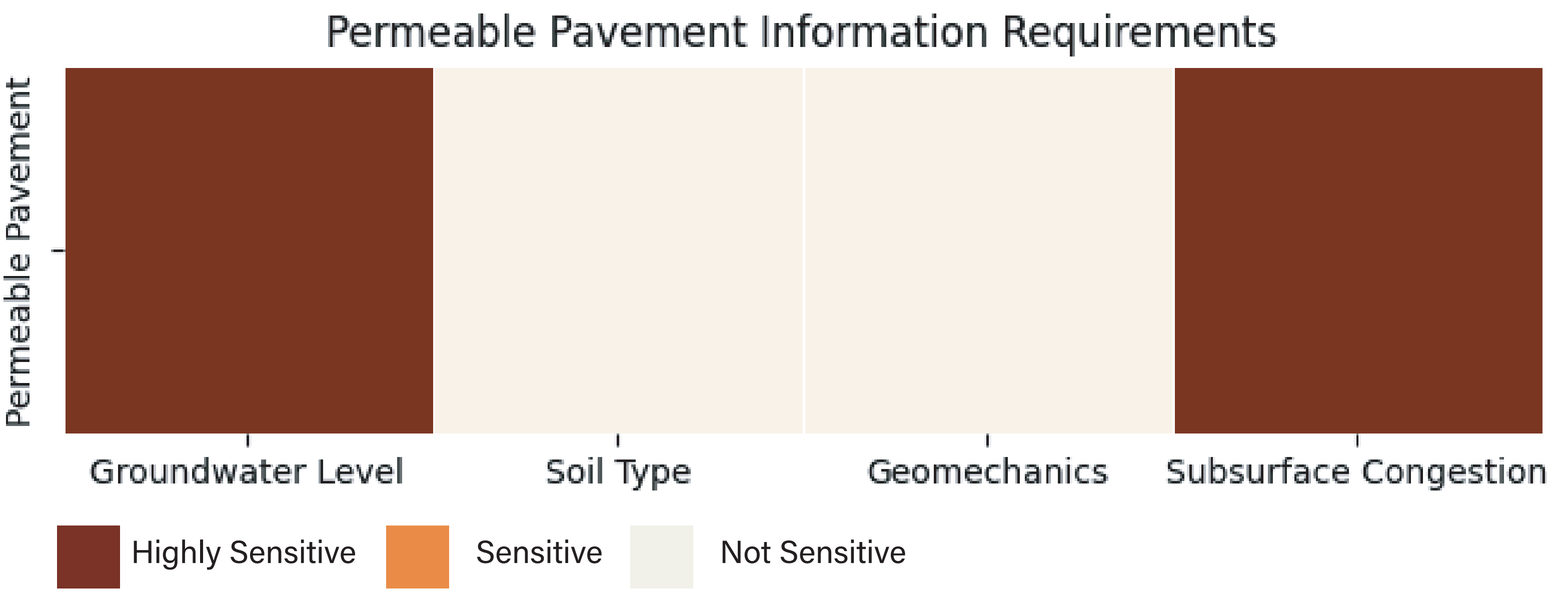
Permeable Pavement

Adaptation: Waterlogging, Drought





Source (left to right): Eco Outdoor Asia,



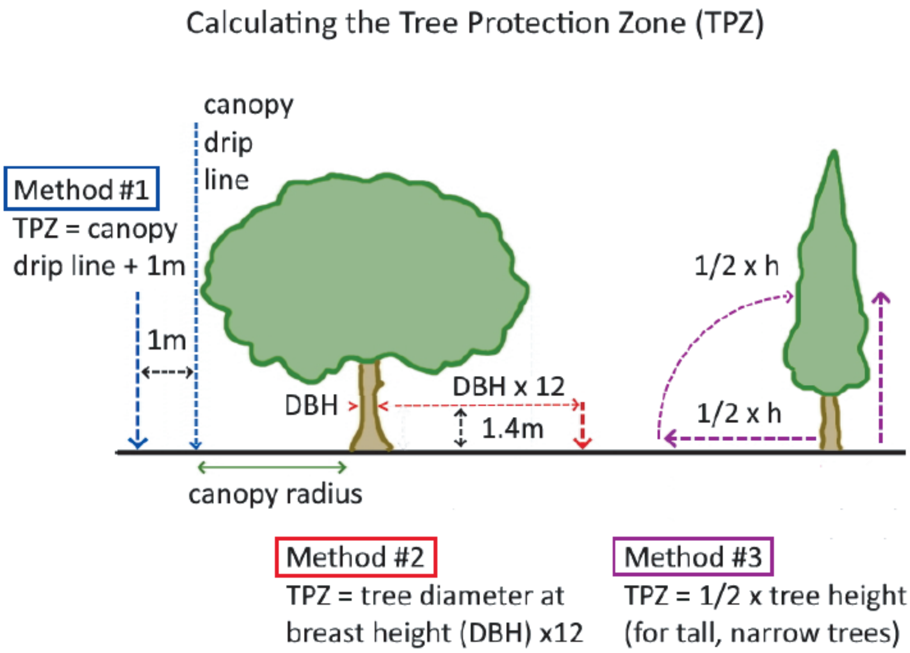
Subsurface Congestion: Solutions that include greenery that has its roots directly on the subsurface require enogh space for roots. (Bouwadaptief). Moreover, additional permeable layers might be added to the subsurface. Thus this intervention is sensitive to the accuracy of subsurface congestion information.

Groundwater Level: The infiltrated water may ort may not be directly in contact with the groundwater. For this reason, it is necessary to have accurate position of the highest average groundwater level.

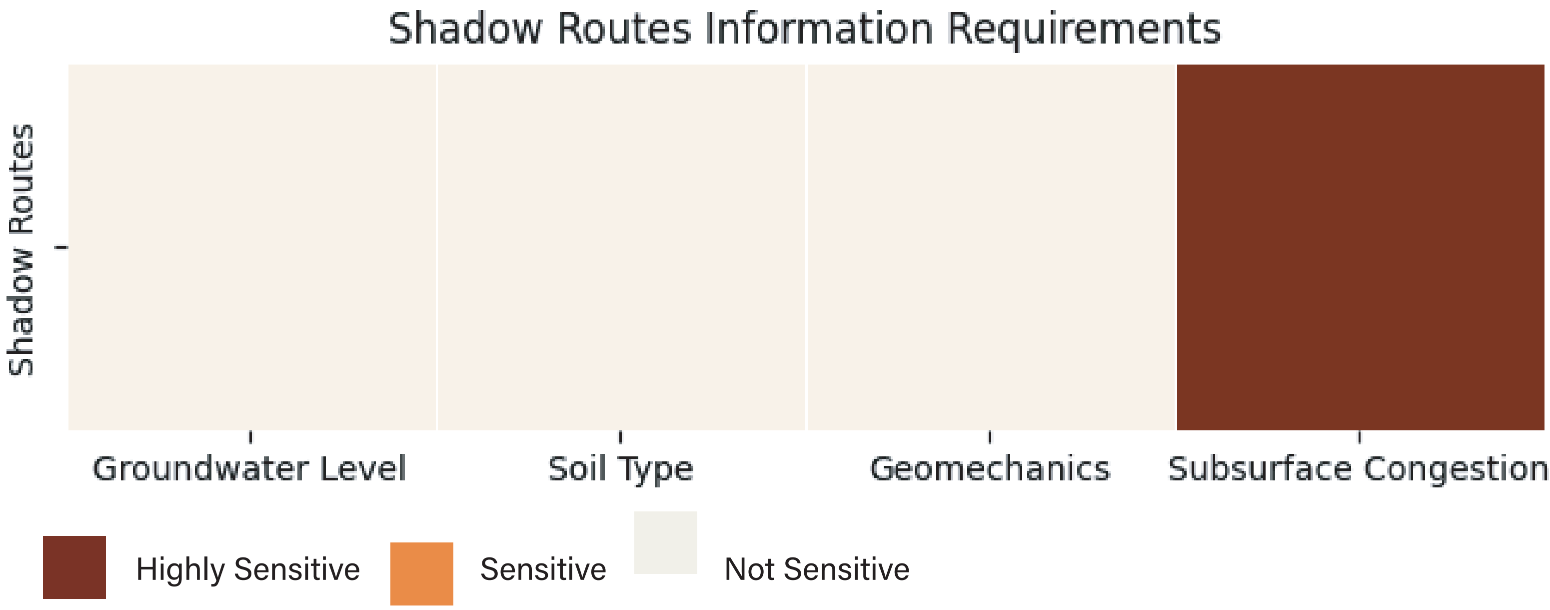
Resolution Requirement: High accuracy is needed for this intervantion regarding the first two meters of subsurface (see technical drawing). Subsurface congestion must be represented on scale, ideally in 3D, and with a resolution of at least half a meter vertically (each permeable layer size). Horizontally, the resolution varies based on the size. The scale of representation varies from 1:100 to 1:10 (architectural and technical drawing). This can be used as reference for resolution requirements.

Shadow Routes

Adaptation: Biodiversity, Heat



Source (left to right): Urban Green-Blue Grids, Deep Green Permaculture

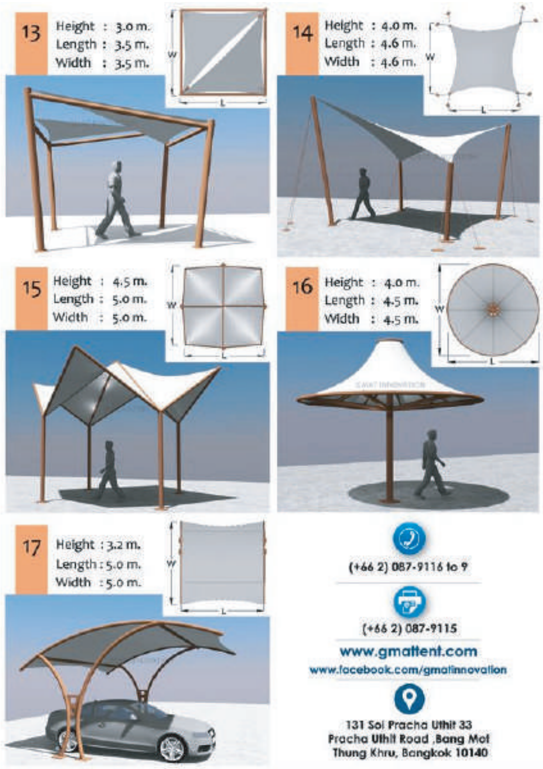


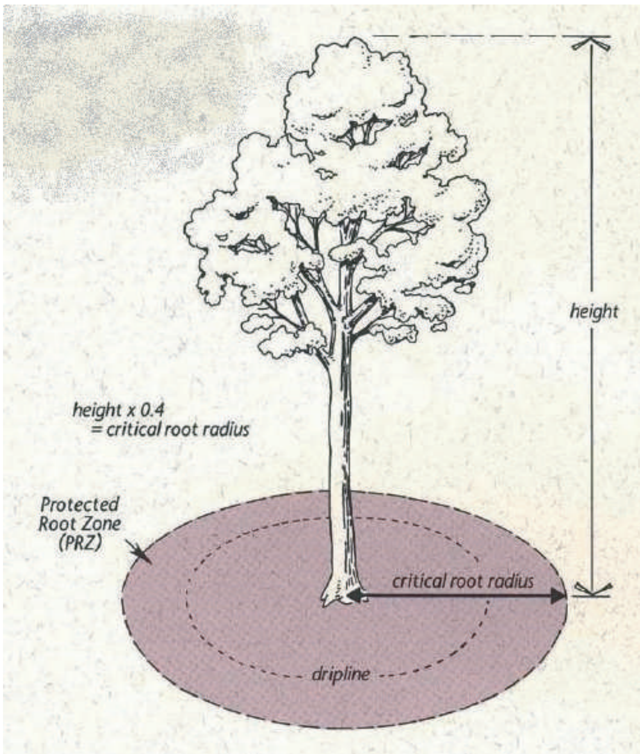
Subsurface Congestion: Solutions that include greenery that has its roots directly on the subsurface require enogh space for roots. (Bouwadaptief). Shadow routes often require the planting of big trees that lead to big shadowing surfaces. Thus this intervention is highly sensitive to the accuracy of subsurface congestion information.

Resolution Requirement: Shadowing routes are often designed in urban planning/design scale. In the case of natural shadowing from a tree, resolution depends on the size of the tree specie and the maximum depth and dimension of the tree roots should be used as reference. As a rule of tumb, tree roots can spread in a radius that is half of the tree's height and reach a depth that is on average around 0.5 to 2 meters. This is the area necessary for the data provider to cover precisely.

Cool Places

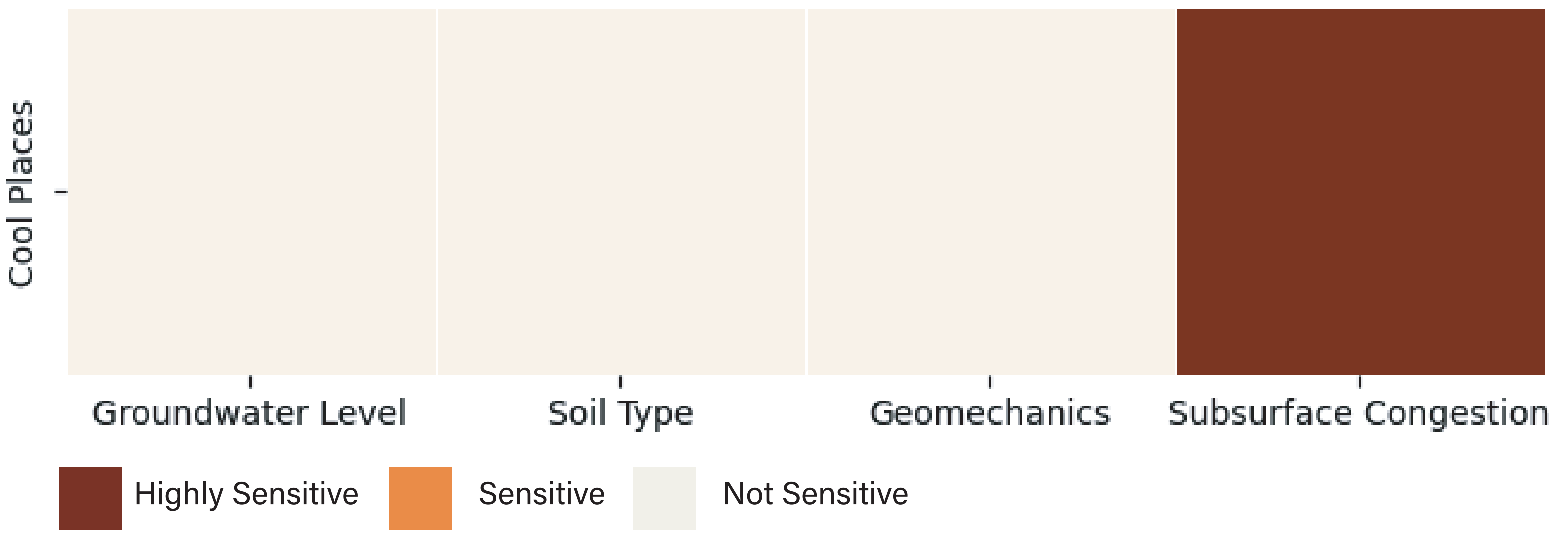
Adaptation: Biodiversity, Heat





Source (left to right): Gmattent, North Carolina Forest Council

Cool Places Information Requirements

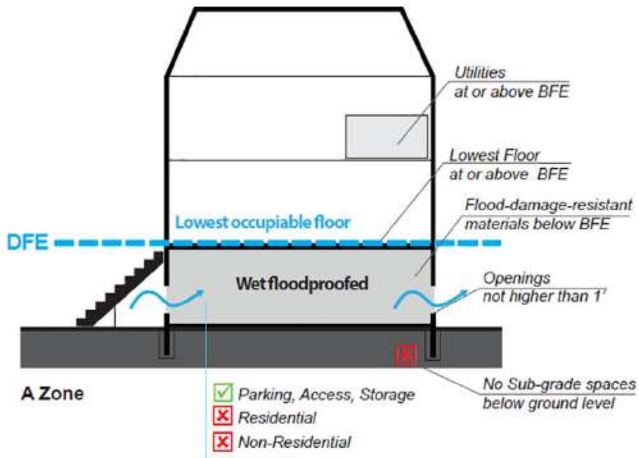


Subsurface Congestion: Solutions that include greenery that has its roots directly on the subsurface require enogh space for roots. (Bouwadaptief). Cool places often require planting big trees with big surfaces to cool a space. Thus this intervention is highly sensitive to the accuracy of subsurface congestion information.

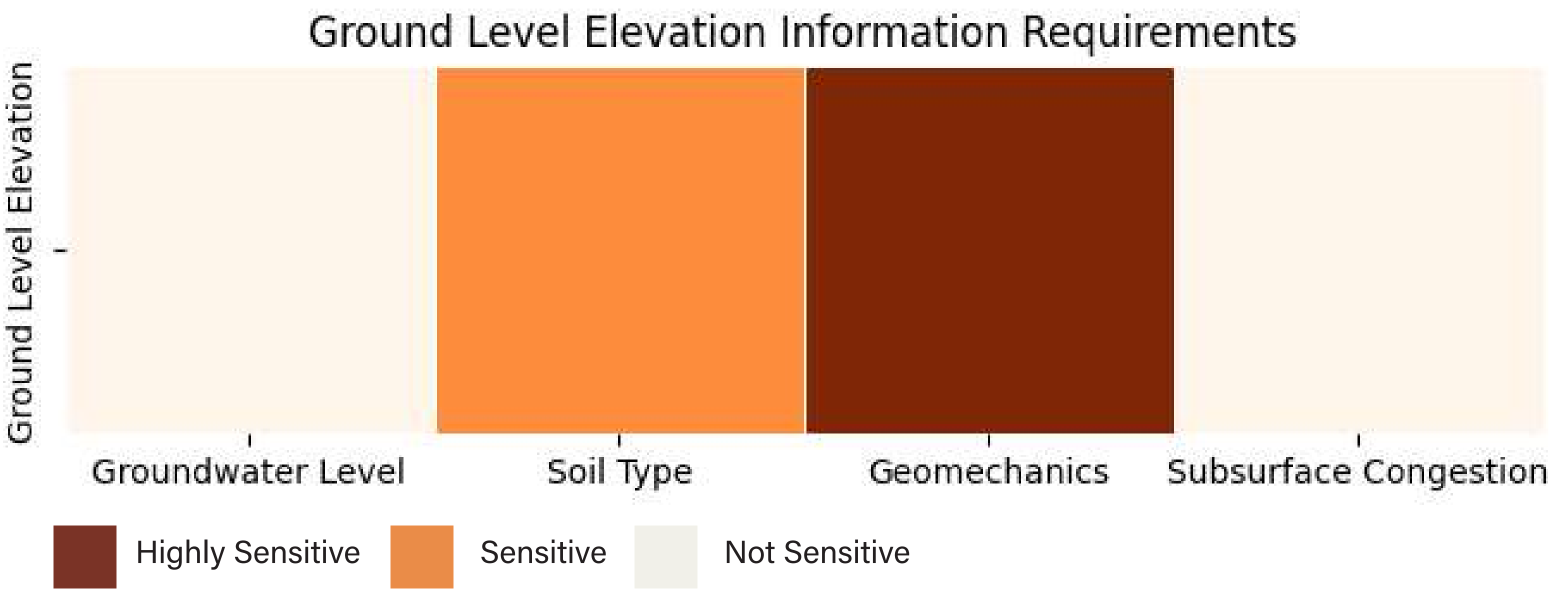
Resolution Requirement: Cool places are often designed in architectural scale (often represented on scale ranging from 1:200 to 1:50). Shadowing structure catalogs represent this intervention as a sigle object. In the case of natural shadowing from a tree, resolution depends on the size of the tree specie and the maximum depth and dimension of the tree roots should be used as reference. As a rule of thumb, most trees require data resoltuion and accuracy for the first 0.5 to 2 meters vertically and horizontally on a radius measuring half of the tree's height. This is the area necessary for the voxel to cover precisely.

Ground Level Elevation

Adaptation: Flood



Source (left to right): Bouwadaptief, NYC Department of Urban Planning



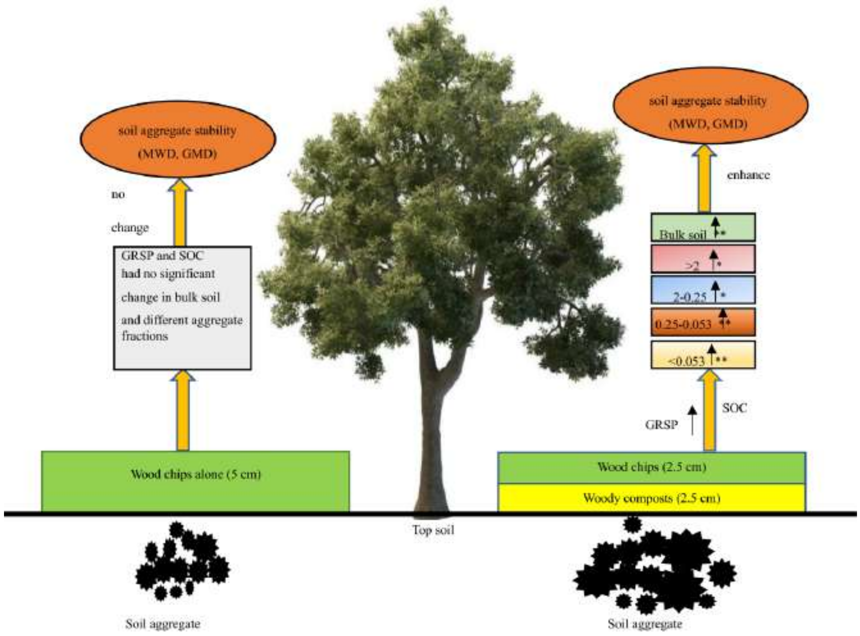
Geomechanics: When raising the ground level it is necessary to evaluate if the subsurface have the geomecahniocs conditions to allow this new weight. Therefore knowledge and accuracy of geomechanics information is essential.

Soil Type: The knowledge of soil type is benefitial for this intervention because some soil types are more prone to subsidence and cannot handle much extra weight.

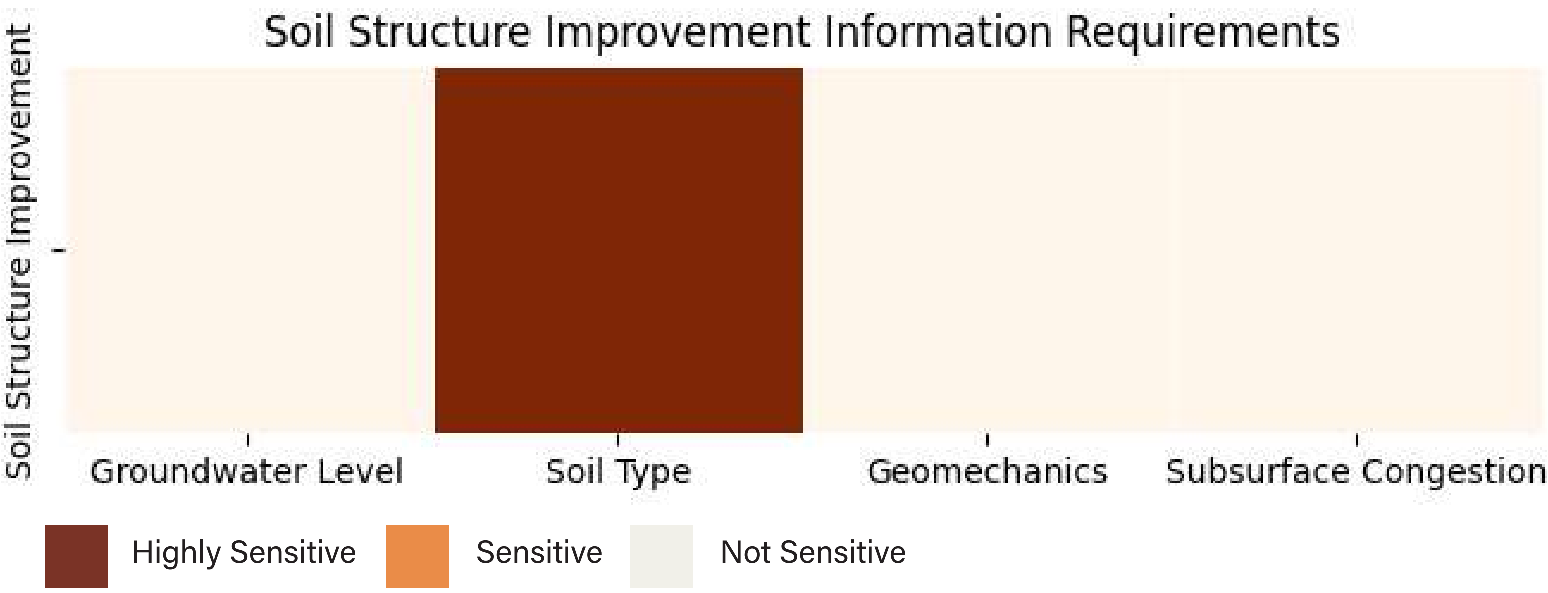
Resolution Requirement: This intervention can be done in many ways, ranging from the elevation of a singular building to a whole neighborhood. Resolution requirement will thus vary greatly. However, anything acceptable for architectural level of detail (scale 1:200 to 1:50) should be enough.

Soil Improvement

Adaptation: Biodiversity, Waterlogging, Drought



Source: Nicholas Alexander, Zhou, W. et al.



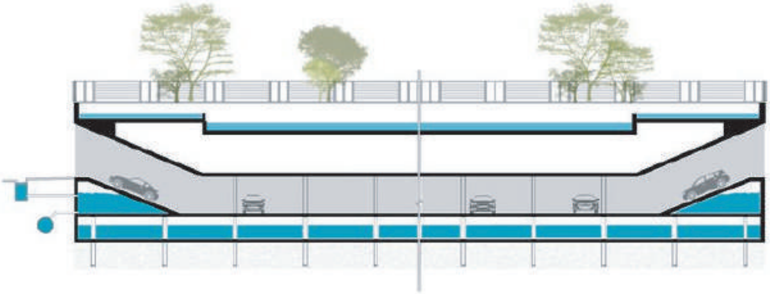
Soil Type: The qualitative aspects of the soil are considered carefully before selecting the improvement method. Therefore knowledge and accuracy of the soil type is needed.

Geomechanics: A solid ground is necessary for this solution (Bouwadaptief), which means it is impacted by Geomechanics information but not as directly dependent as with subsurface congestion.

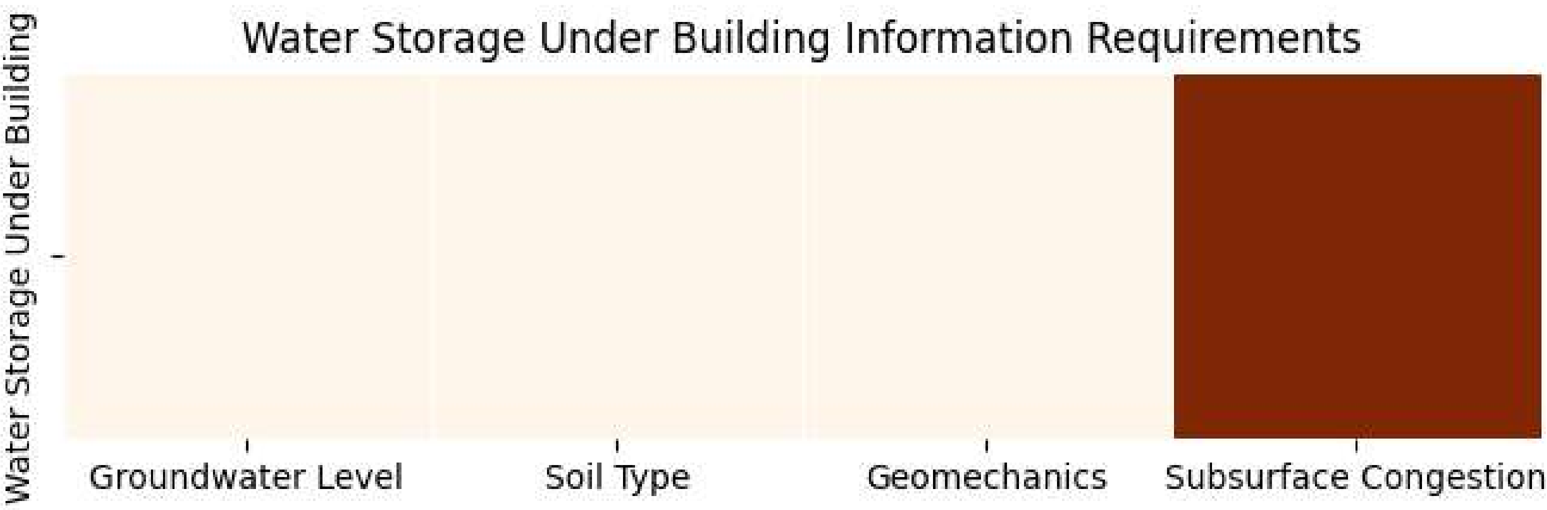
Resolution Requirement: Soil improvement can be done for a single tree or an entire neighborhood. However, as a rule of thumb in gardening this consist of a top layer and the soil close to a tree is used as reference. A tree root is usually 1/2 the tree height on a radius width and has 0.5-2 meter depth. This value can be used as a reference for resolution requirement.

Water Storage Building

Adaptation: Waterlogging



Source (left to right): POP UP by Third Nature, Stefan Al



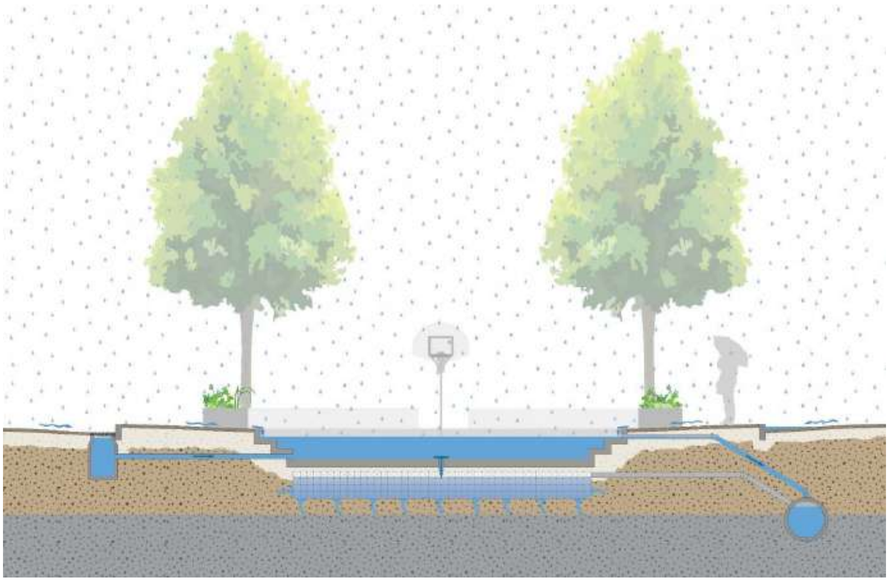
Highly Sensitive Sensitive Not Sensitive

Subsurface Congestion: Water is stored under residual underground spaces, such as the space under entrance or exit in parking spaces. Therefore data accuracy is needed regarding underground free space.

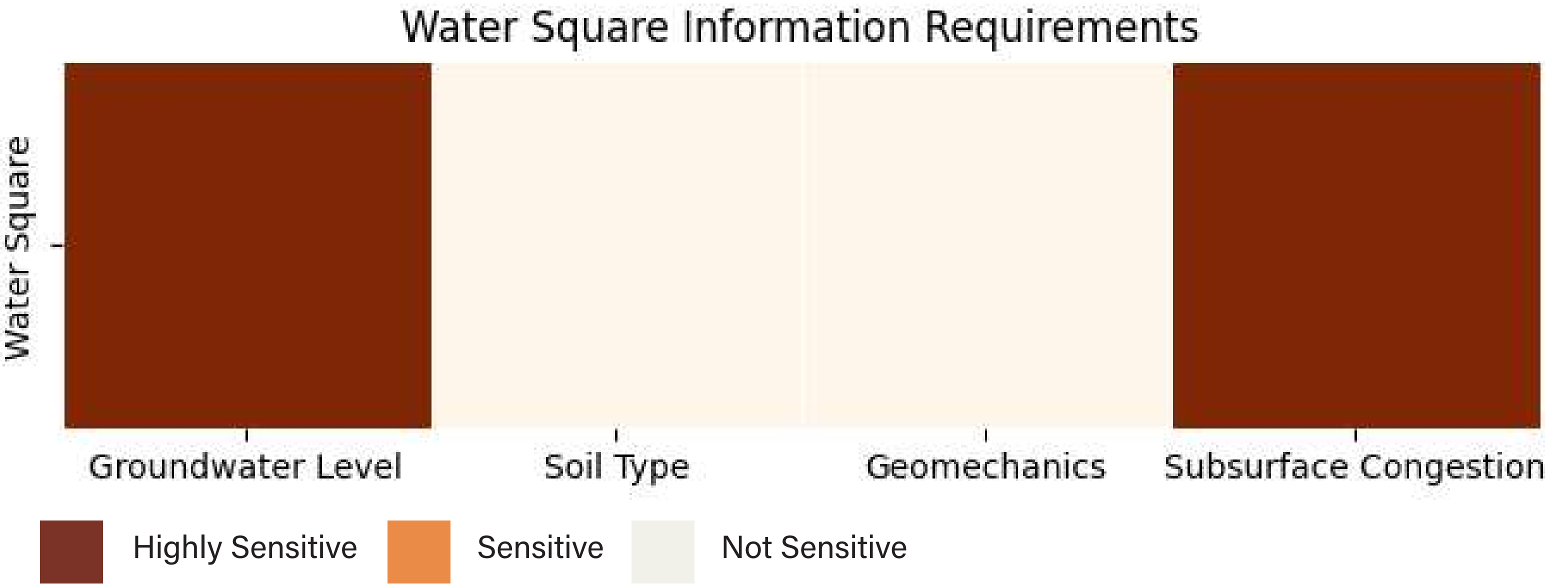
Resolution Requirement: In the case of water storage under parking lots, a common example, the measures of a car can be use for information resolution. This is on average 4.9 m x 1.9 m x 1.8 m.

Water Square

Adaptation: Waterloggin, Flood



Source (left to right): Benthemplein Square (Rotterdam) by De Urbanisten, Groenblauwe Netwerken



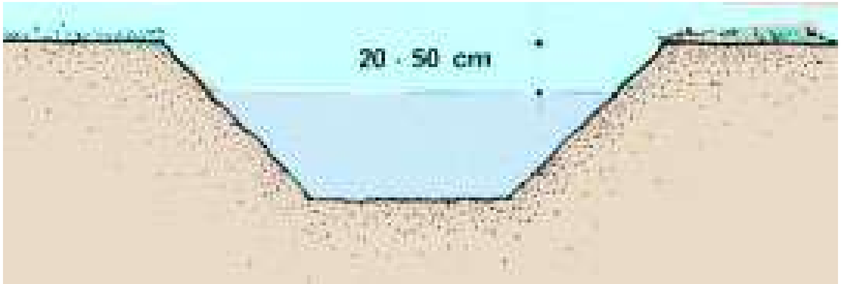
Subsurface Congestion: Water squares are build on the subsurface and therefore require space underground where they are placed. Knowledge and accuracy of congestion is thus needed.

Groundwater Level: Water squares will sometimes be in contact or bellow groundwater levels. In this case, it is important to make the water square watertight. Thus, knowlege of the groundwater levels, and in specific of the average highest level, is necessary.

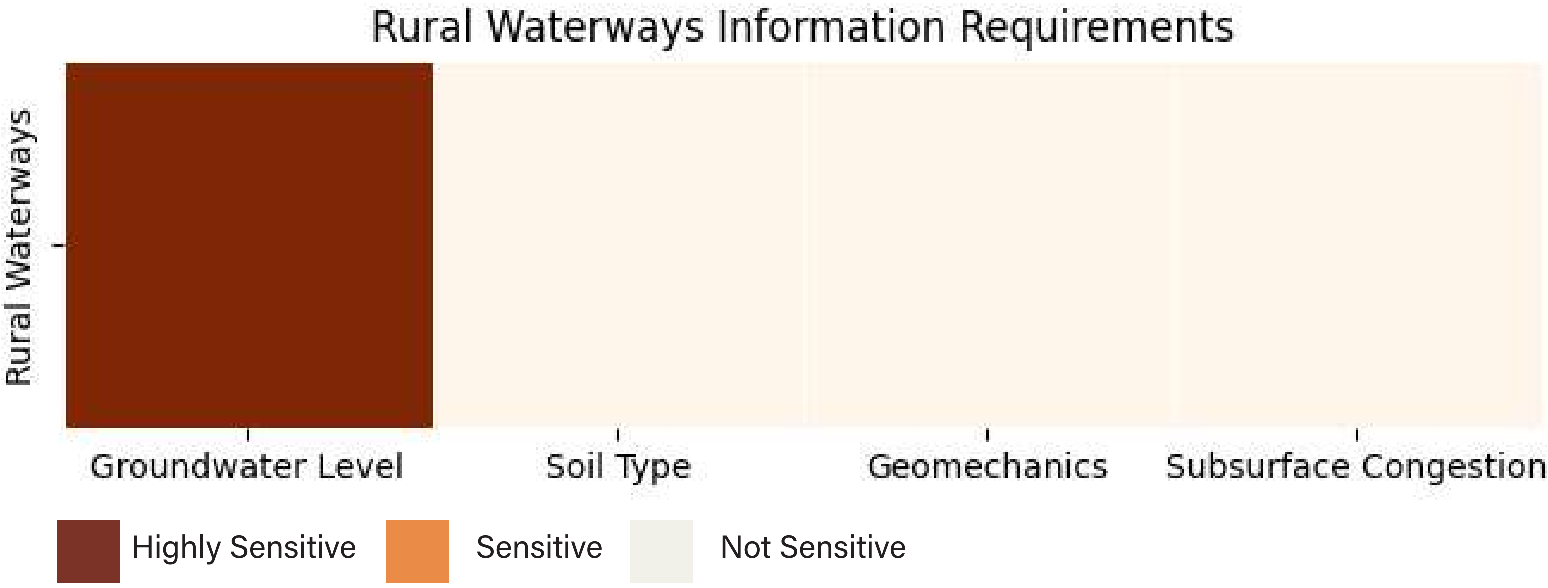
Resolution Requirement: On average, water squares are represented in architectural scale (1:200 to 1:50). The size and shape of water square can vary but a cubic resolution of a meter each way should suffice the resolution needs based on the depth and width of the average water square.

Rural Waterways

Adaptation: Waterlogging, Flood



Source (left to right): Ringdijkpark by Delva, Food and Agriculture Organization of the United Nations

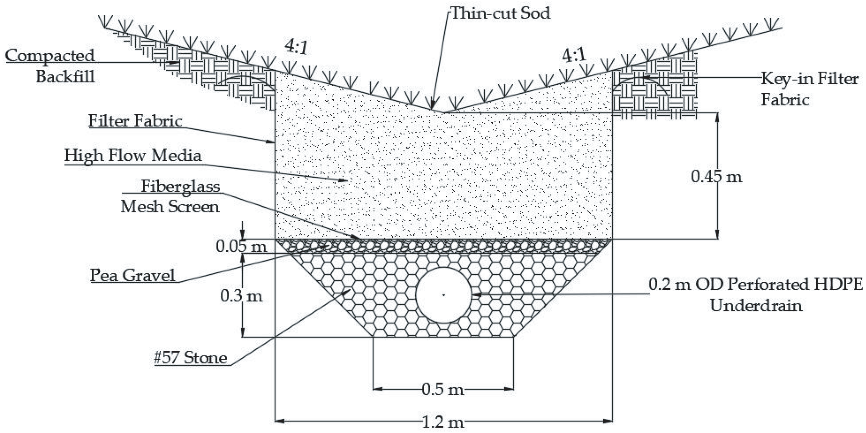


Groundwater Level: Water stored in rural waterways can be released into water surfaces or gradually infiltrate groundwater. For this reason, it is necessary to know with accuracy the groundwater level.

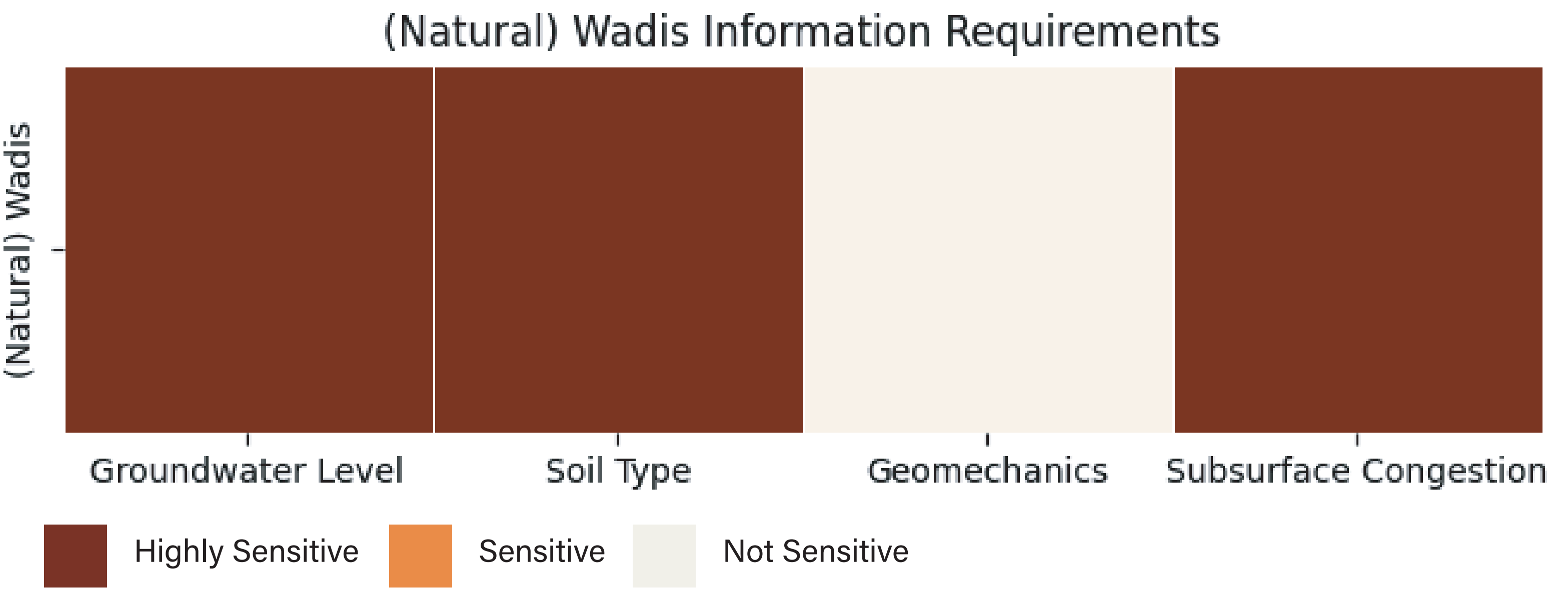
Resolution Requirement: Waterways usally have a depth and width of around 1-2 meter, thus a resolution of 0.5-1 meter in depth and width should suffice resolution requirements.

(Natural) Wadis

Adaptation: Biodiversity, Waterlogging, Drought



Source (left to right): NACTO, KOED



Soil Type: Wadis usually take advantage of infiltrating soil, such as sand. For this reason, accuracy is needed regarding the soil type. A wrong and less infiltrating soil type will have negative consequences.

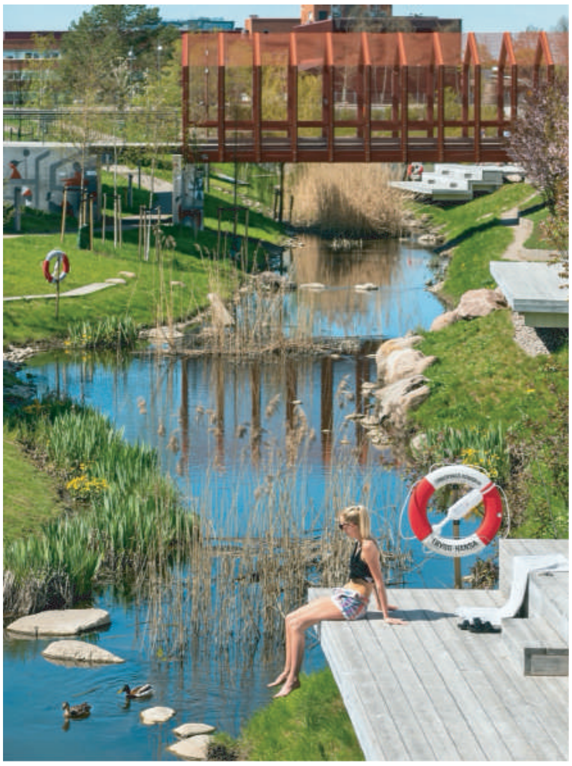
Groundwater Level: A wadi may replenish groundwater by inifiltration. For this reason, accuracy is necessary regarding the groundwater level.

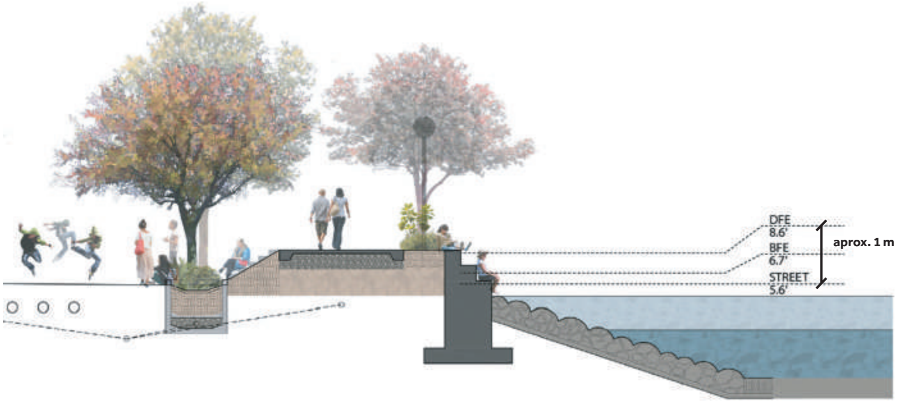
Subsurface Congestion: A wadi requires space underground, often for a continuous long route. Space underground is thus required.

Resolution Requirement: Wadis have on average a depth of one meter and can be divided roughly into two parts of half a meter. Resolution should have 50 cm vertically. Horizontally this solution also is on average one meter wide and would benefit from this level of detail.

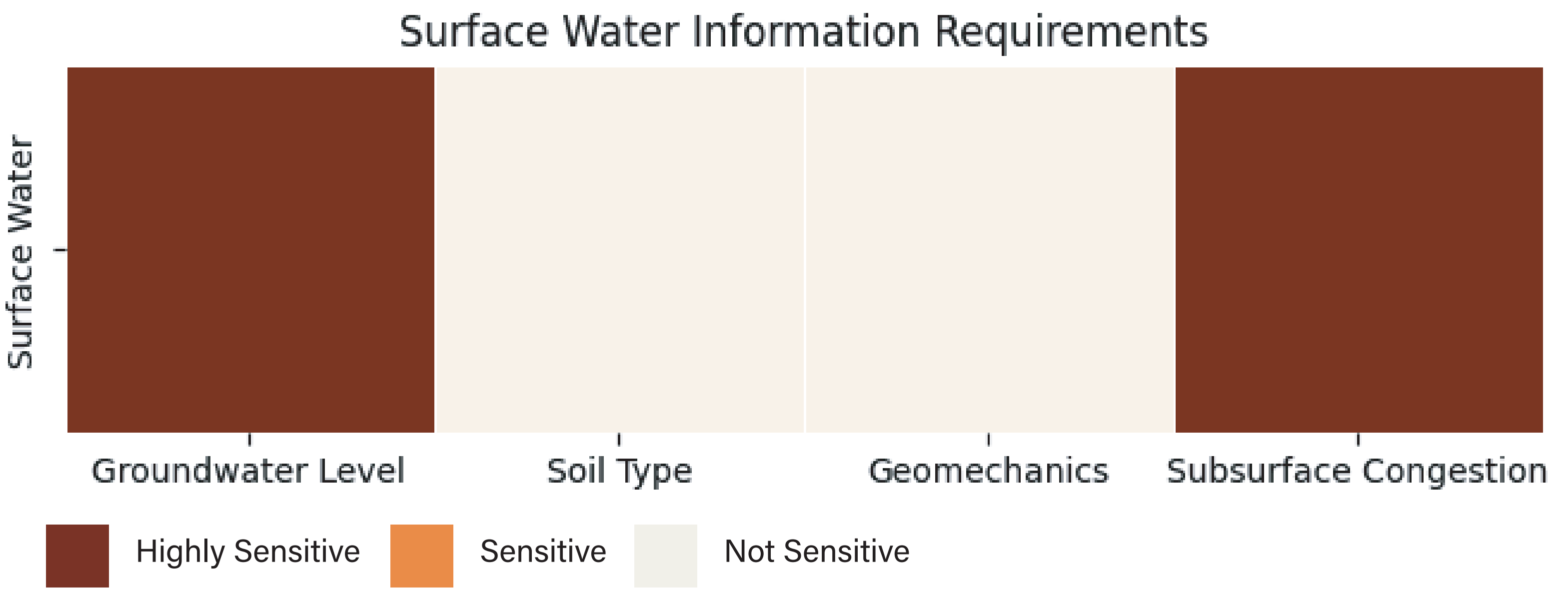
Surface Water

Adaptation: Biodiversity, Waterlogging





Source (left to right): Broparken by White Arkitekter, Kapalama Canal (Honolulu)



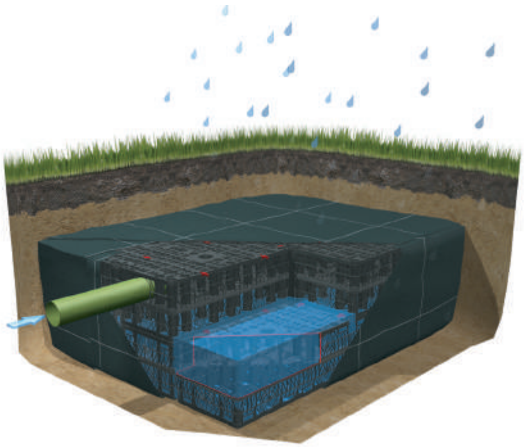
Subsurface Congestion: The creation of surface water can be done by enlarging existing water bodies or through the creation of new ponds and canals. For the creation of new surface water elements, a significant amount of subsurface space is require and thus it is highly sensitive to data accuracy.

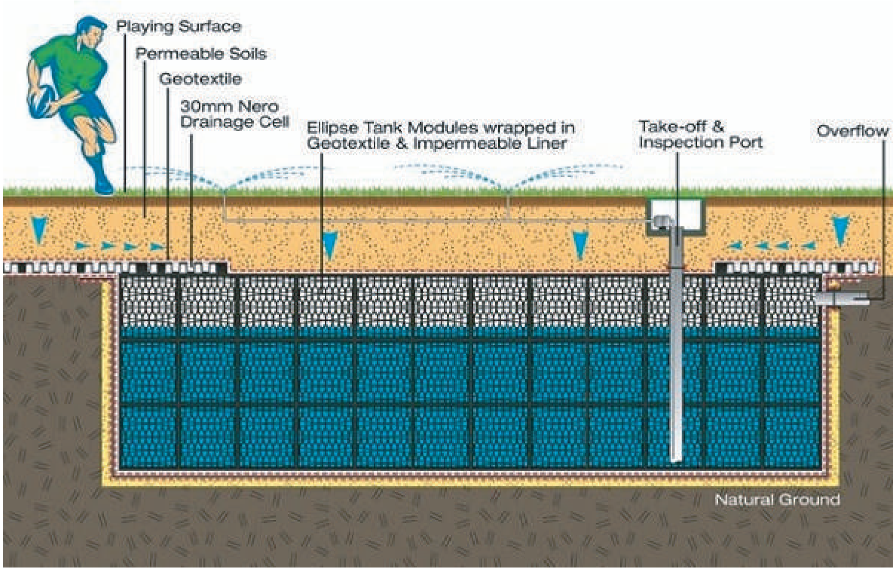
Grounwater Level: Surface water may or may not be in contact with groundwater level. For this reason it is necessary that this data is available and accurate. This is particularly important when creating new elements. By reaching a certain necessary depth one can unwiglingly reach groundwater level if information is incorrect or unknown.

Resolution Requirement: Resolution requirement varies largerly on the width and depth of the surface water element. However, as a generalization based on the standard measures of a canal, one can assume that a level of accuracy should be around a meter in both depth and width.

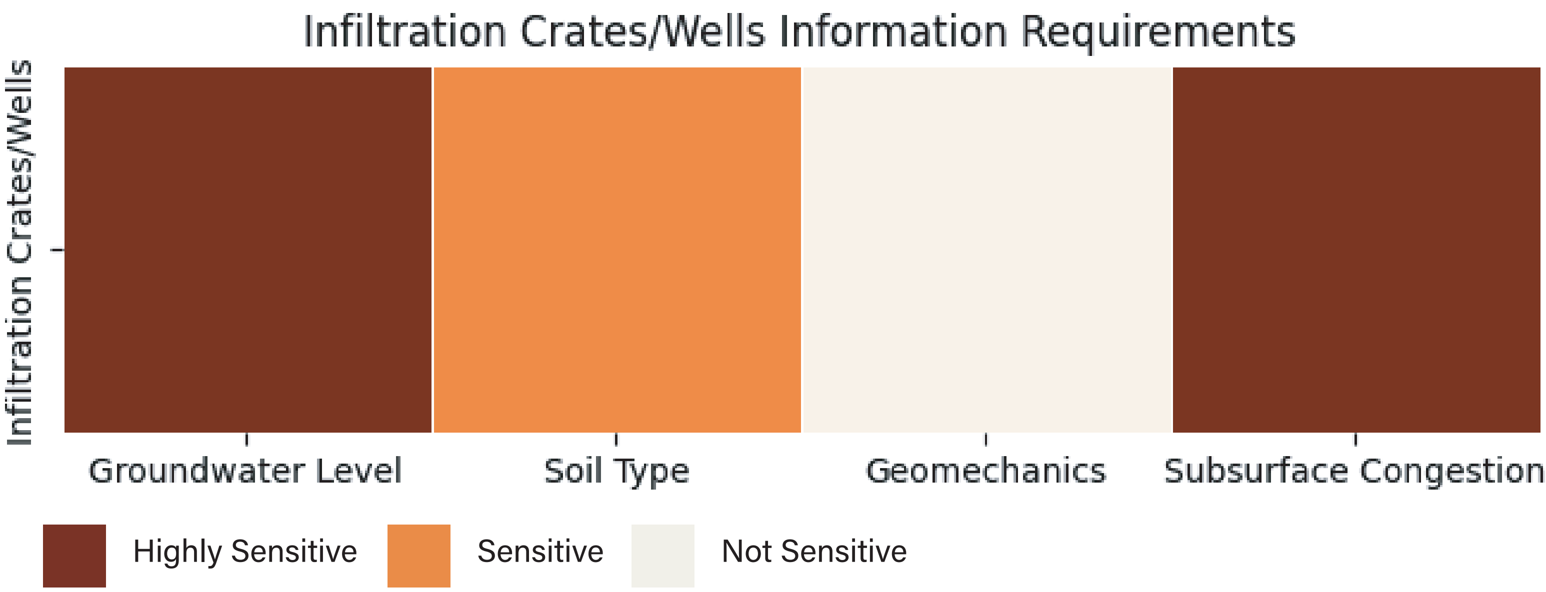
Infiltration Crates/Wells

Adaptation: Waterlogging, Drought





Source (left to right): BPO, Rainsmart Solutions



Grounwater Level: Infiltration units are only effective if placed at least 20 cm above the highest average groundwater level. This intervention is thus highly sensitive to the availability and accuracy of this data.

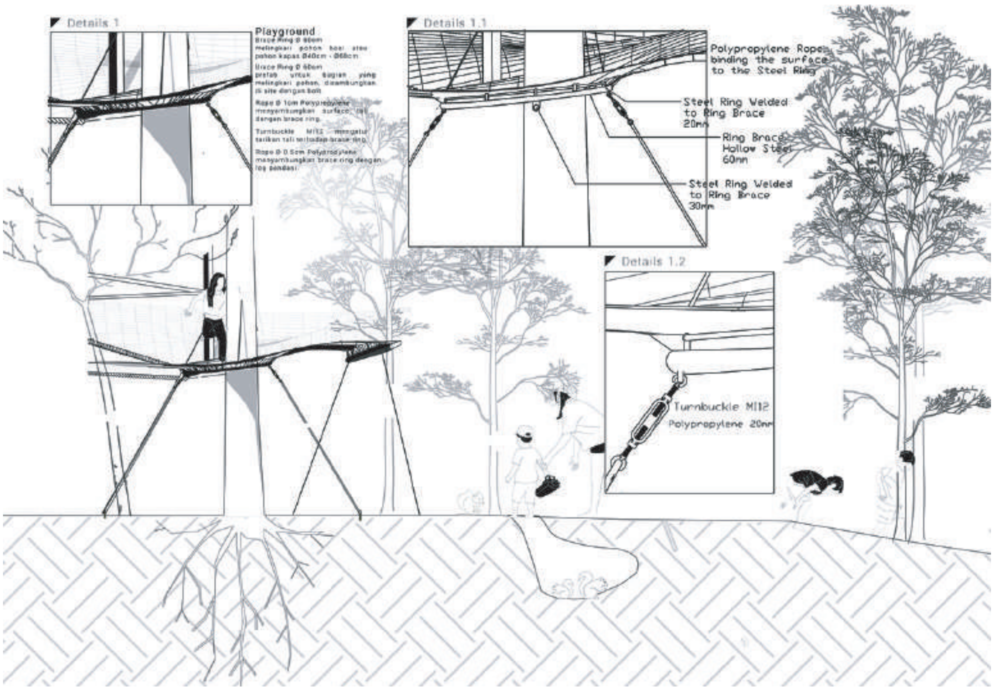
Soil Type: The infiltration capacity of a soil type increases 3.5 times. It benefits from an infiltrating soil, but if data is unknown or innacurate, the intervention will still be functional.

Subsurface Congestion: Even though infiltration units come in different shapes and sizes, they will always require a fixed amount of free space in the subsurface. This make it highly vunerable to knowledge and accuracy of this information.

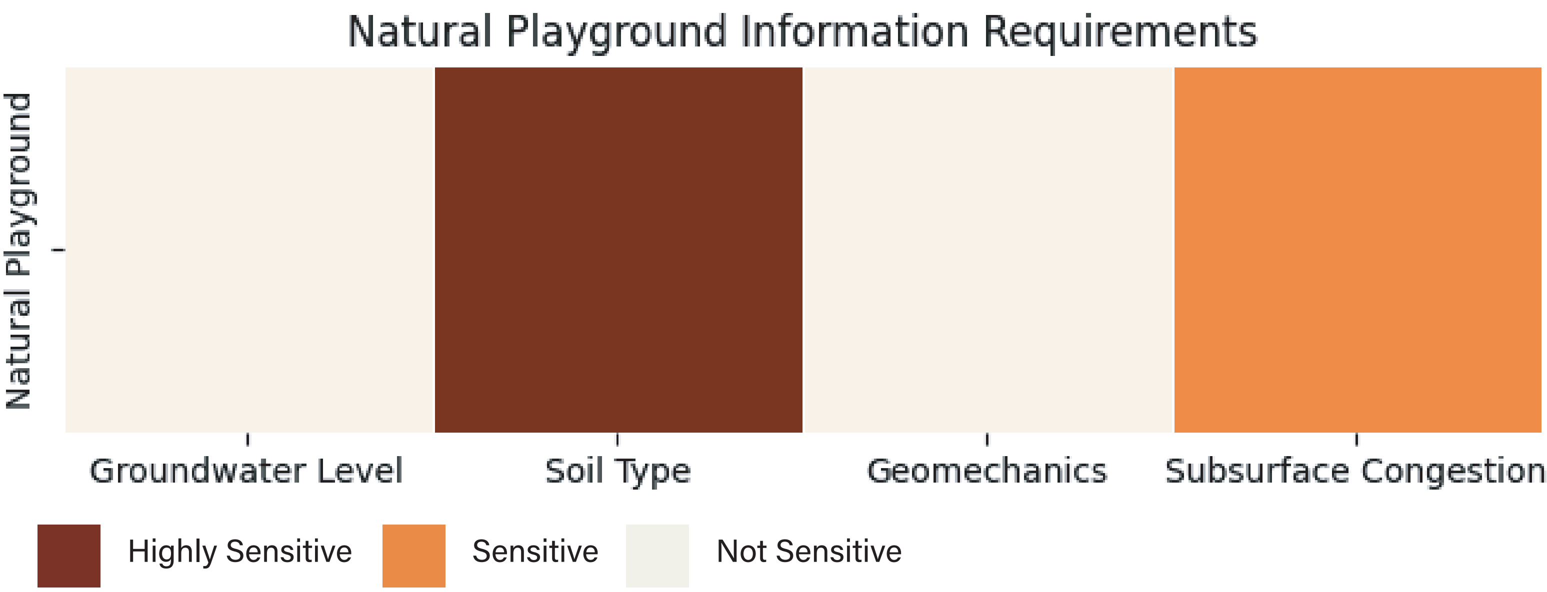
Resolution Requirement: This intervention consist of multiple elements that varies in size and shape. Usually those are in cubic shape of dimenions around 0.3 m on each side, and therefore an accuracy of 0.5 m both on depth and width can be suggested.

Natural Playground

Adaptation: Biodiversity, Waterlogging, Drought



Source (left to right): Centenery Lakes Nature Play, Permeable Playground by Eldwin Timothi Partogi



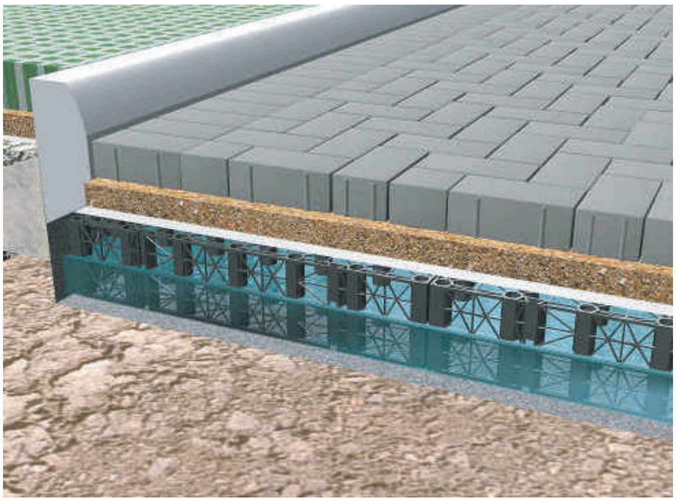
Subsurface Congestion: Solutions that include greenery that has its roots directly on the subsurface require enogh space for roots. (Bouwadaptief). Natural playground often include trees. Thus this intervention is highly sensitive to the accuracy of subsurface congestion information.

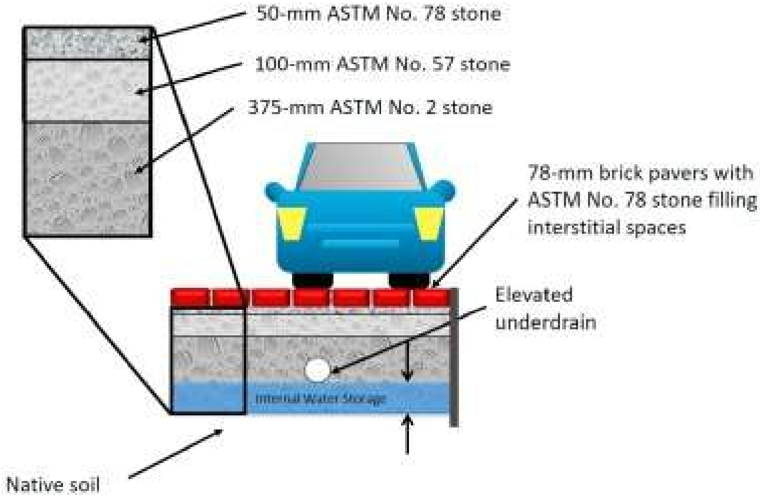
Soil Type: Natural Playground often aid water infiltration. For this purpose, it takes into consideration the infiltration capacity of a soil type. Thus accuracy is needed and innacuracy could cause issues.

Resolution Requirement: Natural playgrounds are often represented as an architectural drawing, ranging from 1:200 to 1:50 as a scale. The horizontal resolution needed will vary on the presence of trees and use of open soil for water infiltration. For the first one, the space needed for a tree roots can be roughly calculated as 1/2 the height of the tree. For both the cases, the first 0.5 meter of the subsurface is trhe most relevant and this value can be used as the depth for resolution requirements.

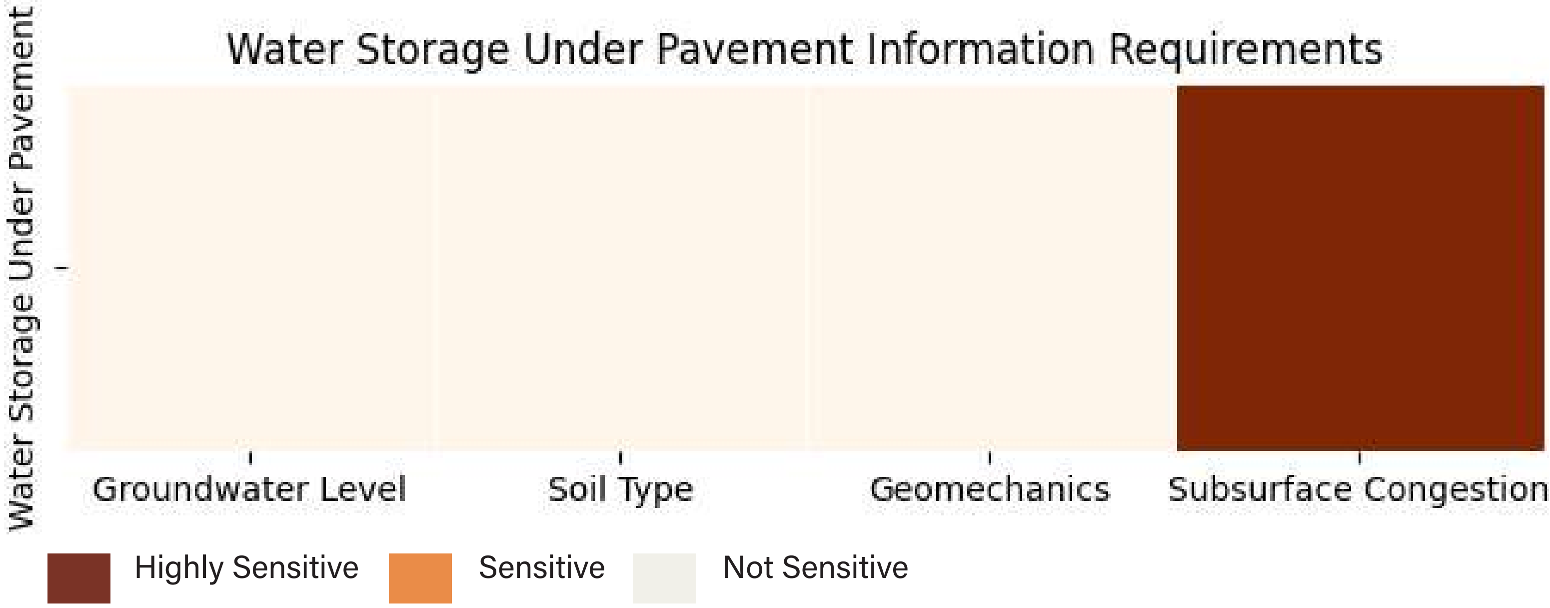
Water Storage Pavement

Adaptation: Waterlogging





Source: Paving Expert, Braswell A. et al.



Subsurface Congestion: This solution requires space underground and therefore requires information on suibsurface congestion.

Resolution Requirement: The infiltration and storage unit often consist of cubic elements (see picture on the left) that have roughly dimenions of 50 cm. Therefore a cubic resolution of half a meter on each way should suffice resolution needs for this intervention.

15

Annex B: Resolution Requirement Code

```python

import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
import random

# Define the values for the rows
# Values correspond to dependency on data availability and accuracy: 100 (high), 50 (average), 0 (low)
values_greenfacade = [0, 0, 50, 100]
values_facadegarden = [0, 0, 0, 100]
values_greengarden = [0, 0, 0, 100]
values_greenfence = [0, 0, 50, 100]
values_soilstructure = [0, 100, 0, 0]
values_elevation = [0, 50, 100, 0]
values_ruralwaterways = [100, 0, 0, 0]
values_treeplanting = [0, 100, 50, 100]
values_downspout = [0, 100, 0, 50]
values_permeablepavement = [100, 0, 0, 100]
values_storagepavement = [0, 0, 0, 100]
values_shadowroutes = [0, 0, 0, 100]
values_coolplaces = [0, 0, 0, 100]
values_naturalplayground = [0, 100, 0, 50]
values_wadis = [100, 100, 0, 100]
values_surfacewater = [100, 0, 0, 100]
values_infiltrationcrates = [100, 50, 0, 100]
values_storagebuilding = [0, 0, 0, 100]
values_watersquare = [100, 0, 0, 100]

# Create a list of tuples containing index names and corresponding data
index_data_pairs = [
    ('Green Façade', values_greenfacade),
    ('Façade Garden', values_facadegarden),
    ('Green Garden', values_greengarden),
    ('Green Fence', values_greenfence),
    ('Tree Planting', values_treeplanting),
    ('Disconnected Downspout', values_downspout),
    ('Permeable Pavement', values_permeablepavement),
```

```
    ('Shadow Routes', values_shadowroutes),
    ('Cool Places', values_coolplaces),
    ('Natural Playground', values_naturalplayground),
    ('(Natural) Wadis', values_wadis),
    ('Surface Water', values_surfacewater),
    ('Infiltration Crates/Wells', values_infiltrationcrates),
    ('Water Storage Under Building', values_storagebuilding),
    ('Water Square', values_watersquare),
    ('Soil Structure Improvement', values_soilstructure),
    ('Ground Level Elevation', values_elevation),
    ('Rural Waterways', values_ruralwaterways),
    ('Water Storage Under Pavement', values_storagepavement)
]

# Shuffle the list of tuples
random.shuffle(index_data_pairs)

# Unpack the shuffled data
shuffled_index_names, shuffled_data = zip(*index_data_pairs)

# Create a DataFrame with the shuffled rows
df = pd.DataFrame(shuffled_data, columns=['Groundwater Level', 'Soil Type', 'Geomechanics', 'Subsurface Congestion'], index=shuffled_index_names)

# Plot the matrix without annotations
plt.figure(figsize=(5, 12))  # Adjust the figure size as needed
sns.heatmap(df, annot=False, cmap="Oranges", cbar=False, linewidths=0.25)
plt.title('Information Dependency: High (Red), Average (Orange), Low (White)')  # Set the title for the graph
plt.show()
```

16

Annex C: Databases Code

```
CREATE SCHEMA public;

CREATE TABLE public.climatethemes (
themename            VARCHAR(100)   ,
CONSTRAINT unq_climatethemes_themename UNIQUE ( themename )
 );

CREATE TABLE public.designinterventions (
name                 CHAR(30)   NOT NULL,
adaptation           CHAR(60)   ,
designstreet         BOOLEAN   ,
designbuilding       BOOLEAN   ,
designsquare         BOOLEAN   ,
source               CHAR(30)   ,
subsurfprop          CHAR(100)   ,
localstandard        VARCHAR(60)   ,
nationalstandard     VARCHAR(60)   ,
CONSTRAINT pk_tbl PRIMARY KEY ( name )
 );

CREATE TABLE public.leidraad (
namestandard         VARCHAR(100)   ,
CONSTRAINT unq_leidraad_namestandard UNIQUE ( namestandard )
 );

CREATE TABLE public.maatlat (
guidelinename        VARCHAR(100)
 );

CREATE TABLE public.subsurface (
nameprop             VARCHAR(100)   ,
CONSTRAINT unq_subsurface_nameprop UNIQUE ( nameprop )
 );

INSERT INTO public.climatethemes( "THEMENAME" ) VALUES ( 'biodiversity');
INSERT INTO public.climatethemes( "THEMENAME" ) VALUES ( 'drought');
INSERT INTO public.climatethemes( "THEMENAME" ) VALUES ( 'flood');
INSERT INTO public.climatethemes( "THEMENAME" ) VALUES ( 'heat');
INSERT INTO public.climatethemes( "THEMENAME" ) VALUES ( 'waterlogging');

INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'greenFacade', 'biodiversity, heat', 0, 1, 0, 'RVO',
'geomechanics, congestion', 'B1, B2, B3, H3', 'biodiversity, heat');
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'facadeGarden', 'biodiversity, heat, waterlogging', 1, 1, 0,
'RVO', 'congestion', 'B1, B2, B3, H3, N1', '');
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING","DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'greenGarden', 'biodiversity, heat, waterlogging, drought', 0, 1,
```

```
'RVO','congestion', 'B1, B2, B3, H2, H3, N1, D1', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'greenRoof', 'biodiversity, waterlogging',
0, 1, 0, 'RVO', null, 'B1, B2, B3, N1', '');
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'greenFence', 'biodiversity, heat', 1, 1, 1,
'RVO', 'geomechanics, congestion', 'B1, B2, H3', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'treePlanting', 'biodiversity, heat', 1, 0, 1, 'RVO',
'geomechanics, congestion, soil type', 'B1, B2, B3, H1, H2', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'birdBoxes', 'biodiversity', 0, 1, 1, 'RVO',
null, 'B3', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'rainBarrel', 'waterlogging, drought', 0, 1, 0, 'RVO',
'soil type, congestion', 'N1, N2, N3, D1, D2', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'loweredVerge', 'waterlogging, flood', 1, 0, 0, 'RVO',
null, 'N1, V1 ', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'lightColorMaterial', 'heat', 0, 1, 0,
'RVO', null, 'H3, H4', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'blinds                           ', 'Heat
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'permeablePavement                ', 'waterlogging, drought
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'coolPlaces                       ', 'biodiversity, heat
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'shadowRoutes                     ', 'biodiversity, heat
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'naturalPlayground', 'biodiversity, waterlogging, drought',
0, 0, 1, 'RVO', 'congestion, soil type', 'B1, B2, B3, N1, D1', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'wadis', 'biodiversity, waterlogging,
drought',
1, 0, 0, 'RVO', 'soil type, groundwaterlevel', 'B1, B2, B3, N1, N2, N3, D1, D2', null);
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'surfaceWater                     ', 'biodiversity, waterlogging
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'infiltrationCrates               ', 'waterlogging, drought
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'waterStorageBuilding             ', 'waterlogging
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'waterSquare                      ', 'waterlogging, flood
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'ruralWaterways                   ', 'waterlogging,flood
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'waterRoof                        ', 'waterlogging
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'groundLevelElevation             ', 'flood
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'soilImprovement', 'biodiversity, waterlogging, drought',
1, 1, 1, 'RVO', 'soil type', 'B3, N1, N2, N3, D1, D2', '');
INSERT INTO public.designinterventions( "NAME", "ADAPTATION", "DESIGNSTREET", "DESIGNBUILDING", "DESIGNSQUARE", "SOURCE",
"SUBSURFPROP", "LOCALSTANDARD", "NATIONALSTANDARD" ) VALUES ( 'waterStorageSurface              ', 'waterlogging

INSERT INTO public.subsurface( "NAMEPROP" ) VALUES ( 'congestion');
INSERT INTO public.subsurface( "NAMEPROP" ) VALUES ( 'geomechanics');
INSERT INTO public.subsurface( "NAMEPROP" ) VALUES ( 'groundwater');
INSERT INTO public.subsurface( "NAMEPROP" ) VALUES ( 'soil type');
```

17

Annex D: Design Survey

Dutch Climate Adaptation Design A

This survey supports an MSc thesis in Urbanism and Geomatics on standardized climate adaptation design. Please select three out of twenty-five climate adaptations interventions for four areas in Utrecht. The results will be compared with the thesis design to better understand data needs in climate adaptation. Responses can be anonymous. **The survey aims to take less than 15 minutes.**

An Amazon digital card of **20 euros** will be gifted to one of the participants. The winner will be contacted via email.

This survey will remain open until 09/06.

For more information please contact M.L.TarozzoKawasaki@student.tudelft.nl

* Indica uma pergunta obrigatória

1. What is your field of expertise? *

   Marcar apenas uma oval.

   - Architectecture
   - Urbanism
   - Landscape
   - Industrial Ecology
   - Other

2. If other, what?

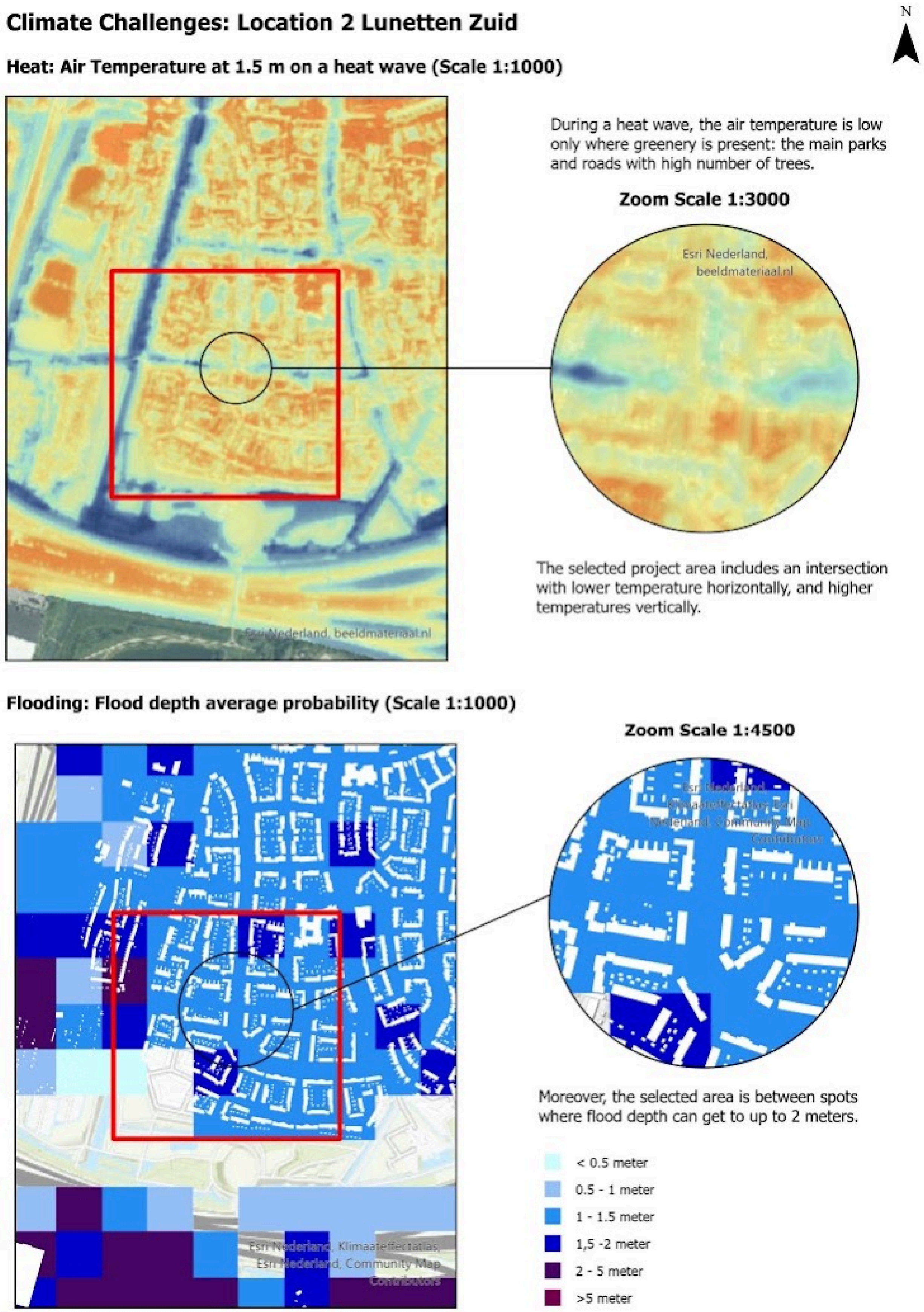
   ____

3. Are you a student? *

   Marcar apenas uma oval.

   - Yes
   - No

4. Considering that this area suffer from heat stress and tendency for flooding, which interventions would your climate adaptation design include? *
Choose 3 interventions.



Marque todas que se aplicam.

- [ ] Green Façade
- [ ] Façade Garden

- [ ] Green Garden
- [ ] Green Roof

- [ ] Green Fence
- [ ] Tree Planting

- [ ] Bird/Bat/Insect Box
- [ ] Rain Barrel

☐ Sunken Street

☐ Light Color/Material

☐ Blinds

☐ Water Permeable Pavement

☐ Cool Places

☐ Shadow Routes

☐ Natural Playground

☐ (Natural) Wadis

☐ Surface Water

☐ Infiltration Crates

☐ Water Storage Under Building

☐ Water Square

☐ Rural Waterways

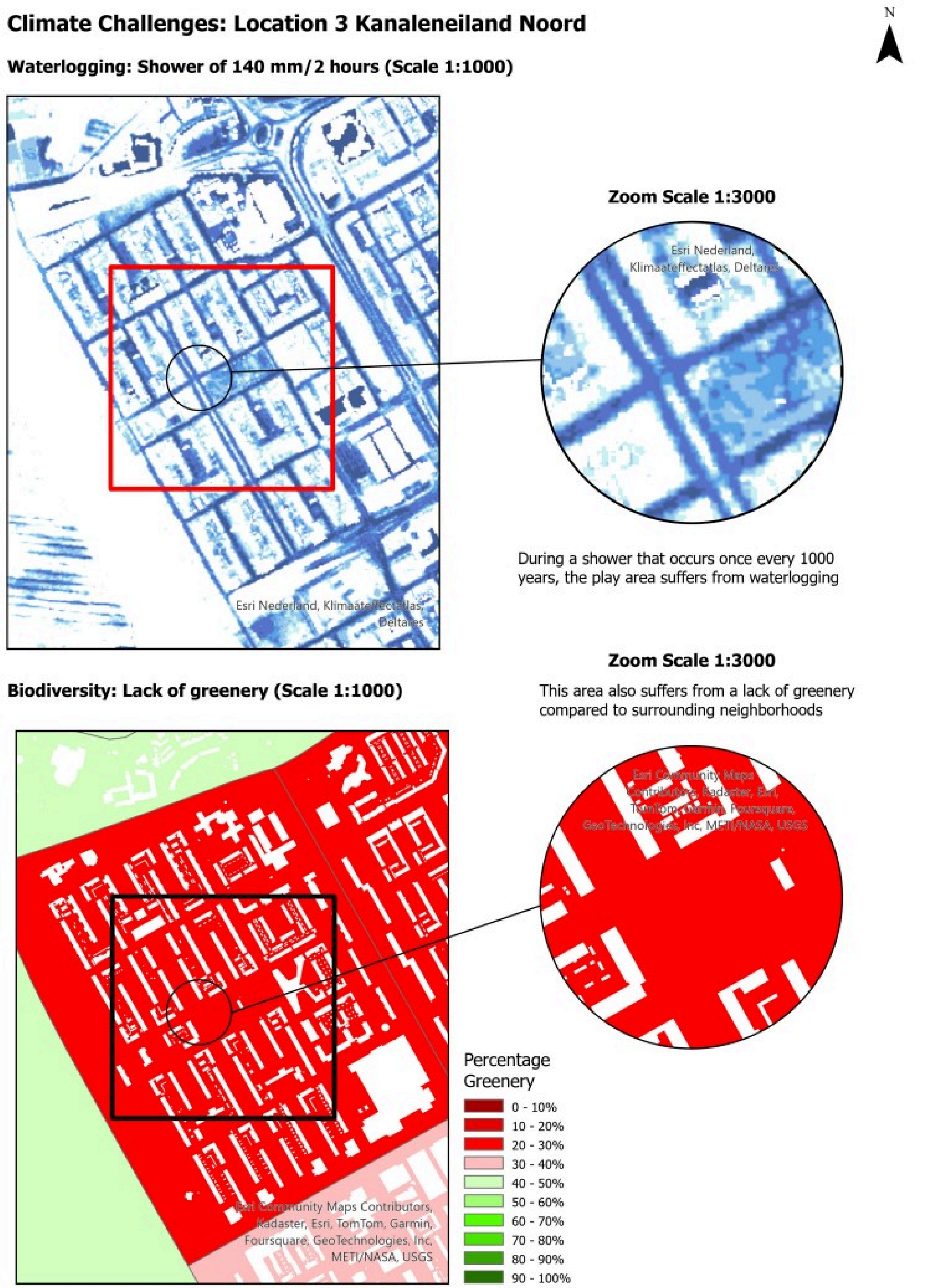
☐ Water Roof

☐ Ground Level Elevation

☐ Soil Structure Improvement

☐ Water Storage Under (Un)Paved Surface

5. Considering that this area suffer from tendency for waterlogging (rain) and lack of biodiversity , which interventions would your climate adaptation design include? **Choose 3 interventions.** *



Marque todas que se aplicam.

☐ Green Façade

☐ Façade Garden

☐ Green Garden

☐ Green Roof

☐ Green Fence

☐ Tree Planting

☐ Bird/Bat/Insect Box

☐ Rain Barrel

Sunken Street

Light Color/Material

Blinds

Water Permeable Pavement

Cool Places

Shadow Routes

Natural Playground

(Natural) Wadis

☐ Surface Water

☐ Infiltration Crates

☐ Water Storage Under Building

☐ Water Square

☐ Rural Waterways

☐ Water Roof

☐ Ground Level Elevation

☐ Soil Structure Improvement

☐ Water Storage Under (Un)Paved Surface

6. Describe the reasoning behind your design in a few words. *

7. Which extra data would have facilitated your design ? *

8. Would you like to participate in a draw for a €20 Amazon gift card? *

Marcar apenas uma oval.

◯ Yes

◯ No

9. If you selected yes please insert an email to be contacted if you are the winner. *

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