Multifunctional Nature-Based Solutions design scenarios to improve urban microclimate and thermal comfort: An ENVI-met simulation study of the Timorpleinbuurt-Zuid neighborhood

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Abstract

Urban environments are getting warmer and warmer because of climate change so there is a need for interventions that can help with cooling. These interventions should also provide co-benefits. A lot of microclimate studies only focus on a few fixed points, or street-wide averages and rarely look at conditions adjacent to an intervention or along a route regarding thermal comfort. Co-benefits such as added bioretention surface area and CO_2 uptake are almost never looked at alongside thermal comfort. To tackle those gaps three nature-based solutions (NBS) scenarios are tested in a thermally uncomfortable street in Amsterdam on the hottest day ever recorded in the city (25 July, 2019), these NBS scenarios are: green façades, bioswales and vegetated pergola. The ENVI-met model had input data of a local weather station and was validated against observations of the Schiphol weather station. So it is used to look at the whole-street conditions and 2 meter wide buffer zones for each NBS intervention at 18:00 and 23:00. A walk-based Physiological Equivalent Temperature (PET) tool of ENVI-met showed proper pedestrian exposure during a route. The Timorpleinbuurt-Zuid neighborhood was selected as a study-case because it is a neighborhood with a lot of high heat exposure and it has a low amount of public green space, so a high impervious cover, but also has urgent rainwater risk, and a high social vulnerability to heat, and it provides local weather data for validation. The results depend on both NBS type and analysis scale (bufferzone or whole street). The pergola has the strongest relief at 18:00, largely seen within its buffer zones where shade covers the sidewalk. Green façades cool more consistently at the street scale and are also staying effective into the evening, while also improving comfort in the bufferzones. The bioswales provide a low amount of thermal comfort at both scales but it has the highest amount of added bioretention surface area and the highest reduction in CO_2 levels. So there are trade-offs so a mixed strategy is recommended. This would be having pergolas on the sun exposed walking routes, green façades to block incoming sunlight on building facades to help with whole street-scale and thermal comfort at 18:00 and 23:00, and bioswales to increase the bioretention surface area and air-quality goals. The bufferzone and walk-based PET are a good way to evaluate the single NBS interventions where people actually move.

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1. Introduction

1.1 Context

1.1.1 Amsterdam

The city of Amsterdam is affected by climate change (Gemeente Amsterdam, 2021a). Extreme weather events such as heat waves, droughts, and extreme rainfall are happening more frequently which affect the residents (Gemeente Amsterdam, 2021a). The municipality of Amsterdam has acknowledged these events. They see the urgency for adaptation initiatives to improve urban resilience against the effects of climate change (Gemeente Amsterdam, 2021a).

The municipality of Amsterdam set-up the Climate Adaptation Strategy in 2020 (Gemeente Amsterdam, 2021a). This is a step in recognizing and mitigating the city's climate change risk (Gemeente Amsterdam, 2021a). The municipality is committed to combating the climate issues that are expected to arise in 2030, 2050 and beyond, detailed in the 'Implementation Agenda for Climate Adaptation' (Gemeente Amsterdam, 2021a). The Implementation Agenda talks about the obstacles Amsterdam faces regarding climate, the policy areas where they have already implemented climate-adaptive norms and guidelines, their goals, and the future research that needs to be done regarding climate change (Gemeente Amsterdam, 2021a). Extreme heat, drought, water nuisance are important adaptation concerns that are important for the national Delta Program and Amsterdam's Climate Adaptation Strategy (Gemeente Amsterdam, 2021a). While doing this, they are also considering solutions that address several climate-related issues simultaneously and create connections to other goals of the city (Gemeente Amsterdam, 2021a, Alves et al., 2024).

Such a goal is water management. Amsterdam wants to reduce flood risks and increasing water supply during dry spells by managing rainwater through infiltration, storage, and rainproof innovations (Gemeente Amsterdam, 2021b). This strategy protects houses and infrastructure from water-related harm while also promoting the vitality of green urban areas (Gemeente Amsterdam, 2021b).

1.1.2 Microclimate

Microclimates play a big role in urban development and climate adaptation (Zhao, 2018). The localized climatic conditions seen in a small area are referred to as microclimates (Yang et al., 2023). These small areas are a neighborhood or street (Yang et al., 2023). Because of things like geography, vegetation, structures, and human activity, conditions such as heat exposure and humidity might differ quite a lot from the surrounding area (Yang et al., 2023). Human health can be directly affected by microclimates (Yang et al., 2023). Because of climate change it will be important developing climate resilient and livable urban settings (Yang et al., 2023). This requires an understanding of microclimate optimization and a focus on microclimate optimization (Yang et al., 2023).

Climate adaptation is one of the big drivers for making Amsterdam greener and more inclusive of nature (Gemeente Amsterdam, 2021b). The municipality says that they can no longer afford to "*waste*" green space because of the rise in the use of green space in recent years (Gemeente Amsterdam, 2021b). The municipality wants as many of Amsterdam's citizens to have access to green space and it wants green space to have as many functions as possible (Gemeente Amsterdam, 2021b). Based on this Amsterdam has made the development of nature-based solutions (NBS) a big component of its climate adaption plan (Gemeente Amsterdam, 2015). European Commission (2015) says that NBS are solutions that are beneficial, that provide environmental, social, and economic benefits at the same time and help build resilience and are *"inspired and supported by nature"*. These strategies make use of vegetation's and natural systems' advantages to reduce the effects of climate change, increase urban (climate) resilience, and make cities more livable (Gemeente Amsterdam, 2015). In addition to mitigating heat stress and preserving water, urban greenery can also provide food production, food regulation, wind and noise reduction, biodiversity, pest management, climate regulation, CO2 uptake, social and emotional functions, health, the economy, recreation, education and the fertility of the soil (Gemeente Amsterdam, 2021b). These are all in line with the city's sustainability and inclusion objectives.

1.3 Nature-based solutions & multifunctionality

The need for open space and greenery is growing as Amsterdam gets denser (Gemeente Amsterdam, 2024a). When comparing the amount of green space in public areas on January 1, 2023 to the situation in 2018, there is a little decline in green public space area (Gemeente Amsterdam, 2024a). There has been a 160 hectare (-1.9%) decline of total public urban green spaces (Gemeente Amsterdam, 2024a). Unfortunately since the sources of the Amsterdam municipality are not current everywhere, there is not an accurate representation of the precise total decline in green space (Gemeente Amsterdam, 2024a).

Nature-based solutions increase human, environmental, and infrastructural resilience to climate effects by restoring and/or mimicking nature (Luedke, 2019). These solutions frequently have positive financial, social, and environmental benefits (Luedke, 2019). NBS's multifunctionality is promising for simultaneously solving a number of urban challenges (Raymond et al., 2017). At the site level, multifunctionality refers to how green spaces are designed and maintained to combine multiple functions in one place (Choi et al., 2021). The goal of multifunctionality planning is to minimize trade-offs and conflicts while creating synergies between functions (Hansen et al., 2017). Multifunctional NBS provide thorough solutions to challenging urban issues by combining a variety of functions including social welfare, biodiversity preservation, and urban climate regulation (Gómez Martín et al., 2020). But in order to fully make use of NBS, the designer must comprehend implementation, how NBS are designed and how they can be integrated properly into the current gray infrastructure (Kabisch et al., 2016).

Multifunctionality is critical for cities given their numerous problems and space constraints (Ahern, 2011). But this is often not given enough consideration when designing urban infrastructure changes (Hansen et al., 2017; Ommer et al., 2022). Long-term issues may come from this if the NBS chosen to solve one issue has unexpected trade-offs with other unexpected issues (Salmond et al., 2016). A few important factors need to be taken into account when managing risks associated with climate change using nature-based adaptation measures (Alves et al., 2024).

The advantages of NBS are becoming more widely accepted but there are still challenges in maximizing their multifunctionality in urban settings (Kabisch et al., 2022). Strategic planning will be essential for avoiding limited solutions and integrating NBS into a linked, multifunctional network of urban green spaces and urban blue spaces (Kabisch et al., 2016). To properly apply NBS, more understanding of what it actually is and how to properly use it is essential (Kabisch et al., 2016). A long-term view and the diversity of potential co-benefits should be included in this assessment (Kabisch et al., 2016). This makes it that additional research is needed to examine the effects of particular NBS typologies on microclimate conditions and determine the trade-offs involved in their use (Kabisch et al., 2016) to come up with NBS for Amsterdam. In order to improve the integration of NBS's multifunctionality in urban design, more research is required to estimate the impacts of particular NBS for a specific place as well as to incorporate more co-benefits and analyze their synergies and trade-offs (Choi et al., 2021; Sarabi et al., 2022). Multifunctionality is frequently mentioned but it is rarely used to its full potential (Langergraber et al., 2021). Then so, NBS' ability to handle multifunctionality is typically overlooked (Langergraber et al., 2021). It is essential to do a thorough and comprehensive evaluation of all the possible co-benefits, and trade-offs to determine what the environmental feasibility is of NBS' use (Susca, 2021).

The goal is to find out which multipurpose NBS should be used to provide plenty co-benefits but with a focus on reducing the PET of Amsterdam neighborhoods during a hot summer day. So with a focus on microclimate changes, proper NBS typologies, and implementation of trade-offs to help give important information to develop livable, sustainable, and resilient cities regarding climate change.

1.4 Research gap and thesis aim

The aim is to investigate how NBS design scenarios can be used to reduce the PET level during hot summer days for Amsterdam neighborhoods while simultaneously providing multiple co-benefits, with the use of Timorpleinbuurt-Zuid neighborhood as a study-case. With high-resolution data it can help with evaluating the local effects of NBS implementation and this gives decision-makers and urban planners important information on which NBS kinds should be prioritized in order to achieve intended microclimate goals (Cortinovis et al., 2022).

Problem statement

Climate change is causing extreme weather events like heat waves and extreme rainfall to occur more frequently in Amsterdam (Gemeente Amsterdam, 2021a). It creates an unpleasant microclimate for people residing in Amsterdam which are affected by these types of extreme events (Gemeente Amsterdam, 2021a). The municipality of Amsterdam has created policies and strategies for climate adaptation and they state NBS as a way of reducing the effects of climate change, after realizing the importance of tackling this problem (Gemeente Amsterdam, 2021a). According to Alves et al. (2024) the municipal stakeholders are interested in adding advantages beyond stormwater management and heat stress prevention, they want improvement of biodiversity and better air quality which are a few of the additional benefits that have been they want to look at as well.

Obstacles and knowledge gaps

A knowledge gap is the multifunctionality values of NBS measured. Even though normally NBS are frequently recommended as ways to improve urban microclimates, the majority of research to date has tended to evaluate their effectiveness by using a single, isolated indicator, such as air temperature, PET or CO_2 concentration, so the understanding of how NBS types really function in urban places where several environmental and practical factors interact is limited by this indicator approach that only looks at one single indicator. That means there is a lack of NBS assessments that simultaneously measure:

- Thermal comfort (PET)
- Air temperature reduction
- CO_2 uptake
- Added bioretention surface area
- Additional trade-offs e.g. visual obstruction, required space and maintenance costs.

Another gap is the use of a climate modeling tool (BIO-met tool of the modeling software ENVI-met) that measures the PET when you walk through an environment, the BIO-met thermal comfort walk function for the reason that it is a recently newly implemented ENVI-met tool part of the ENVI-met software (August 2024) (ENVI-met, 2024b). The tool is used for simulating dynamic thermal comfort walks (ENVI-met, 2024b), most current and past research only use static PET measurements at fixed points, like at a certain hour and a certain place without the option to move. So far dynamic simulations that model how pedestrians experience thermal conditions while moving are rare in NBS scenario testing because it is so new to be able to model it.

1.5 Research questions

Main research question: *Which multifunctional nature-based solutions can be used to reduce Physiological Equivalent Temperature in Timorpleinbuurt-Zuid neighborhood during a hot summer day while also providing co-benefits for urban climate resilience?*

Sub-research questions

How do microclimate conditions vary across Timorpleinbuurt-Zuid during a hot summer day, and what are the biophysical features influencing these variations?

Which custom-designed NBS interventions are most effective in reducing PET in Timorpleinbuurt-Zuid and what additional co-benefits do they provide?

What are the trade-offs between multifunctional NBS in Timorpleinbuurt-Zuid?

2. Theoretical Framework

2.1 Ecosystem Approach

A fair and equitable approach to managing land, water, and living resources is the 'Ecosystem Approach' (Figure 1) (CBD, 2010; Cohen-Shacham et al., 2016). This approach encourages conservation and sustainable usage (CBD, 2010; Cohen-Shacham et al., 2016). A workshop organized by the United Nations states that viewing cities as ecosystems helps recognize people as an integral part of these systems (Marcotullio et al., 2003). This approach applies scientific methodologies to understand the biological structures, processes, and interactions within ecosystems (Marcotullio et al., 2003; CBD, 2010; Cohen-Shacham et al., 2016). This provides a framework for analyzing the complexity of urban environments (Marcotullio et al., 2003; CBD, 2010; Cohen-Shacham et al., 2016).

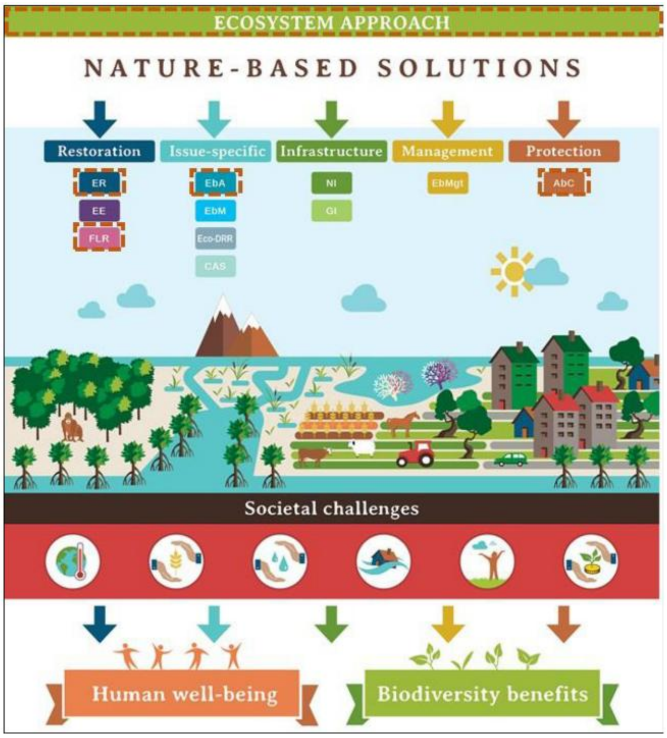


Figure 1: Ecosystem approach related to NBS (Cohen-Shacham et al., 2019)

An ecosystem is any functional unit of life that can exist at different spatial scales, ranging from microhabitats to complete biomes (CBD, 2010; Cohen-Shacham et al., 2016). The Ecosystem Approach can be adapted easily based on local, national, regional, or global contexts (CBD, 2010; Cohen-Shacham et al., 2016).

Cohen-Shacham et al. (2016) say that the Ecosystem Approach has a solid conceptual foundation for NBS and a framework for designing and implementing them. Because NBS are rooted in ecosystem dynamics, management strategies must be in line with ecological functions in order to be successful (Cohen-Shacham et al., 2016). In particular the Ecosystem Approach helps NBS by stating the significance of ecosystem services as solutions for societal challenges (Cohen-Shacham et al., 2016). It also is promoting context-specific strategies (in accordance with cultural and legal norms and practices) over universally applicable ones (Cohen-Shacham et al., 2016). And it makes sure that climate adaptation and biodiversity preservation are central to planning (Cohen-Shacham et al., 2016).

The Ecosystem Approach provides a proper conceptual foundation for creating NBS interventions, though being a bit more comprehensive than NBS (Cohen-Shacham et al., 2016). It guarantees that NBS strategies are incorporated into broader ecological and societal systems rather than existing as just stand-alone actions (Cohen-Shacham et al., 2016). The Ecosystem Approach gives practitioners and policymakers a structured method to implement and assess NBS by connecting ecosystem functions with practical solutions (Cohen-Shacham et al., 2016).

Microclimate regulation is the focus. The Ecosystem Approach can be the foundation for analyzing NBS effectiveness in reducing heat stress. Also how effectively NBS interventions contribute to urban climate adaptation while also promoting biodiversity and environmental resilience will be looked at by making use of the "Ecosystem Approach" as a framework.

2.2 Nature-based solutions (NBS)

2.2.1 NBS

NBS is a concept that includes an array of specific approaches (Cohen-Shacham et al., 2016). These approaches come from various disciplines, but they focus on ecosystem services and seek to solve societal challenges (Cohen-Shacham et al., 2016). They promote benefits to biodiversity and human well-being and their NBS framework was made by the Ecosystem Approach (Cohen-Shacham et al., 2019). The NBS framework sees human well-being and preservation of biodiversity reliant on resilient and functioning natural ecosystems (CBD, 2004; Cohen-Shacham et al., 2019). The European Commission (2015) talk about NBS and say that they are practical, that these NBS are beneficial approaches that work with nature to solve challenges and by doing those it delivers environmental benefits, social benefits and economic benefits. They help make communities become more resilient and support sustainable development (Maes & Jacobs, 2015; Cohen-Shacham et al., 2016). The European Commission talks about the need for "innovating with nature" by using the NBS to drive economic growth and build stronger communities that are more sustainable and why it is important (Maes & Jacobs, 2015; Cohen-Shacham et al., 2016). They see that urban areas face major challenges: human health concerns, climate change etc. (European Commission, 2015). They want to take care of these issues, so what they have done is that they have developed a framework that focuses more on urban ecosystems (Faivre et al., 2017; Raymond et al., 2017; Cohen-Shacham et al., 2016). This approach they created wants to make healthier cities and more sustainable cities (Faivre et al., 2017; Raymond et al., 2017; Cohen-Shacham et al., 2016).

2.2.2 Principles for effective NBS

Bulkeley et al.'s (2023) "Enhancing Urban Nature Provision in the Netherlands" research paper looks at the development of high-quality urban NBS and the use of high-quality urban NBS in Dutch cities. They did this by referencing global research and best practices. Four essential principles that are necessary for effective urban NBS are listed in the report:

1. Providing multiple benefits→ Effective urban NBS are made to simultaneously solve several societal issues (Bulkeley et al., 2023). Addressing adaptation to climate change, biodiversity loss, economic development, and improving well-being are all included in this (Bulkeley et al., 2023). NBS have the potential to provide multiple benefits in many areas (Bulkeley et al., 2023). However, many NBS focus on only one objective, missing opportunities to support urban communities more broadly (Bulkeley et al., 2023). Multiple-benefit urban NBS are thought to be more efficient and better in quality (Bulkeley et al., 2023).
2. Context sensitivity→ The particular context of the site are critical components of urban nature provision success (Bulkeley et al., 2023). Projects that disregard local values run the danger of not realizing their full potential (Bulkeley et al., 2023).
3. Ensuring equity→ To guarantee that the advantages of NBS are distributed across all layers of society, particularly the most disadvantaged or vulnerable, equity is essential in the provision of urban nature (Bulkeley et al., 2023). If intentional measures aren't taken to spread the advantages of urban NBS equally then social inequality may worsen already-existing inequalities (Bulkeley et al., 2023). Certain urban nature initiatives can disproportionately help rich areas while neglecting vulnerable groups (Bulkeley et al., 2023). In order to prevent socioeconomic inequalities and gain broad support for urban nature provision efforts, it is essential to tackle gaps in access to and allocation of benefits from these projects (Bulkeley et al., 2023).
4. Taking care of the root causes of environmental challenges→ Effective urban NBS must actually focus on the underlying causes of biodiversity loss and climate change, so no superficial or weak attempts (a.k.a. "*greenwashing*") (Bulkeley et al., 2023). This involves making sure that NBS aren't only used as a front for continuing with routine company operations that worsen environmental damage (Bulkeley et al., 2023). Instead, NBS should function as a starting point to deal with more extensive environmental issues, such as storing carbon, reducing changes in land use that negatively impact biodiversity (Bulkeley et al., 2023). This encourages sustainable production and consumption in the public consciousness which helps protecting the environment (Bulkeley et al., 2023). By doing this, urban green may greatly contribute to the development of wider public support for environmental action (Bulkeley et al., 2023).

Bulkeley et al., (2023) stresses that neither worldwide nor in the Netherlands has a defined framework based on principles for the provision of urban nature been established. This brings a challenge as well as a chance. According to Bulkeley et al., (2023) the Netherlands' creation of a new mandate for urban nature supply may establish an international standard. The Netherlands can take the lead in providing high-quality urban NBS by implementing fundamental ideas taken from global best practices (Bulkeley et al., 2023). These guidelines would protect NBS's quality while guaranteeing that it will benefit people and ecosystems in the long run (Bulkeley et al., 2023). These principles can support the idea that NBS has to be designed in a strategic way to improve urban microclimate conditions and at the same time align with more comprehensive ecosystem-based adaptation (EBA) strategies.

2.3 Ecosystem-Based Adaptation

The concept of Ecosystem-Based Adaptation (EBA) was created as a framework to explore how ecosystem services might mitigate the effects of climate change on human beings (Cohen-Shacham et al., 2016; Staudinger et al., 2012; Locatelli et al., 2011). Recognized by the Convention on Biological Diversity (CBD) in 2009, EBA is a key tool in climate adaptation planning (CBD, 2010; Rizvi et al., 2015; Cohen-Shacham et al., 2016). The framework promotes sustainable management, conservation, and restoration of ecosystems to provide social, economic, and environmental co-benefits (Cohen-Shacham et al., 2016). The EBA can be implemented at many levels. It usually produces advantages at the local level (Cohen-Shacham et al., 2016; Locatelli et al., 2011; Rizvi, 2014).

		Nature-Based Solutions (NBS)	Ecosystem-Based Adaptation (EBA)
'Nature-based'?	Forms of nature included	Mixed perceptions of what constitutes nature; artificial (e.g. biomimicry) or hybrid solutions (combining natural and engineered components) sometimes included	Dissimilar to NBS: nature entails ecosystems and biodiversity but not artificial forms of nature
	Functions of nature	Utilitarian conceptualization of nature; nature can provide multiple benefits to society	Similar to NBS
	Nature as intervention – examples	Wide-ranging perceptions of what interventions are considered NBS; variety in scope, scale and range of functions Main examples: green roofs and walls, sustainable urban drainage systems (SUDS)	Dissimilar to NBS: generally shared view of what are relevant examples; refers to the management, conservation and restoration of ecosystems Main examples: coastal defence through vegetation, wetland management, urban green spaces
'Solutions'?	Objectives and expected benefits	Aimed at addressing social, economic and environmental issues simultaneously Explicitly solution-oriented	Similarly aimed at addressing multiple sustainability challenges Emphasises climate change adaptation as key outcome
	Governance approaches	Involves trade-offs between co-benefits; integrative and holistic approach promoted Characterised by involvement of a variety of stakeholders	Similar to NBS; advocates de-compartmentalisation within governmental organisation for more effective governance Similar to NBS; advocates participatory, community-based management approaches
	Socio-spatial embeddedness	Alignment with socio-ecological and institutional context is essential to effective functioning Urban context increasingly recognised as key context for NBS implementation	Similar to NBS; advocates adaptation to place-based features and relies on contributions by local communities Increasing attention for embedding in an urban context

Figure 2: Ecosystem-Based Adaptation contrasted to NBS (Dorst et al., 2019)

EBA applications often include:

- Helping build urban resilience against extreme weather (Cohen-Shacham et al., 2016).
- Improving thermal comfort by mitigating urban heat islands (Cohen-Shacham et al., 2016).
- Supporting stormwater management and biodiversity conservation (Cohen-Shacham et al., 2016).

Since NBS are used to analyze microclimate regulation, so on a local scale, EBA presents a theoretical basis for evaluating NBS's effectiveness in lowering the heat stress and providing other environmental co-benefits.

2.4 Ecosystem services

Different urban planning approaches influence how cities adapt to the effects of climate change (Bona et al., 2022). The implementation and effectiveness of NBS play a key role in this process (Bona et al., 2022). These approaches influence factors such as cooling capacity (Ronchi et al., 2020), the impact of floods throughout extreme weather events (Qi et al., 2020), and increasing the density of green areas while guaranteeing permeability (Bona et al., 2022). So then when adopting NBS, including ecological elements into a true dynamic green infrastructure should be considered (Ronchi et al., 2019) at every stage of the design process (Van Cauwenbergh et al., 2022; Boros & Mahmoud, 2021).

Ecosystem services are the benefits that ecosystems give to people (Hansen et al., 2017). Tzortzi et al. (2022) thinks that NBS are a useful instrument for improving ecosystem services, valuing environmental and sociocultural issues, and providing integrated benefits with water and environmental management techniques (Cui et al., 2021).

Ecosystem services increase both human well-being and the advancement of society by bringing a wide range of goods and services provided by natural ecosystems (Hansen et al., 2017). These services can be divided into several groups (Figure 3):

- Regulating services→ These comprise of regulating important environmental processes including plant pollination, water filtration, flood control, and climate regulation (Hansen et al., 2017).
- Provisioning services→ Natural resources and raw materials such as food, water, timber are derived from ecosystems (Hansen et al., 2017).
- Cultural services→ Intangible benefits that people receive from ecosystems such as recreational space, cultural values and aesthetic values (Hansen et al., 2017).

- Habitat (biodiversity) services → Habitat for species and having structural/native biodiversity (Hansen et al., 2017).

Figure 3: Urban greenery brings several ecosystem services, categorized here (Hansen et al., 2017)

NBS support these services, making them essential for socioeconomic development and effective ecosystem management. (Hansen et al., 2017). The high cost-benefit ratio of NBS over conventional solutions, which represent a flexible approach to sustainable growth and inclusive growth at a reasonable cost, is an important benefit (Wendling & Dumitru, 2021; European Environment Agency et al., 2021; European Commission, 2015). This makes it that NBS are a valuable tool for creating a shared, circular, and sustainable economy in urban areas (Bona et al., 2022).

	ECOSYSTEM SERVICES - BENEFITS	FINE SCALE	LOCAL SCALE	REGIONAL SCALE
PROVISIONING SERVICES	Nutrition and food security	Ground-level and roof gardens, planting boxes, temporary re-use of space for growing food	Allotment gardens, edible forests, food sites (for fishing, mushroom and berry picking), edible greening	Crops, pastures, wild food
	Drinking water and water resources	Permeable vegetated surfaces that increase infiltration	Ponds, streams, shores, reed beds, ground-water protection	Water-shed protection, lakes, oceans, flooding areas
REGULATION & MAINTENANCE	Carbon sequestration	Installing NBS with low carbon footprint, use biochar in substrates	Green areas, trees, management without using fossil fuels	Low-carbon approaches, Protecting and restoring forests, coastal biotopes, peatlands
	Biodiversity including genetic resources	Vegetated roofs, parks, open waters, plants propagated from wild local origin, woodland	Variety of NBS using local declining species propagated from wild origin, open waters	Connectivity, large nature areas, conservation areas, variety of landscapes
	Pollinators for food security and biodiversity	Native flowers from early spring to late autumn, forage plants for larvae, nesting sites (sand, soft wood)	Meadows and parks rich with nectar plants, habitat for species in decline, linear NBS (e.g. transport corridors)	Connectivity, large nature areas, reconfiguration of infrastructure (e.g. streets into greenspace)
	Flood risk control, storm-water management	Permeable vegetated surfaces, green roofs, local green, sustainable drainage	Trees, flood areas, meandering rivers, bogs, mangroves, permeable pavements, green tramways	Watersheds with abundant vegetation and tree cover, large deltas, wetlands and bogs, flood plains

Figure 4: Examples of various ecosystem services and other NBS benefits related to relevant NBS types at different scales, (Somarakis et al., 2019; Faehnle et al. 2014).

R & M	Erosion control	Using mulch, compost, plant residues as soil cover; planting of seagrass and mangroves	Revegetation of riverbanks, meandering riverbeds, agroforestry	Preservation of forests and vegetation cover
CULTURAL-SOCIAL	Aesthetic improvement	Vegetated roofs and facades, multisensory NBS, restoring waterways in cities	NBS nourishing all senses, local nature, meandering riverbeds	Large connected green infrastructure,
	Cultural heritage	Individual trees, plantings, nature elements; sites with historical, cultural, or identity value	Local vegetation, official heritage sites, valuable sites for recreation and nature appreciation	Nature conservation areas, use of local vegetation in NBS
	Active life style	Easy access to inspiring green space for all (including children, elderly and disabled)	Gradients of challenge, elongated green spaces, connectivity, variation, attractions	NBS for soft mobility - forests, meadows, bogs, parks, and streets transformed into greenways
	Restoration from stress or illness	Quiet lush NBS, views from windows to NBS, easy access	NBS supporting walking and relaxed social activities	Large nature areas
	Knowledge creation, education and awareness raising	Indigenous species, pollinators, variety of NBS, biodiversity elements, long-term research sites	(Semi-)wild nature, open waters, remnant forests, meadows, dead wood, long-term research sites	Large nature areas with little maintenance, natural dynamics, nature conservation areas
	Social cohesion, social capital	Community gardens	Co-management & co-planning of green space	Co-management & co-planning of landscape

Figure 4: Examples of various ecosystem services and other NBS benefits related to relevant NBS types at different scales continuation, (Somarakis et al., 2019; Faehnle et al. 2014).

ECONOMIC	Touristic development	Diverse NBS based on local species at tourist attractions and hotels	Lush and diverse NBS along major touristic routes	Large destinations with local nature, land-race and wild species
	Increased regional value	Visible vegetated roofs and facades	NBS providing recreational opportunities: open waters, forests, parks	Large preserved nature areas with recreational opportunities
	Other economic benefits	Nature-based tourism	Reduced costs for water treatment	Production of timber, food, plants for NBS

Figure 4: Examples of various ecosystem services and other NBS benefits related to relevant NBS types at different scales continuation, (Somarakis et al., 2019; Faehnle et al. 2014).

2.5 Co-benefits/multifunctionality

NBS multifunctionality allows them to have several ecosystem services and benefits to society at once (Figure 4) (Somarakis et al., 2019). In contrast to conventional grey infrastructure, the NBS act as an integrated strategy for mitigating and adapting to climate change while simultaneously improving social well-being, economic value, and environmental quality (Susca, 2021).

2.5.1 Environmental co-benefits

By lowering the urban heat island (UHI) impact, increasing CO2 uptake, bettering air quality, and regulating stormwater runoff, NBS help combat climate change (Choi et al., 2021). Trees and green facades are examples of NBS kinds that impact air temperature, but also lower building energy use and they filter air pollutants etc. (Susca, 2021). Habitat connectivity and biodiversity are made better by green and blue infrastructure and an improved habitat connectivity and biodiversity improves the ecosystem resilience of a place (Choi et al., 2021). Water infiltration and water retention and avoiding stormwater overflow in urban drainage systems are also dealt with by some NBS types because they decrease the effects of floods and extreme weather events (Ommer et al., 2022).

2.5.2 Economic co-benefits

Long-term financial benefits can be gotten from the use of NBS (Susca, 2021). NBS does have an effect on the increase of natural cooling and lowering the need for heating in the winter and air conditioning in the summer, so it lowers the energy costs of buildings (Susca, 2021). The green areas and streets lined with trees can raise property values and increase the economic vitality of urban areas etc. (Choi et al., 2021). NBS strategies instead of conventional gray infrastructure strategies provide a more affordable option for climate adaptation but also disaster risk reduction in a city (Ommer et al., 2022). NBS could be a financially good investment for helping the microclimate because of its flexibility and normally it could have low maintenance expenses (Raymond et al., 2017).

2.5.3 Social and well-being co-benefits

The well-being of communities and their respective public health are very well impacted by NBS when they are there because they bring fair and easy access to urban nature and this is important to equality of access because everyone has access to it (Raymond et al., 2017; Somarakis et al., 2019). Views of the outdoors from the windows and entrance of a house are essential (Somarakis et al., 2019). Urban residents say themselves that when they can get to green areas they say they feel less stressed and that they have better mental health and that they do more physical activity (Susca, 2021). It is also likely to increase neighborhood satisfaction since the residents are more likely to spend more time outside and benefit from being near to 'nature' (Somarakis et al., 2019).

NBS lowers respiratory disorders and heat-related illnesses mostly for vulnerable groups, because they help with improving air quality and decrease the exposure to bad air pollutants (Ommer et al., 2022). To make sure that all socioeconomic groups have equal access to the benefits of green infrastructure this helps broader environmental justice objectives (Raymond et al., 2017).

Another social co-benefits is cultural heritage that plays a big role in place identity (Somarakis et al., 2019). Examples of these are historic gardens, native plants found in the area, common animals and individual trees can all be valuable (Faehnle et al., 2014; Folmer et al., 2018). At the smaller urban scale NBS betters the well-being of urban residents because it creates a sense of place identity (both for the individual person and for the whole community of the city) that improves public spaces (Hadavi et al., 2017; Somarakis et al., 2019).

2.6 NBS approaches

The NBS concept have several approaches that vary in purpose and in how directly they influence ecosystems (Cohen-Shacham et al, 2019) and can be seen in Figure 5, Figure 6 and Figure 7: The NBS approaches fall into five main types:

- Ecosystem restoration approaches→ This type covers methods including forest landscape restoration, ecological engineering, and ecological restoration (Cohen-Shacham et al., 2019).
- Issue-specific ecosystem-related approaches→ This type includes ecosystem-related methods to solve specific issues, such as ecosystem-based adaptation, ecosystem-based mitigation, climate adaptation services, and ecosystem-based disaster risk reduction (Cohen-Shacham et al., 2019).
- Infrastructure-related approaches→ This type includes natural infrastructure and green infrastructure approaches (Cohen-Shacham et al., 2019). They stress the adoption of NBS in the creation of infrastructure (Cohen-Shacham et al., 2019).
- Ecosystem-based management approaches→ This type includes integrated water resources management and integrated coastal zone management, which focus on regulating ecosystems to provide sustainable outcomes (Cohen-Shacham et al., 2019).
- Ecosystem protection approaches→ This type involve area-based conservation strategies, like managing protected areas and implementing other successful conservation measures (Cohen-Shacham et al., 2019).

Figure 5: NBS as an umbrella term for ecosystem-related approaches (Cohen-Shacham et al., 2016).

Category of NbS approaches	Examples
Ecosystem restoration approaches	Ecological restoration Ecological engineering Forest landscape restoration
Issue-specific ecosystem-related approaches	Ecosystem-based adaptation Ecosystem-based mitigation Climate adaptation services Ecosystem-based disaster risk reduction
Infrastructure-related approaches	Natural infrastructure Green infrastructure
Ecosystem-based management approaches	Integrated coastal zone management Integrated water resources management
Ecosystem protection approaches	Area-based conservation approaches including protected area management

Figure 6: Categories and examples of NBS approaches (Cohen-Shacham et al., 2016).

Because of the study's urban focus makes the main emphasis is on issue-specific ecosystem-related approaches, namely Ecosystem-Based Adaptation (EBA).

	Name	Definition	Purpose
	Ecosystem Approach	Strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way (CBD, 2004).	Primary framework developed to implement CBD (CBD, 2004).
Under the NbS umbrella	Forest landscape restoration	The long-term process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes (IUCN and WRI, 2014).	To address the need for large scale forest restoration.
	Ecosystem-based adaptation	The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (CBD, 2009).	To address the effects of climate change via adaptation measures.
	Ecological restoration	The process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed (SER, 2004).	To reverse degradation induced by unsustainable human activity on ecosystems.
	Protected Areas	A clearly defined geographical space, recognized, dedicated and managed through legal or other effective means to achieve the long-term conservation of nature with associated ecosystem services and cultural values (Dudley, 2008).	To conserve nature (biodiversity and geodiversity) and to provide a range of ecosystem services that do not conflict with nature conservation.

Figure 7: Details of the five ecosystem-based approaches (Dorst et al., 2019)

2.7 Types of NBS

Eggermont et al. 2015 created a typology that describes NBS across two gradients: 1. *"How much ecosystem service and stakeholder group targeting does a given NBS include?,"* and 2. *"How much biodiversity and ecosystem engineering is included by a specific NBS?"* Eggermont et al. (2015) suggest that trade-offs between ecosystem services are likely to occur (Howe et al., 2014). This makes it becomes harder to optimize the delivery of these services when multiple services are involved (Eggermont et al., 2015). Also meeting the specific needs of all stakeholder groups at the same time becomes more challenging (Eggermont et al., 2015). The more services and stakeholder groups that need to be considered the lower the ability to satisfy everyone's needs (Eggermont et al., 2015). Eggermont et al. (2015) identify three main categories of nature-based solutions (NBS). The first type is based on the level of engineering or management applied to biodiversity and ecosystems (Eggermont et al., 2015). The second type considers the number of ecosystem services that need to be provided (Eggermont et al., 2015). The third type focuses on the number of stakeholder groups involved and the likelihood of maximizing the delivery of the targeted services (Eggermont et al., 2015).

Type 3 NBS involve heavily regulating ecosystems or developing entirely new constructed ecosystems (Figure 8) (Eggermont et al., 2015). Examples are green walls and green roofs, which help reduce urban heating and filter polluted air (Eggermont et al., 2015). Concepts such as "green" and "blue infrastructures" (Benedict &

McMahon, 2006) and goals like *"restoring heavily deteriorated or polluted areas"* are associated with Type 3 NBS (Eggermont et al., 2015).

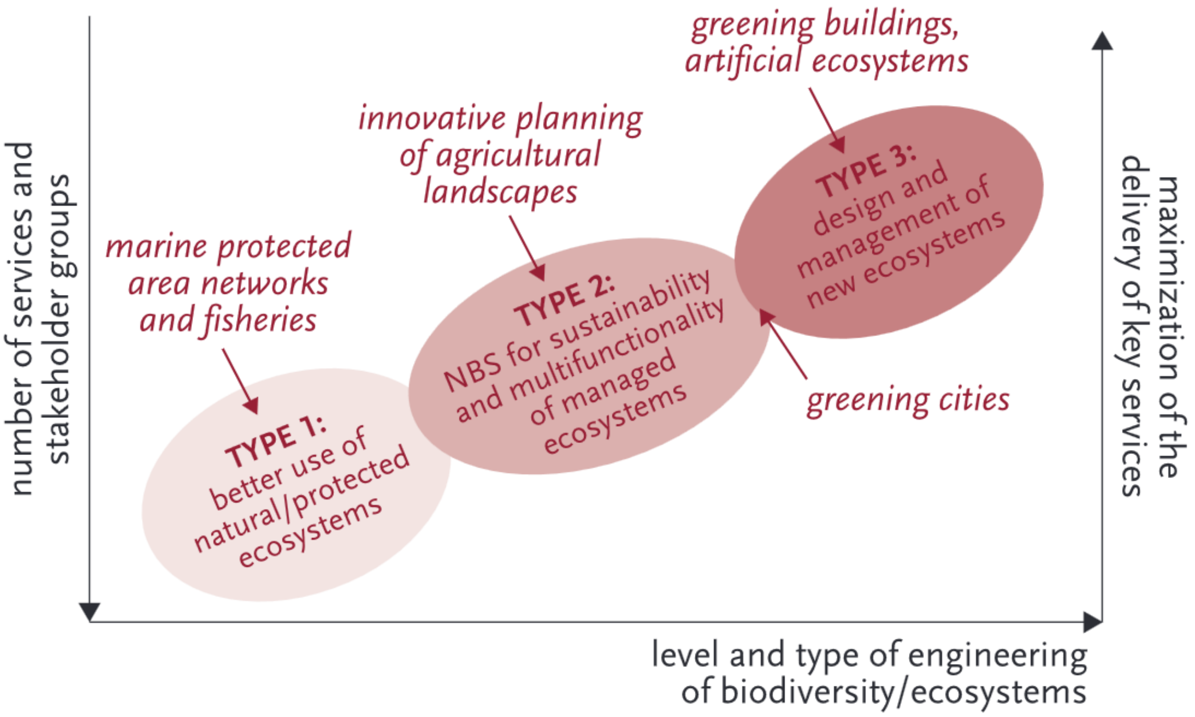


Figure 8: Schematic representation of the range of NBS approaches (Eggermont et al, 2015)

Three degrees of NBS usage in the built environment can be distinguished by:

1. Natural raw materials derived from the biological cycle are referred to as "*green building materials* (Bona et al., 2022; Eggermont et al., 2015)." Their processing must use little energy, carbon, water, and chemical usage to minimize its bad impacts on the environment (Bona et al., 2022; Eggermont et al., 2015). After the material usage cycle, the environment should be able to safely receive nutrients again thanks to optimal manufacturing and building techniques (Bona et al., 2022; Eggermont et al., 2015).
2. Green building systems (systems for greening buildings) are living and green elements that are used into the structure and utilized to green buildings (Bona et al., 2022; Eggermont et al., 2015). Examples of these elements include living walls, house trees, green roofs, and façade greenery (Bona et al., 2022; Eggermont et al., 2015).
3. Areas of land next to buildings e.g. pocket parks, urban plazas, and tiny community parks, are referred to "*green urban sites*" (Bona et al., 2022; Eggermont et al., 2015). They play a blue-green role in cities of open spaces with plants and water-sensitive urban design (Bona et al., 2022; Eggermont et al., 2015). These types of environments provide a range of ecosystem services while also providing resilient and regenerative solutions to tackle multiple urban challenges (Bona et al., 2022; Eggermont et al., 2015). Examples for this are lowering noise pollution and slowing down climate change (Bona et al., 2022; Eggermont et al., 2015).

All of these levels strengthen the ecosystem services that NBS interventions give while furthering urban sustainability goals (Bona et al., 2022). And all these will be considered when creating the NBS typologies.

2.8 Trade-offs and challenges

NBS adoption in an urban environment has sound good so far but actually it is not without (negative) trade-offs even though it can have many benefits (Figure 9) (Somarakis et al., 2019). Unfortunately there is a good chance for both positive effects and negative effects to come with each NBS, so this means that each NBS's effectiveness needs to be evaluated at the beginning of a planning process (what type of NBS will be implemented, where will it be put, what dimensions will it have etc.) to make sure that both the positive effects and negative effects are kept to a minimum (Somarakis et al., 2019). Unfortunately what has been seen sometimes is that people from low-income neighborhoods could be displaced by rising property values as a result of poorly designed NBS initiatives (which is gentrification) (Choi et al., 2021). On top of that, some components of green infrastructure, including specific tree species and green roofs, may make allergically sensitive people more susceptible to allergic reactions and higher pollen levels (Susca, 2021). For example, planting trees in urban areas may have advantages like reducing heat island effects and sequestering carbon, but it may also increase the risk of fires (Lehvävirta, 2007), allergic reactions (Cariñanos et al., 2019), and emissions of natural volatile organic compounds (Livesley et al., 2016). This makes it important that choosing the ideal species, in addition to the spatial layout, management practices, and optimal amount of vegetation needs a careful analysis adapted to each local setting (Somarakis et al., 2019). Space limitations in crowded urban settings and the expenses are another difficulty to balance because people can have different needs and putting the NBS can hinder the needs (parking space lost) and the costs could become too high (implementation and maintenance) (Seddon et al., 2020).

BENEFITS	LOCAL RISKS	WIDE-SCALE RISKS
Reduction of air pollution	Release of VOC, increased pollution by slowing air flow	Pollution emissions during production and transport
Support biodiversity, offer space for declining species	Damaging biodiversity via transport of exotic species	Homogenised landscapes with one-size-fits-all solutions
Mitigation of urban heat island	Heat retention via prevention of air flow	Increased global warming due to carbon release during production and transport
Preventing and recovering from pluvial flooding	Flood risk not reduced enough due to poor solutions	Exacerbating cloud bursts and sea level rise due to carbon release
Improved landscape and greenspace connectivity	Malfunctioning connectivity for the related organisms	Wide-scale dispersal of unwanted organisms
Noise abatement	Noise from management machinery or unexpected forms of use	Noise from production and transport
Social cohesion and social inclusion	Exclusion due to failure of recognising different user groups' needs	Segregation due to unequal access to NBS
Offer public space and accessibility	Spaces remaining unused	Wasted natural resources
Savings in energy use and costs via cooling	Cooling impact not achieved due to unsuitable plants	Fossil fuels used for material production
Increased value of the space or area	Inequality among different societal groups, space needed for NBS	Gentrification of urban areas

Figure 9: Examples of benefits versus possible harmful impacts of NBS (Somarakis et al., 2019).

2.9 Physiological Equivalent Temperature

An important human thermal comfort indicator is called: 'Physiological Equivalent Temperature' (PET) (Calfapietra & European Commission 2020). This thermal comfort indicator is used by a lot of academic studies to see how well NBS types reduce urban heat stress (Calfapietra & European Commission 2020). ENVI-met is used a lot in case study applications to look at the microclimate of an area, mostly looking at urban areas (Calfapietra & European Commission 2020). A study was done for the city of Bilbao where Acero & Herranz-Pascual (2015) have shown how ENVI-met could be used to give a detailed spatial resolution modeling of NBS benefits in an urban space (Calfapietra & European Commission 2020). They did this to see how various greening scenarios could improve outdoor thermal comfort conditions (Calfapietra & European Commission 2020; Acero & Herranz-Pascual, 2015). Also they showed the value of considering various plant systems. Then they came to the conclusion that including grass and trees within the chosen street canyons might result in a PET decrease of up to 10°C (Calfapietra & European Commission 2020; Acero & Herranz-Pascual, 2015).

PET is a thermal index based on the human energy balance (Matzarakis et al., 1999). The PET basically represents the air temperature of an area where core and skin temperatures of the body match those of the actual environment (Coccolo et al., 2016). These temperatures are determined using the Munich Energy-Balance Model for Individuals (MEMI), which calculates the human body's heat balance (Figure 10) (Höppe, 1999). PET considers factors such as air temperature, mean radiant temperature, wind speed, relative humidity, metabolic rate, and clothing insulation (Höppe, 1999). It is useful for seeing what the thermal component of different climates are because it has a strong physiological foundation which can make it a reliable measure for thermal comfort because what is measured via air temperature in degrees might not make it similar to how it is felt (Matzarakis et al., 1999). Unlike other thermal indexes, PET is expressed in degrees Celsius (°C), making it easier to understand (Matzarakis et al., 1999). The PET results of a microclimate simulation can also be visualized with charts, graphs or bioclimatic maps (Matzarakis et al., 1999). The PET graphs show the PET' variations over a time period (hours, days, weeks etc.) and bioclimatic maps show the spatial distribution of PET in an area at a certain time (Matzarakis et al., 1999).

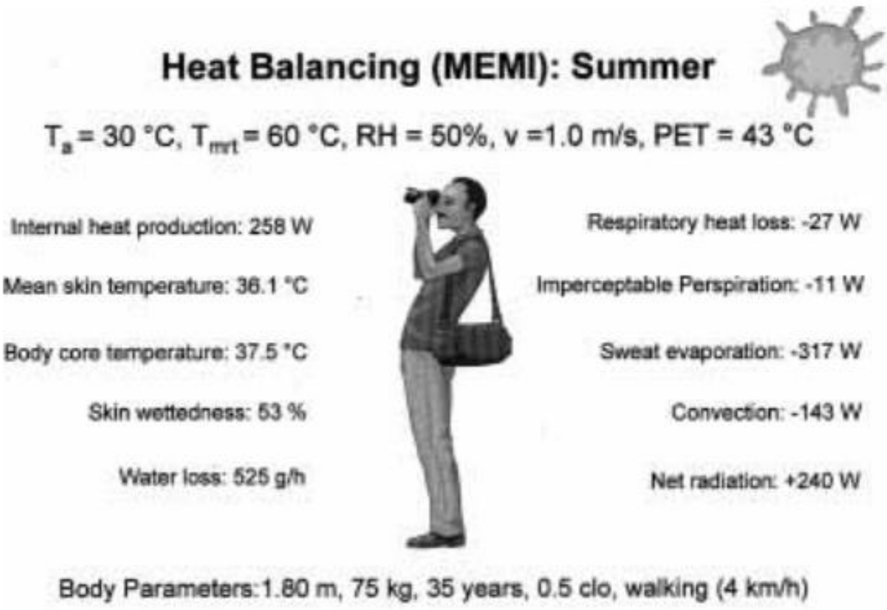


Figure 10: Sample heat-balance calculation with the Munich energy-balance model for individuals (MEMI) for warm and sunny condition (Höppe, 1999)

A big part of the NBS methodology is the PET temperature scale (Semeraro et al., 2024; Matzarakis et al., 1999). This scale (Figure 11) is good for evaluating and improving microclimate conditions in urban areas because it actually shows at which PET level you feel comfortable to uncomfortable (Semeraro et al., 2024; Matzarakis et al., 1999). The outcome of the NBS scenarios regarding their PET reduction is one of the most important things to look at for the NBS scenarios.

PET (°C)	Thermal Perception	Grade of Physiological Stress
<4	Very cold	Extreme cold stress
4–8	Cold	Strong cold stress
8–13	Cool	Moderate cold stress
13–18	Slightly cool	Slight cold stress
18–23	Comfortable	No thermal stress
23–29	Slightly warm	Slight heat stress
29–35	Warm	Moderate heat stress
35–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

Figure 11: Scale of PET (Semeraro et al., 2024; Matzarakis et al., 1999)

2.10 Framework usage

The Ecosystem Approach and Ecosystem Based Adaptation within the NBS framework is implemented that are guided by the NBS principles of providing multiple benefits, context sensitivity, ensuring equity, and addressing root causes. Across three NBS design scenarios one main outcome (PET) and several indicators are used and compared and those indicators are grouped into three co-benefit categories: environmental co-benefits, social co-benefits and economic co-benefits. Regarding the environmental co-benefits these indicators are air temperature, CO_2 uptake and for rainwater indicator the added bioretention surface area. For the social co-benefits as indicator it is added vegetation and for economic co-benefits it is costs (implementation and maintenance) of the NBS implementation, which are treated in the trade-offs. Each scenario is evaluated by both the outputs of the indicators and the four trade-offs (implementation and maintenance cost, ground space, impacts on access and parking, visibility/perceived safety), the NBS types were selected in a way that they bring four ecosystem services with their implementation (regulating ecosystem services, provisioning ecosystem services, cultural ecosystem services and habitat services) and that fit within the street profile of the neighborhood.

2.11 Research for Design

Research for Design (RfD) is a research method about gathering all the knowledge you need before starting creating a design-based solution for an issue or project (van den Brink et al., 2017). It is mostly used in landscape architecture practice and with this method you need to take your time to really understand a place's context, you need to understand the limits you have to work within, and the opportunities you might encounter (van den Brink et al., 2017; Nijhuis & de Vries, 2020). You look at the bigger picture first instead of using design itself as a way to experiment (e.g. compared to the Research Through Design process) (van den Brink et al., 2017; Nijhuis & de Vries, 2020). By using RfD the research works as a foundation to create an optimal outcome (van den Brink et al., 2017). It sets the stage for better and more thoughtful input for making decisions during the design phase of the research done (van den Brink et al., 2017).

3. Methodology

3.1 Research design & implementation

The RfD method is used at the beginning of the process as a way to set up and shape the design ideas of the NBS scenarios that will later get tested with simulations. The first research you do is going through scientific articles and papers to figure out what actually matters when it comes to cooling cities down and which types of NBS could help with increasing bioretention area for rain issues and sequestrate CO2 and what their trade-offs are. I also looked at online maps provided that showed things like where people are more (socially) vulnerable to heat, how much green space there is (public green), which areas are mostly covered in paved surfaces, the Urban Heat Island effect and where there is a lot of water nuisance regarding rain water not getting properly processed after a rainwater downpour to choose an area to analyze the microclimate of and design the NBS scenarios for. By doing the literature research and analyzing the baseline scenario of the neighborhood it helps me decide which NBS interventions make the most sense to try out in this specific neighborhood. The literature background study is the basis for the simulation-based design tests. It tells what to test regarding performance but also how to interpret the results, like using PET to see how much cooler it felt and checking CO2 sequestration and added bioretention surface area as indicators. So the RfD is woven right into the 'preparatory' phase and forms how the whole NBS design testing process is thought out in here.

The theoretical context needs to be reflected within the research process with the use of theoretical concepts and the main theoretical concept is the 'NBS approach' to adapt to climate change. Within the NBS approach the ecosystem services and co-benefits/multifunctionality approach is made use of as input and guidance for the NBS scenarios. There is quantitative microclimate modeling methods (GIS and ENVI-met) and urban microclimate science via thermal comfort models. Trade-offs of the NBS implementation scenarios will be discussed. These concepts and approaches are the foundation for the development of the NBS scenarios, simulation-based assessment of the NBS scenarios and the testing of NBS scenarios and the analysis of the NBS scenarios.

The workflow consists of the following steps (Figure 12):

Step 1→ Gathering and preparing data

Multiple data sources are an input for the ENVI-met 3D model of the neighborhood where the NBS scenario testing will be done. Weather data from the local weatherstation D2231 is used for model validation. The weather station is from the Amsterdam Atmospheric Monitoring Supersite (AAMS) program and that is a program done by the AMS Institute and WUR (AMS-Institute, 2016). The Schiphol weather station for meteorological data is used for modeling the meteorological conditions of the neighborhood (temperature and relative humidity). Data of the urban geometry from PDOK and Amsterdam Maps (building materials, building heights) will be used and put it into QGIS for the QGIS to ENVI-met plugin. Then land cover data of built-up spaces and green spaces will be implemented and analyzed for microclimate analysis and biophysical feature analysis. You get these datasets from the websites of PDOK, Google Maps and Amsterdam Maps (municipality data of Amsterdam). High temperature hotspots and microclimate fluctuations will be spatially mapped in the neighborhood via the QGIS to ENVI-met plugin for the simulation of baseline weather conditions on July 25, 2019. 25 July, 2019 was selected as the day because it was the hottest recorded day ever in Amsterdam and the Netherlands (Olsthoorn, 2022). GIS datasets of the land use, vegetation and urban morphology will be integrated and the GIS spatial inputs will be prepared for ENVI-met NBS scenario simulations.

Most of the spatial data used came from PDOK website and Amsterdam Maps website. From the PDOK website the pulled building outlines (BAG) and surface types (BGT) were all downloaded of the whole neighborhood and a lot of the data will be filtered out that will not be used as input layers, so only the surface layers and building layers are looked at. These input layers give an overview of the 2D neighborhood area but they did not include details like wall materials of the buildings which are important for the thermal modeling part. To work around that some assumptions will be made based on the typical building materials used in the facades of Amsterdam buildings from every time period, and also backed up with a site visit of the neighborhood to confirm the façade surfaces'material. From Amsterdam Maps website the tree types of the neighborhood and their location within the neighborhood are also input layers for the plugin. Some values have to be estimated like the height of vegetation and the trees and the moisture percentage of the soil at a certain depth because that information is not available. These estimates for sure influence how well the model will simulate for example cooling from the plants and NBS types so it is something to keep in mind when looking at the results.

Step 2→ Design prototyping and microclimate simulation

Design prototyping in Sketchup, ENVI-met and QGIS and microclimate simulation of the NBS scenarios will be done in ENVI-met and QGIS. The Timorpleinbuurt-Zuid baseline microclimate conditions will be simulated and analyzed in ENVI-met. When these baseline conditions are simulated, the air temperature and relative humidity values will be validated to see if the model closely follows the Schiphol weatherstation values. Then based on the highest average PET level at an hour of the daytime and an hour of the nighttime the street will be chosen for analysis of the NBS scenarios. Then a deeper look is done. That deeper look is done by looking into the chosen street by looking at the PET map at 18:00 and see where the painpoints are regarding heat stress, also the dimensions of the street and buildings will be looked at as input for the design of the scenarios. Based on this and literature research the three NBS scenarios will be chosen as scenarios for modeling. Before and after of the NBS scenario interventions are put in the model (visualized via Sketchup), where the air temperature and PET is calculated to assess the human thermal comfort and also other chosen environmental co-benefits are assessed. The development of NBS scenarios will be done to create three NBS intervention scenarios for the street with the highest average PET in the neighborhood.

Metrics for environmental co-benefits:

- Air quality improvement→ CO_2 sequestration (mg/m³)
- Stormwater management→ Added bioretention surface area (m2)

Step 3→ Data analysis & interpretation

The most important indicator will be the quantification of the PET (°C) reduction caused by the NBS scenarios using the BIO-met tool within ENVI-met. Analysis by comparison is then done before and after the implementation of NBS→ Air temperature (°C), PET (°C) levels and co-benefits. Comparative evaluation is done across three NBS scenarios using ENVI-met simulation results.

Metrics for social & well-being co-benefits assessment (GIS):

- Increase in vegetated area (m²)

Trade-offs are:

- Implementation and maintenance cost (€/m²/year)
- Ground space requirement (m²)
- Impact on access/use
- Added vegetation area (m²)
- Effects of the vegetation on perceived safety

Datasets that are used in the thesis (see Appendix):

- GIS data→ PDOK and Amsterdam Maps datasets
- Climate data→ Schiphol weather station and the local weather station in the neighborhood (D2231)
- Microclimate simulation results→ ENVI-met outputs

The effectiveness of NBS scenarios will be assessed by comparative analysis and simulation-based assessment between the scenarios itself. Simulations of ENVI-met before and after are conducted, evaluate variations in temperature, PET and other co-benefits. BIO-met's thermal comfort analysis will be used to identify thermal comfort improvements, a comparison of PET before and after NBS implementation will be made. Scenario-based comparisons will be analyzed by the various NBS scenarios to find the best option for improving the microclimate and co-benefits provision. The results are visualized with QGIS maps, ENVI met visualizations of PET cooling and reduction effects.

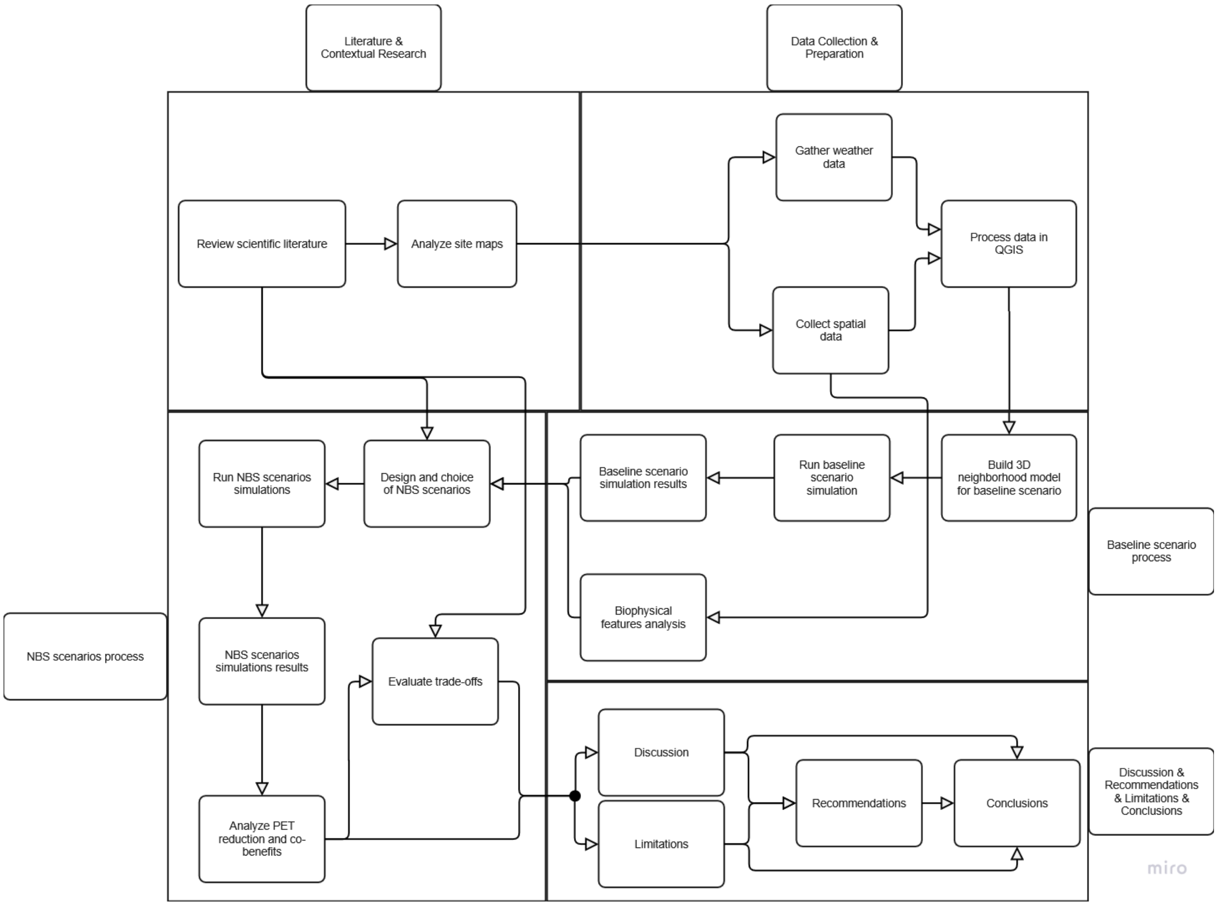


Figure 12: Methodology workflow

3.2 Study area

The Timorpleinbuurt-Zuid neighborhood in Amsterdam was chosen as the area to model the impact of NBS on the microclimate because it has a mix of microclimate challenges, environmental challenges, social challenges and infrastructural challenges explained in sub-chapter 3.2.1 up to and including sub-chapter 3.2.5. There are a lot of issues spatially, environmentally and socially which make it a good place to test the NBS and their multiple benefits.

3.2.1 Social vulnerability to stress

The “Sociale Kwetsbaarheid Hitte” (social vulnerability to heat) map shows that Timorpleinbuurt-Zuid is very vulnerable to heat (RIVM, 2023) (Figure 13). That is mostly so because many people there have lower incomes comparatively and a good part of the population is classified as elderly comparatively (RIVM, 2023). Both of these groups are more at risk when extreme heat takes place so they are more likely to suffer from (serious) health problems (RIVM, 2023).

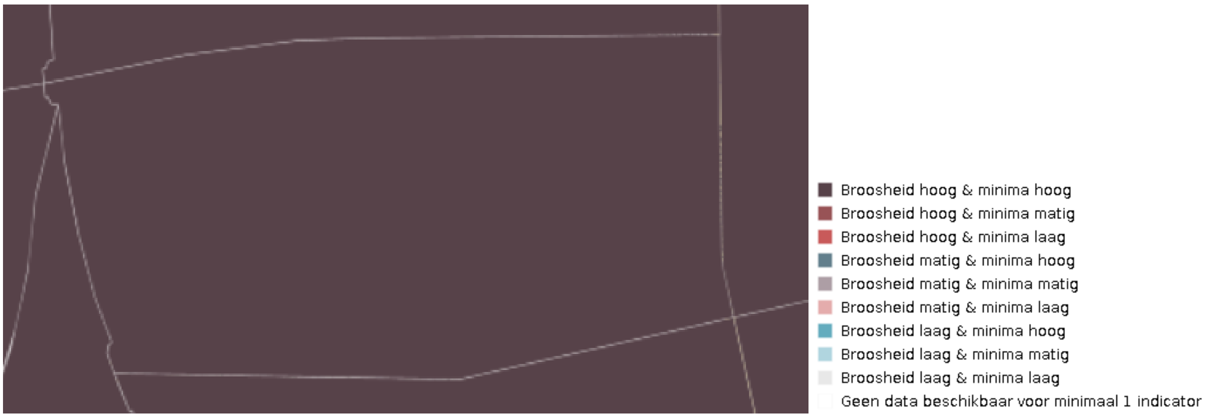


Figure 13: Social vulnerability to stress (RIVM, 2023)

Dealing with heat in neighborhoods like this is not just about temperature reduction but it is also about fairness with the way some socially vulnerable neighborhoods suffer more from heat then other neighborhoods. Kabisch et al. (2022) and Bulkeley et al. (2023) say that green spaces like trees, parks, and gardens need to be shared fairly across the city so everyone would have access, very much so for people who are more at risk.

3.2.2 Low public green space coverage

Plants and trees help cool cities down (Kabisch et al., 2016). They can reduce extreme heat in small areas by providing shade and releasing moisture into the air (Calfapietra & European Commission, 2020). But according to the "Groen per buurt kaart" (green space per neighborhood map, Figure 14) and the "Groen binnen openbare ruimte kaart" (amount of green space inside the public space map, Figure 15) there isn't much public green space in Timorpleinbuurt-Zuid, less than 20%, and only 10-20% of the total area of the neighborhood has green space (Cobra Groeninzicht, 2021). This low amount of greenery makes the area even hotter because there's nothing to reduce the heat that builds up in the paved surfaces and the built-up places (Perini & Magliocco, 2014).

Figure 14: Amount of green space per neighborhood (Cobra Groeninzicht, 2021)

Figure 15: Amount of green space in public space

The municipality of Amsterdam (2021b) says that in the small crowded neighborhoods green space has to do more than just look 'nice'. They say that it needs to cool the area, but also support local wildlife and improve how the neighborhood feels (Gemeente Amsterdam, 2021b). Somarakis et al. (2019) says that green spaces in cities should work in multiple ways at once when there's not much room to begin with.

3.2.3 Impervious surface coverage

The "Grijs per buurt kaart" (unpaved surfaces map, Figure 16) shows that more than 80% of Timorpleinbuurt-Zuid is covered by hard surfaces (Cobra Groeninzicht, 2021). These hard surfaces are roads, rooftops, and pavements. These impervious surfaces do not let water go into the soil so rain runs does not have much space to infiltrate, and during the day these surfaces take up heat and stay hot, making the area even warmer (Patel et al., 2025; Croce & Vettorato, 2021).

Figure 16: Impervious surface coverage per neighborhood (Cobra Groeninzicht, 2021)

Gill et al. (2007) and Choi et al. (2021) state that swapping out some of these impervious surfaces for more natural surfaces that are more absorbent regarding heat can help cool cities down and manage rainwater better. Timorpleinbuurt-Zuid has so much paved surfaces so it can be a great place to test how NBS might help fix these heat problems and water problems.

3.2.4 Urban Heat Island (UHI) effect

The UHI-effect map (Figure 17) shows that Timorpleinbuurt-Zuid is one of the hottest spots in Amsterdam (ANK, 2017). It gets seriously hot. That kind of heat is not just uncomfortable but it can be dangerous for people's health (RIVM, 2023). The extreme UHI-effect in this neighborhood make it clear that action is needed so trying with NBS scenarios could bring a more pleasant environment in a place that is so vulnerable to heat.

Figure 17: UHI-effect neighborhood (ANK, 2017)

3.2.5 Water nuisance

In Amsterdam's "Wateroverlastkaart" (water nuisance map, Figure 18), several streets in the Timorpleinbuurt-Zuid area (Javastraat, Balistraat, Eerste Atjehstraat, Tweede Atjehstraat and Insulindeweg), are marked as "extremely urgent" when it comes to water nuisance, with Molukkenstraat being "very urgent" and with the highest risk being Javastraat and the Tweede Atjehstraat (Gemeente Amsterdam, n.d., a). The streets are very vulnerable to flooding because of rain and because of poor drainage and a lot of impermeable surfaces (Gemeente Amsterdam, n.d., a). Both homes and businesses there often suffer from water damage (Gemeente Amsterdam, n.d., a). The municipality has shown in red that this neighborhood is a big priority for climate adaptation to excessive rainwater.

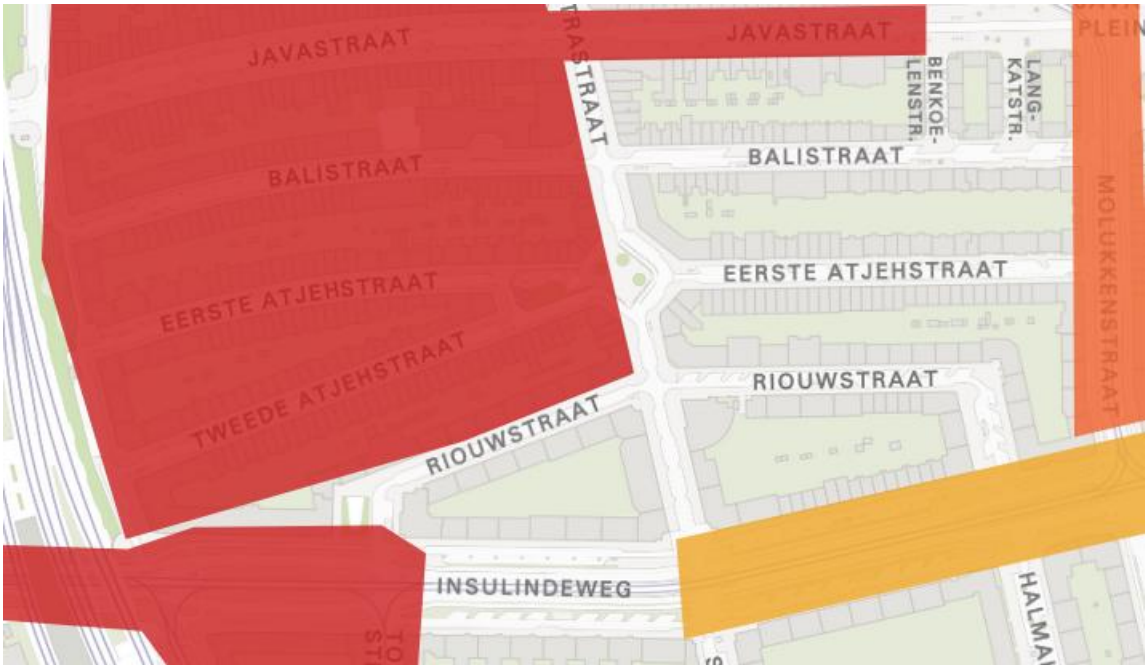


Figure 18: Rainwater nuisance (Gemeente Amsterdam, n.d., a)

The Gemeente Amsterdam (2021b) say that green infrastructure is the most important for reducing surface water buildup in the city which is is also stated by Susca (2021) and Choi et al. (2021) who say that NBS helps manage stormwater and also improve local climate conditions. That's why this neighborhood is a great case study for exploring how NBS can reduce both rainwater flooding and heat in cities.

3.2.6 Location

The location of the study area is in the city of Amsterdam, The Netherlands. More specifically it is a neighborhood located within the Amsterdam-Oost district (Figure 19).

Figure 19: Location Timorpleinbuurt-Zuid neighborhood

The local weatherstation D2231 is located within the upper right corner of the Timorpleinbuurt-Zuid neighborhood on the intersection of the Balistraat and Benkoelenstraat (Figure 20).

Figure 20: Location local weather station D2231

3.2.7 Microclimate conditions

Microclimate conditions are the specific atmospheric features, e.g. temperature, humidity etc. that are present in urban spaces like individual streets or neighborhoods and are directly shaped by urban form, vegetation, and surface materials (Javanroodi & Nik, 2019; Perini & Magliocco, 2014).

Air temperature

Air temperature is a really important thermal condition of the air (Szagri et al., 2023). It can fluctuate in an area because of things like shade, surface albedo, and sun exposure (Szagri et al., 2023).

PET

PET is a thermal comfort index derived from human energy balance (Matzarakis et al., 1999). It represents experienced heat stress in degrees Celsius by combining air temperature, humidity, wind speed, and mean radiant temperature (Matzarakis et al., 1999; Höppe, 1999). In urban environments it is often used to determine outdoor thermal comfort (Fan et al., 2023).

Carbon level (atmospheric CO_2 concentration)

The term 'carbon level' refers to the atmospheric concentration of carbon dioxide (CO_2), which is measured in milligram per cubic meter (mg/m3) (Gratani & Varone, 2013). It is an important part in the global and urban heat balance and is an indication of the buildup of greenhouse gases (Gratani & Varone, 2013). Increasing CO_2 levels are linked to climate warming and an increased energy imbalance in cities, energy imbalance means that it traps extra heat in the urban atmosphere by letting sunlight in but making it harder for heat to escape. (IPCC, 2013).

3.2.8 Biophysical features

Biophysical features are physical and natural components of the urban environment that impact environmental processes and form local microclimate conditions of a certain urban environment (Gavsker, 2023; Hidayati et al., 2021). Examples of biophysical features are: built-up land, vegetation and water bodies (Hidayati et al., 2021). Because they influence how a city interacts with natural processes (such as heat, the water cycle and airflow), these features are important to studies of urban ecology and climate (Hidayati et al., 2021; Gavsker, 2023).

Vegetation type and density

The classification (trees, bushes, grass, etc.) and spatial coverage of greenery within an area are referred to as vegetation type and density (Figure 21 and Figure 22 show the ones in the Timorpleinbuurt-Zuid neighborhood) (Hidayati et al., 2021). Through evapotranspiration and shadowing, these elements affect local cooling while influencing surface temperatures and air quality (Bowler et al., 2010; Hidayati et al., 2021). Stronger microclimate regulation is typically the outcome of denser vegetation (Wang et al., 2023; Sun et al., 2024).

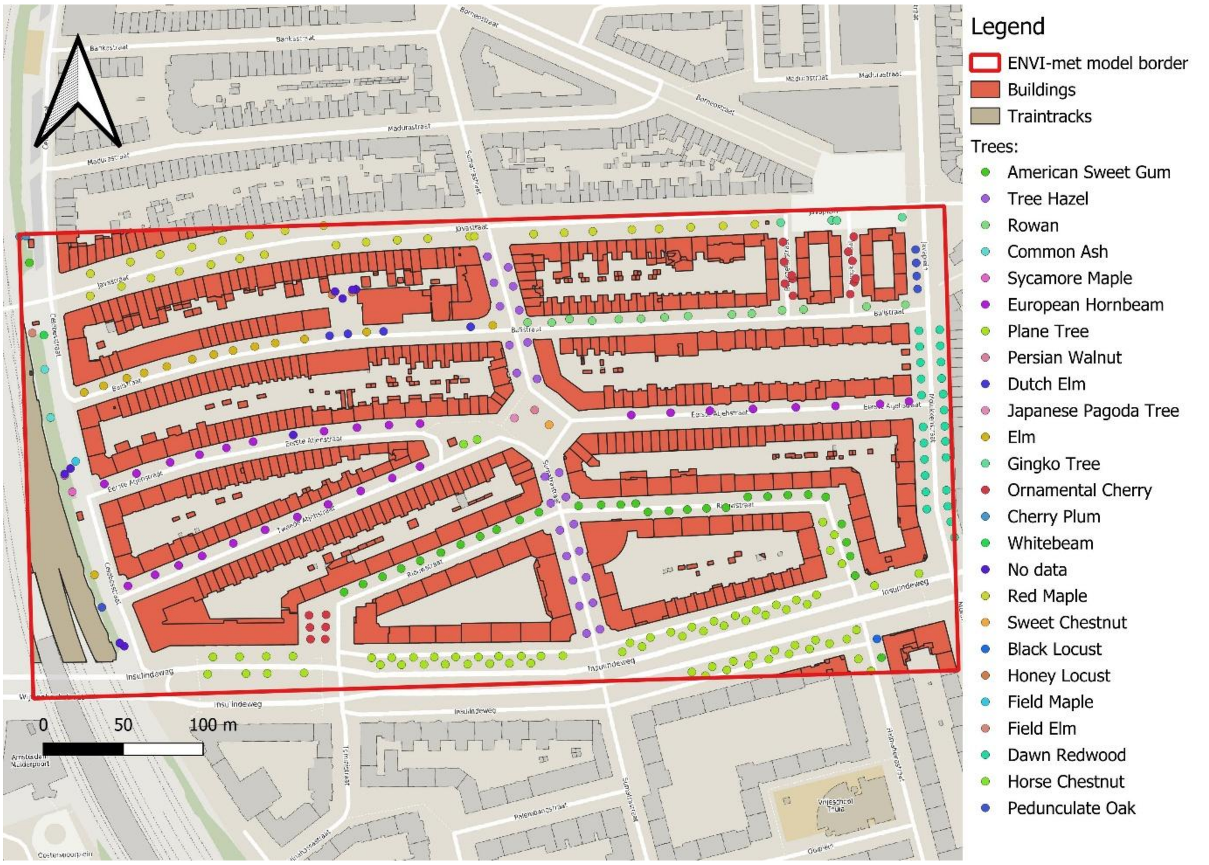


Figure 21: Tree types and distribution in the Timorpleinbuurt-Zuid neighborhood

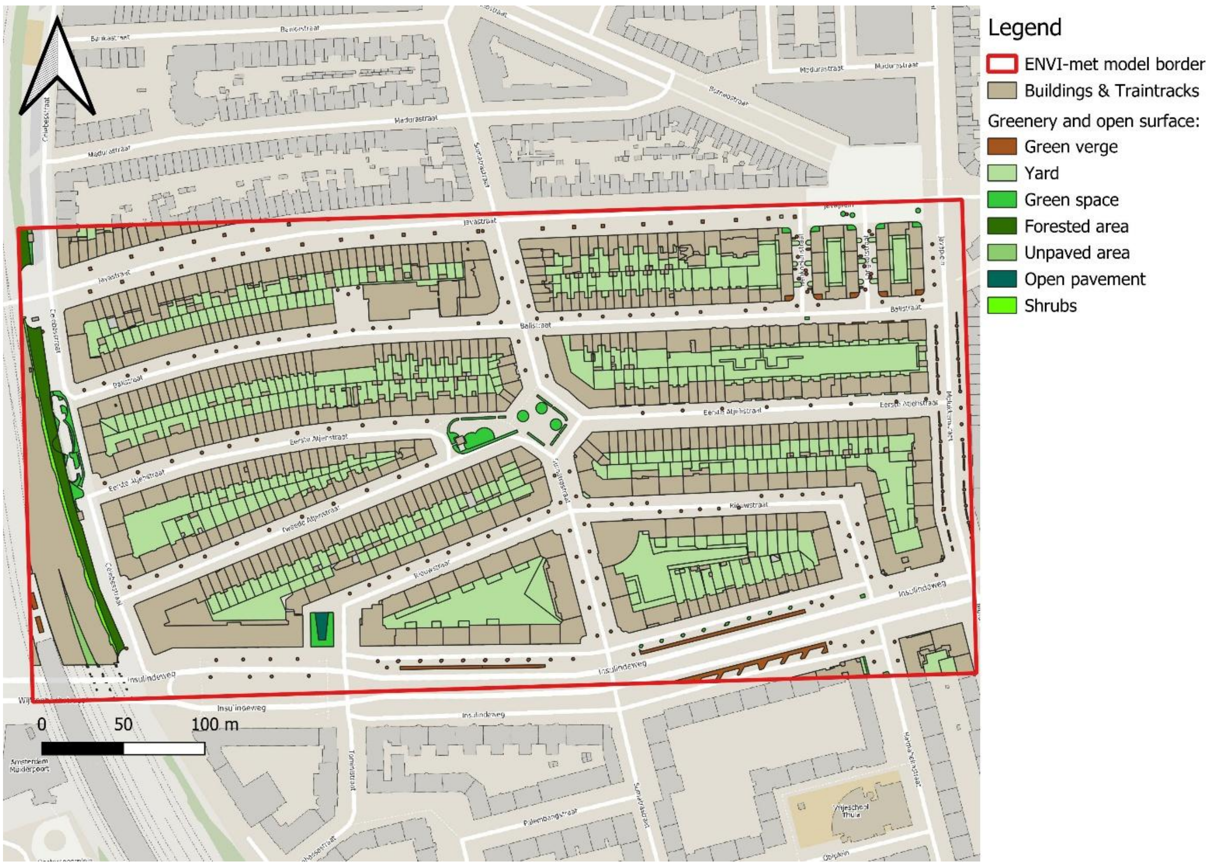


Figure 22: Green space and unpaved areas in the Timorpleinbuurt-Zuid neighborhood

Land cover classification

Land cover classification is about the surface characteristics e.g. built-up areas, vegetation etc. (Figure 23 shows the land cover of the neighborhood) (Patel et al., 2025). It has a notable impact on evapotranspiration potential, heat absorption and surface albedo, all of which influence the local microclimate (Kamal et al., 2021; Patel et al., 2025).

Figure 23: Surface coverage in the Timorpleinbuurt-Zuid neighborhood

Surface permeability

Surface permeability is the ability of urban surfaces e.g. soil, pavement, or vegetation cover, to make it possible for water to flow through it(Croce & Vettorato, 2021). The process via which water flows through these permeable surfaces is known as (storm)water infiltration (Croce & Vettorato, 2021). They determine the efficiency of rainwater absorption into the subsurface, which lowers surface runoff and helps cool cities through evapotranspiration and soil moisture (Gill et al., 2007). In urban regions the low permeability decreases the possibility of natural cooling and raises the risk of flooding (Gill et al., 2007).

Surface materials

The horizontal surfaces of cities are made of surface materials, such as permeable pavement, concrete, asphalt etc. (Croce & Vettorato, 2021). These materials' thermal characteristics (albedo, emissivity, and heat capacity etc.) have a great effect on how heat is absorbed, stored, and released (Croce & Vettorato, 2021).

Impervious surface coverage

Impervious surface coverage refers to how much of the land is covered by materials like roads, sidewalks and parking lots etc. that don't let water infiltrate into the ground (Patel et al., 2025). These surfaces limit evapotranspiration and increase runoff, which means less natural cooling so that they trap more heat and can affect the local microclimate a lot (Gill et al., 2007; Croce & Vettorato, 2021; Hidayati et al., 2021).

Building façade characteristics

Building façade characteristics include things like the material, color, texture, and reflectivity of a building's exterior (Figure 24, building year decides the façade coverage) (Santamouris, 2014). These elements influence how much heat the façade absorbs, stores, and gives off (Ali-Toudert & Mayer, 2007; Santamouris, 2014). That heat exchange can directly affect how comfortable it feels for people walking nearby the facades (Ali-Toudert & Mayer, 2007). When façades absorb a lot of heat, they can make street-level areas even hotter (Santamouris, 2014).

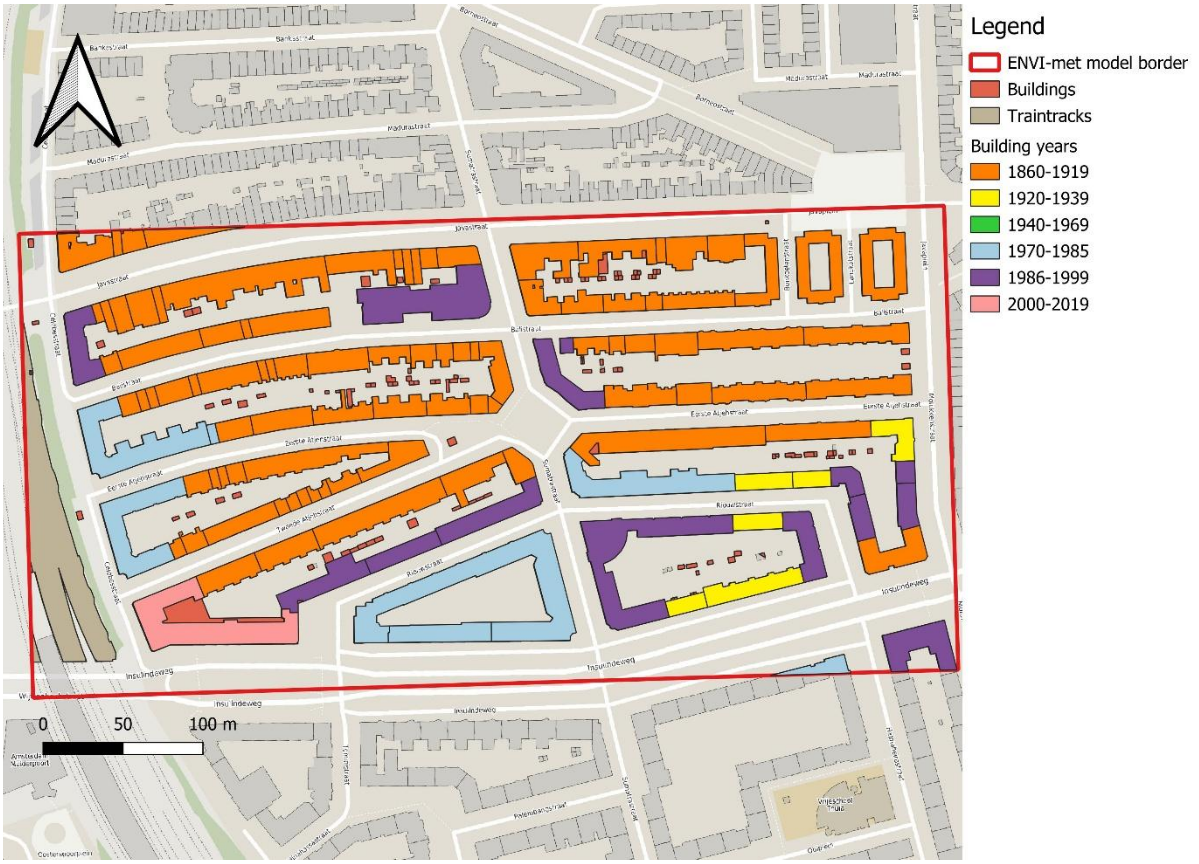


Figure 24: Building types in the Timorpleinbuurt-Zuid neighborhood

3.2.9 Individual streets

In this part the biophysical features of each individual street in the neighborhood are looked at. It is written out here but presented as an overview in Table 1 in the Appendix.

Celebesstraat

Area is shown in Figure 25.

Biophysical features

With a variety of street trees and access to the neighborhood's largest green area (not accessible however, on an elevated slope adjacent to the train tracks), Celebesstraat has a good amount of greenery. The street's tree cover isn't particularly dense.

The land cover in Celebesstraat is diverse. Brick, sand, lighter pavements, vegetated soil and smaller vegetated strips along the sidewalks are part of the land cover.

There is some surface permeability made by tree pits, vegetated areas beside the road, and the playground. The permeability is higher than usual for the area.

There is a good amount of impermeable surface cover in Celebesstraat. A lower impervious ratio results from the street's narrow profile, tree beds, and adjacent green space.

The majority of the buildings in the Celebesstraat are composed of brick (reinforced and aerated brick).

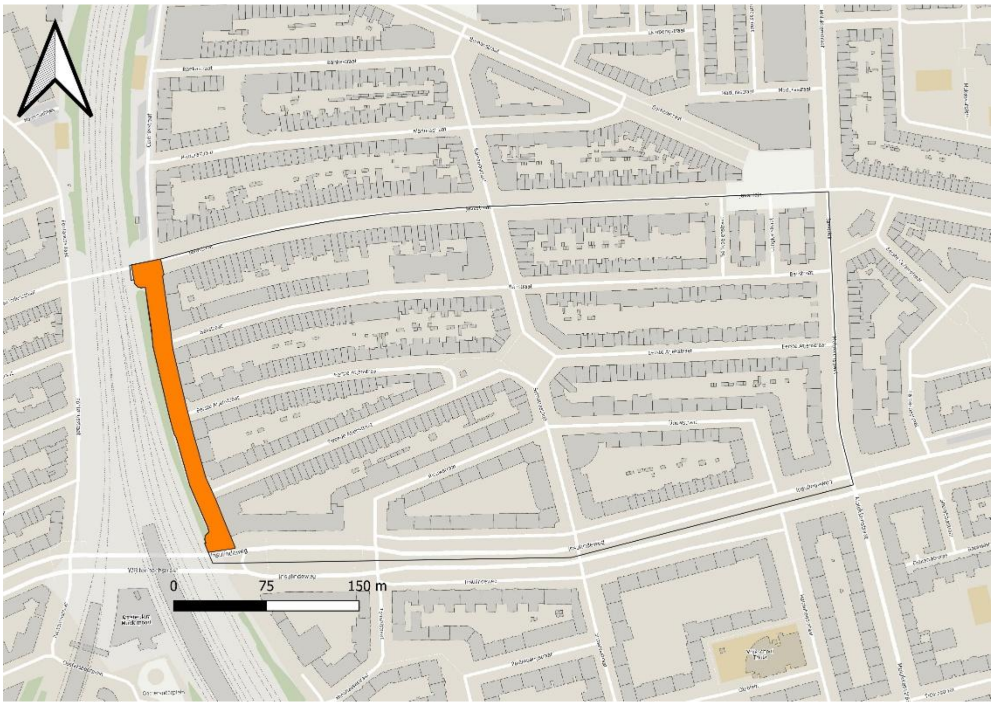


Figure 25: Celebesstraat

Riouwstraat

Area is shown in Figure 26.

Biophysical features

Riouwstraat has an average level of vegetation, with trees lining both sides of the street only in the right half of the street (the part of the street separated by the Sumatrastraat). The density isn't very high.

The land cover in Riouwstraat includes a combination of paved surfaces (light concrete tiles and bricks, red bricks), some really small open surface areas and really small residential green verges.

Limited water infiltration is made possible by the tree pits in the street, and a tiny vegetated area on the left side of the street.

Riouwstraat is made up of a variety of materials, such as brick walkways, concrete paving, and a small asphalt area (cycling roads).

There are a low amount of permeable surfaces in the street. Only where there are tree pits are, tiny green verges and the small playground in the left half of the street near the Insulindeweg.

There are brick (reinforced) buildings in the whole street and concrete buildings (only in the upper right side of the Riouwstraat).

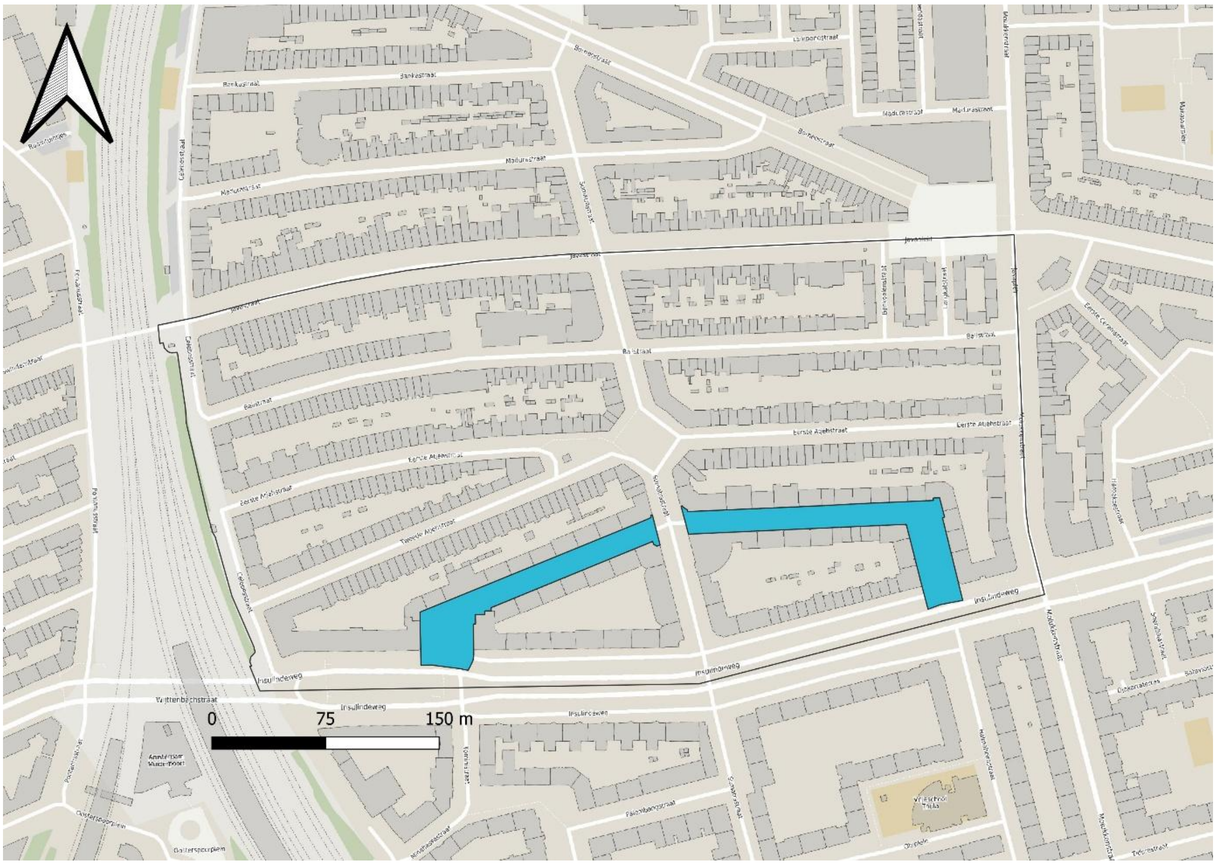


Figure 26: Riouwstraat

Sumatrastraat

Figure is shown in Figure 27.

Biophysical features

On both sidewalks on Sumatrastraat, there is a continuous row of young street trees (so relatively small tree crown coverage). There is a little square with a greater concentration of mature trees and green space near the intersection with Eerste Atjehstraat.

Tree pits, light concrete paving, and a tiny amount of asphalt make up the land cover of the Sumatrastraat. Limited water infiltration because of the tree pits and tiny green verges. The majority of the street's surface is made of light concrete pavement, red tiles and a small patch of asphalt of the bike path. This street does not have any impervious surface coverage except for the tree pits and tiny green verges. This limits the water infiltration.

The buildings that are primarily made of brick (burned and reinforced types) are in the street.

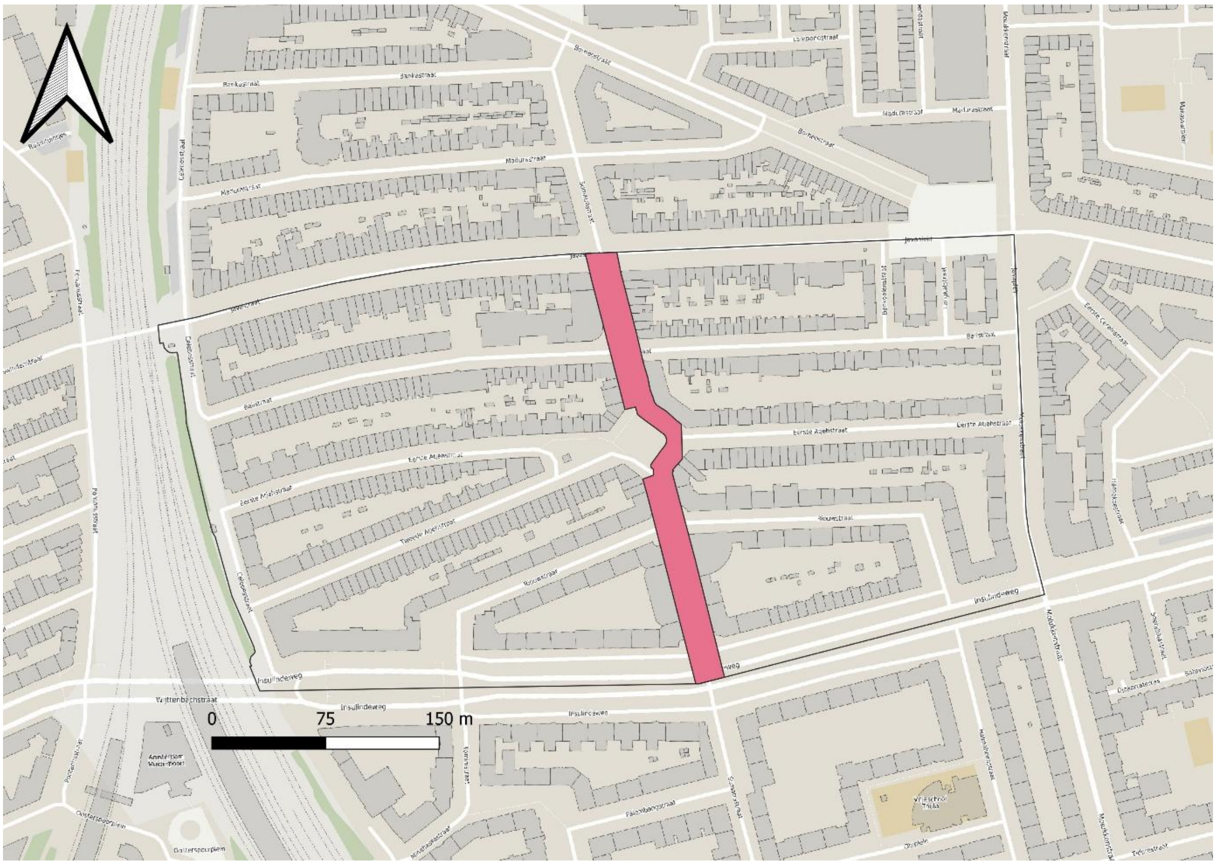


Figure 27: Sumatrastraat

Tweede Atjehstraat

Area is shown in Figure 28.

Biophysical features

Tweede Atjehstraat is lined with trees on one side of the street sidewalks, but has a consistent layer of tree crown coverage. The tree crowns lack density.

Tree pits are on the sidewalk edges and red brick paved surfaces make up the street's surface cover. The street is not very wide.

Tweede Atjehstraat has a low surface permeability. Tree pits and small green verges allow for some infiltration of rainwater, which can contribute to evaporative cooling, but the rest of the street is completely paved.

Surface materials in Tweede Atjehstraat are mostly red brick and stone.

This street does not have any impervious surface coverage except for the tree pits and green verges. This limits the water infiltration.

The entire street is bordered with brick (burned type) mid-rise residential buildings.

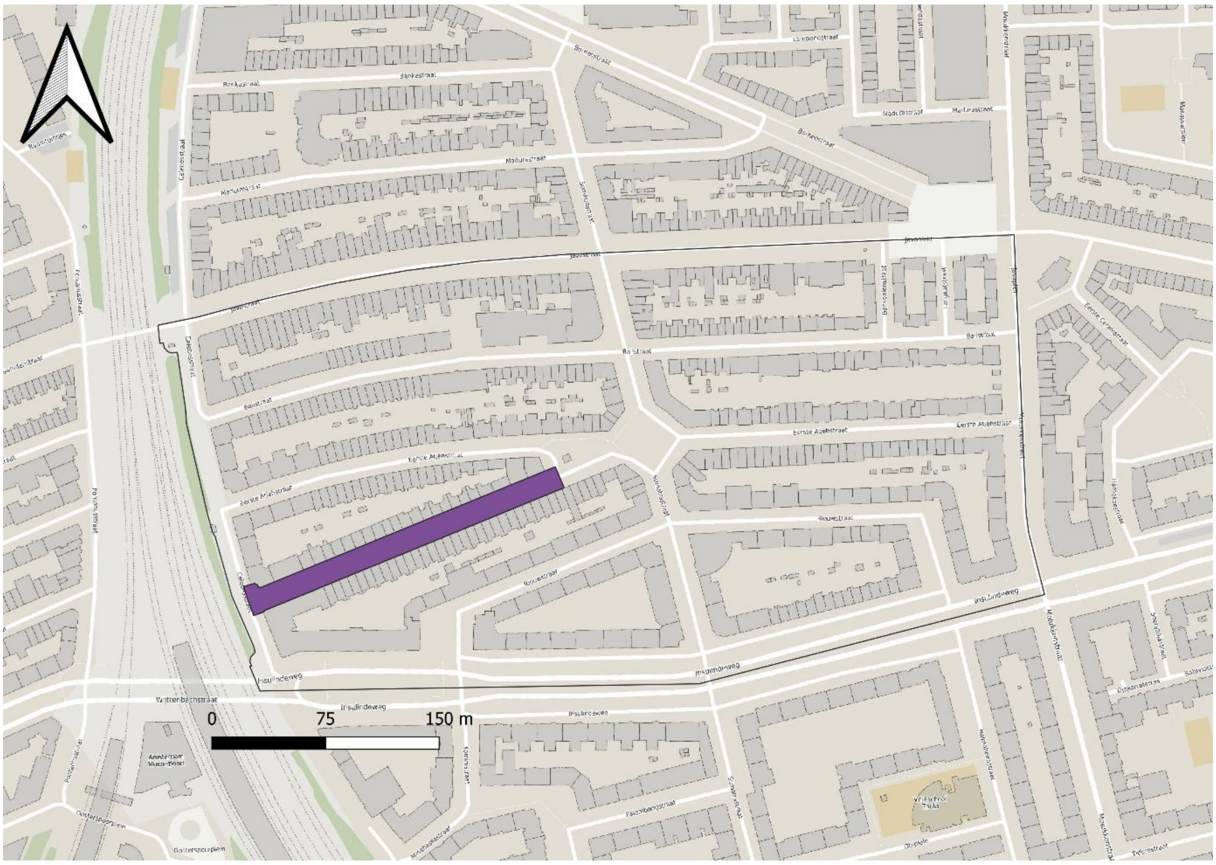


Figure 28: Tweede Atjehstraat

Eerste Atjehstraat

Area is shown in Figure 29.

Biophysical features

The trees border a large portion of Eerste Atjehstraat. The tree coverage is not evenly distributed though. There are fewer trees on the eastern part of the street than on the west side of the Sumatrastraat divide. The western part has a more continuous tree line.

Road surfaces, tree pits, tiny green verges and paved walkways make up the land cover of the Eerste Atjehstraat. The street's eastern section has light concrete tiles, while the western section is paved primarily with red brick.

The Eerste Atjehstraat's surface permeability is comparable to that of the other streets in the neighborhood, only the square is the exception because it has some more open surfaces. Small green areas and tree pits help some water infiltration, primarily at the square.

The main materials that make up the street surface are concrete tiles and red brick pavement.

Eerste Atjehstraat is mainly covered with tree pits and small green verges regarding impervious surface coverage. It has a comparatively balanced surface layout at the central square. There is a good amount of green space in the area.

Mid-rise buildings that were mostly made of brick (burned type and reinforced type) cover most of the street.

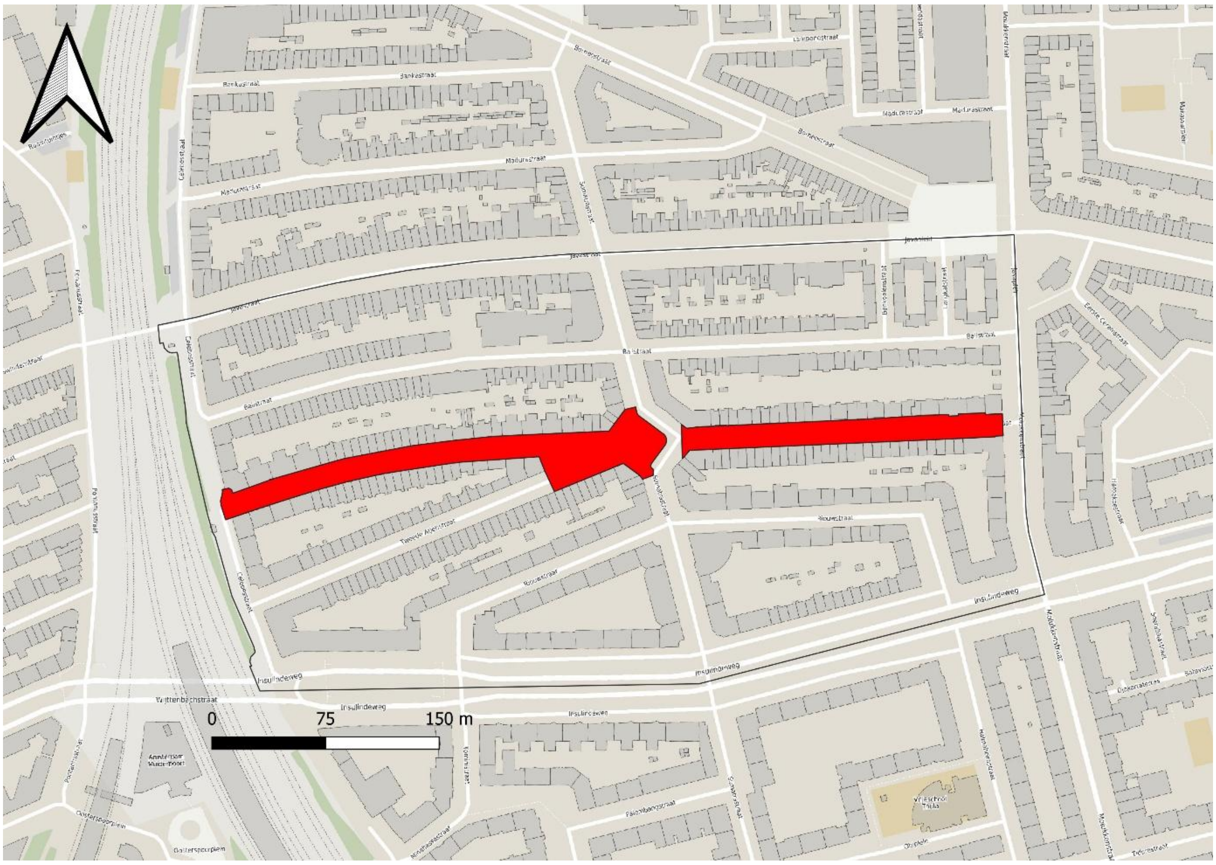


Figure 29: Eerste Atjehstraat

Balistraat

Area is shown in Figure 30.

Biophysical features

Balistraat is lined with trees. It has some larger green spaces, particularly on the right side of the street, and one of the highest tree densities in the whole neighborhood. The trees in this street also have one of the biggest tree crowns in the whole neighborhood. The neighborhood's greenest and most vegetated areas are close to the intersection of Benkoelenstraat and Langkatstraat.

Red brick paving and red concrete street tiles are the man-made surface coverage in the street. It has relatively more tree pits and green verge areas compared to other streets in the neighborhood.

The street has limited surface permeability, although higherpermeability than the other streets of this neighborhood. Small green verges and tree pits let water in.

Concrete, stone, and brick make up the majority of Balistraat's pavement.

In comparison to the other streets, this one has somewhat less impermeable surfaces. The street and sidewalks are paved. The street itself has more tree pits and thin green verges that are more abundant than in the other streets.

The houses in the Balistraat are primarily brick façades (burned type).

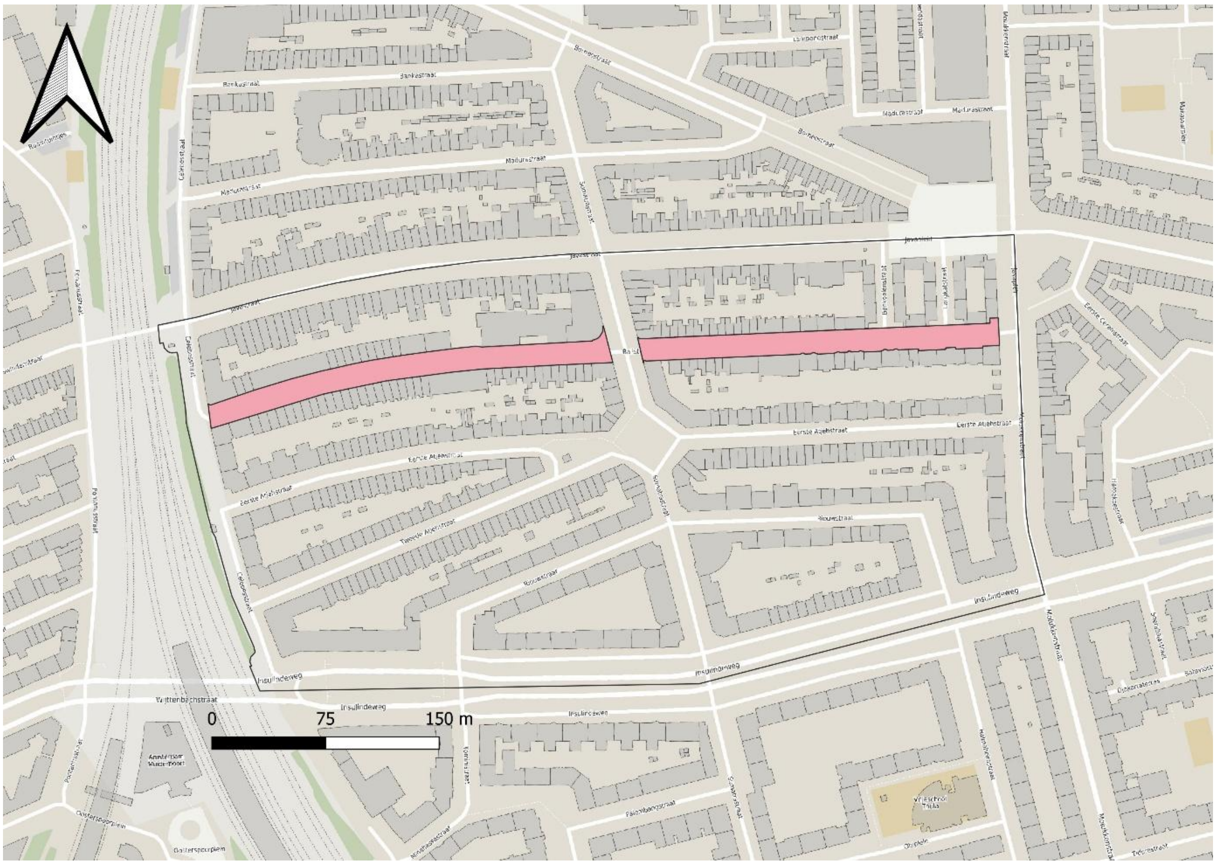


Figure 30: Balistraat

Benkoelenstraat

Area is shown in Figure 31.

Biophysical features

It is one of the neighborhood's most densely vegetated streets. It is a short and narrow street flanked by trees.

Benkoelenstraat's land cover has small green verges, vegetated parts, and red brick paving.

Benkoelenstraat has higher than average surface permeability because of the high amount of open surface area. The open surface areas, tree pits, and green strips all help rain water to seep in the soil.

Red brick tiles make up nearly all of the surface along Benkoelenstraat.

The coverage of impervious surfaces is the majority of the street. It is still quite low when compared to the other streets. The overall imperviousness is decreased as a result of the street's low width, little surface area, and vegetated open soil area.

The building facades of the Benkoelenstraat are made of brick (burned type).

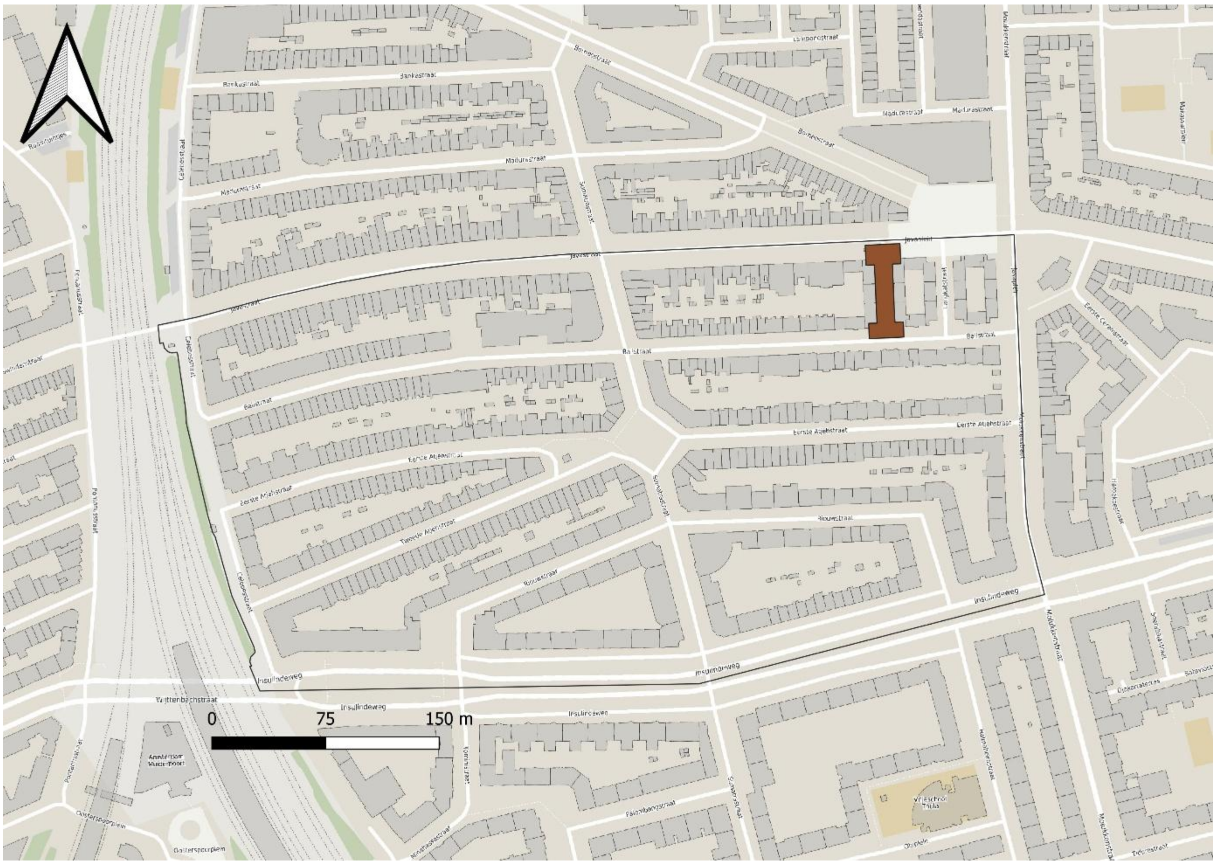


Figure 31: Benkoelenstraat

Langkatstraat

Area is shown in Figure 32.

Biophysical features

Langkatstraat has the second-highest tree density of the whole neighborhood (Benkoelenstraat has the highest). In the street the trees create an almost continuous canopy. Just like the Benkoelenstraat, there are green verges that border the street. The street has a continuous tree distribution.

Langkatstraat's land cover consists of open vegetated areas and red brick tiles.

The Langkatstraat has good surface permeability, similar to the Benkoelenstraat, which also has lots of green verges and tree pits. Rainwater can go into the soil in these places.

Red pavers and bricks make up the majority of the street surface.

In the neighborhood the Langkatstraat has one of the lowest percentages of impervious surface coverage.

The buildings along Langkatstraat are made of brick (burned type), same type of houses as the Benkoelenstraat. The streets has a small profile that creates a somewhat enclosed space.

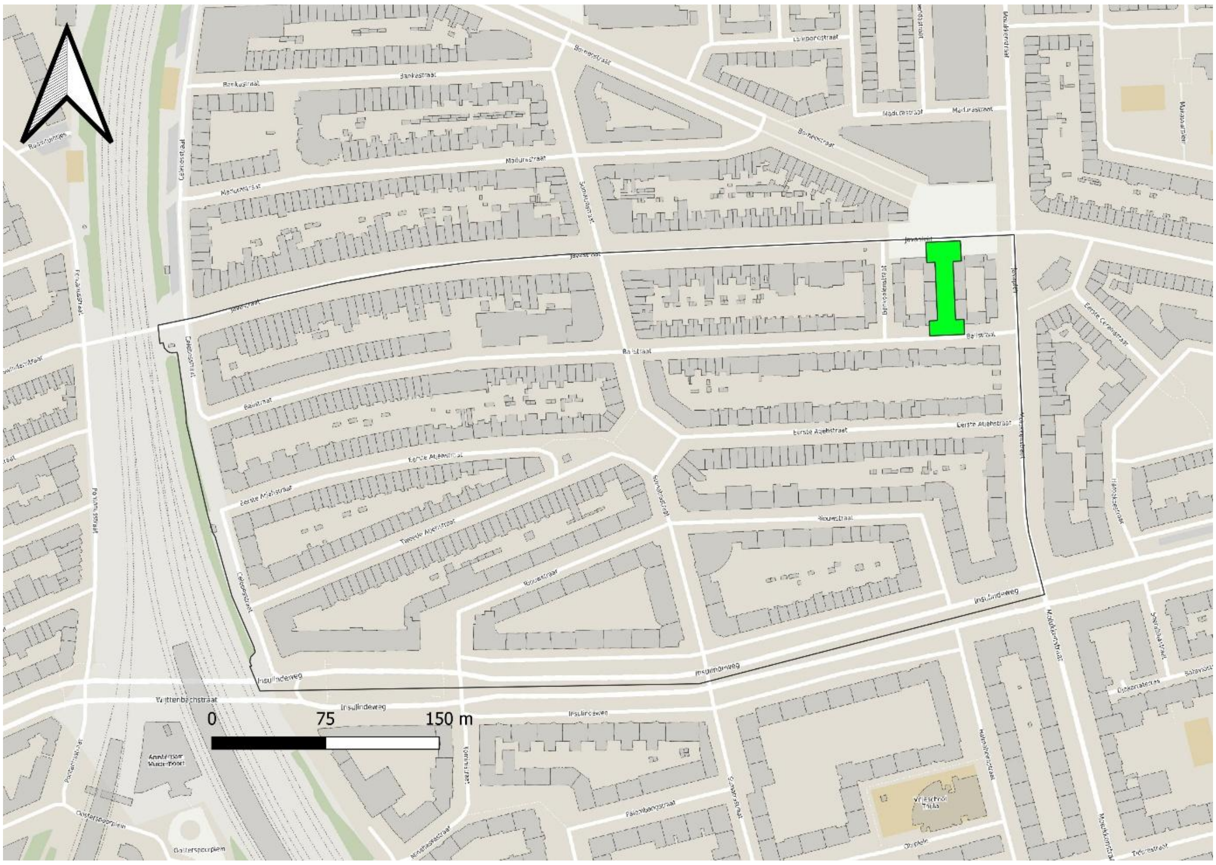


Figure 32: Langkatstraat

3.3 ENVI-met program

3.3.1 ENVI-met

The ENVI-met program is used to model the Timorpleinbuurt-Zuid neighborhood and simulate the microclimate variables (e.g. potential air temperature). This program makes it possible to measure how the build environment affects the local microclimate of the neighborhood (Barnstorf et al., 2023).

A grid size of 2x2x2 meters is selected for the 3D modeling of the neighborhood, resulting in a total of 290 grids in length, 145 grids in width, and 20 grids in height (Figure 33, Figure 67 in the Annex shows the QGIS to ENVI-met plugin). In order to give a detailed depiction of the neighborhood, the 2 x 2 x 2 meters resolution was used (so not 3 x 3 x 3 meters because the resolution is a bit undetailed to model properly and a 1 x 1 x 1 meters resolution takes too long to model). To prevent modeling instabilities a grid will be created at the edge (Barnstorf et al., 2023; ENVI-met GmbH, 2023a). In ENVI-met the building cells next to the model border should have a clearance distance of at least half the height of the tallest structure next to the boundary of the model (ENVI-met GmbH, 2023a). By doing this appropriate airflow is guaranteed (ENVI-met GmbH, 2023a). Boundary effects that can result in instability or illogical wind patterns in the simulation are then avoided (ENVI-met GmbH, 2023a).

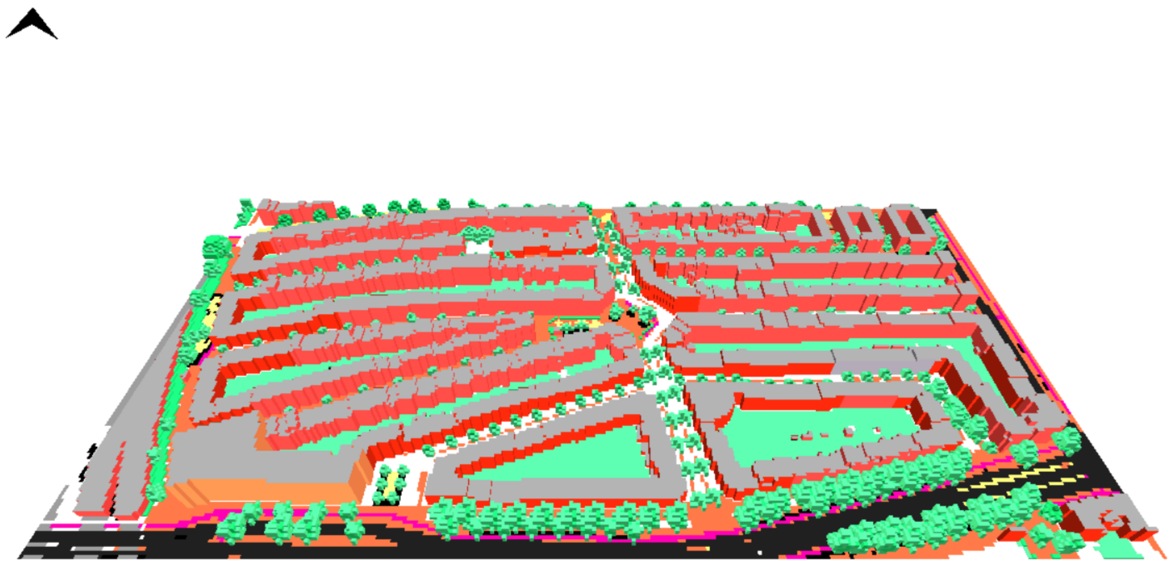


Figure 33: Timorpleinbuurt-Zuid neighborhood in ENVI-met Spaces

The soil, the atmosphere and the surface are the layers (such as different surface coverings, walls, buildings, and plants) the model of the area takes into account (Barnstorf et al., 2023). The 3D model's meteorological data includes average wind speed and direction and also the highest and lowest readings for air temperature and relative humidity (Barnstorf et al., 2023; ENVI-met GmbH, 2023a). These values will be taken from data of the Schiphol weather station on the day of 25 July 2019, the hottest recorded day ever in the Netherlands, 36.3 °C in Amsterdam (Olsthoorn, 2022).

Three NBS scenarios will be modeled. Every scenario implements one type of NBS. The NBS scenarios use the Type 3 NBS that can play a big role in improving microclimate regulation (Eggermont et al., 2015). These NBS help with stormwater management, CO2 sequestration, and urban cooling (Eggermont et al., 2015). The first scenario uses the green wall vegetation NBS type. The second scenario uses the bioswale/wade NBS type. The third scenario will use the vegetated pergola NBS type. The scenarios are different based on where NBS is used, while keeping the urban layout and man-made surfaces the same in other areas (Barnstorf et al., 2023).

The modeling materials were chosen based on visiting the study area in real life, QGIS surface layer analysis and through the use of Google Maps. The wall materials for the buildings were chosen via Google Maps and site visits. These wall materials are: Brick (burned), Brick (reinforced), Brick (aerated) and Concrete (lightweight). The surface materials were identified using QGIS surface layer analysis, Google Maps and site visits. These surface materials found are: sand, sandy loam substrate, concrete pavement light colored, concrete pavement grey, asphalt road with red coating, red stone brick road, asphalt road, asphalt with gravel, yellow stone brick road and granite pavement. The tree species were found using the Amsterdam Maps tree species date. These species in the neighborhood are: American sweet gum, tree hazel, rowan, sycamore maple, European hornbeam, London plane tree, Persian walnut, Dutch elm, Japanese pagoda tree, elm, ginkgo tree, Japanese cherry, whitebeam, red maple, sweet chestnut, honey locust, field maple, dawn redwood, horse chestnut and pedunculate oak. The vegetation found was done via site visits, Google Maps and QGIS surface layer analysis. Vegetation types found were: Grass, hedges, shrubs and trees.

The neighborhood will be presented via ENVI-met's 3D representation which is put together after combining the 2D model parameters (Barnstorf et al., 2023; ENVI-met GmbH, 2023a). ENVI-met replicates what happened on 25 July, 2019 with regards to the weather conditions using this 3D model of the Timorpleinbuurt-Zuid neighborhood and the input of meteorological data from the Schiphol weather station (Barnstorf et al., 2023; ENVI-met GmbH, 2023b). Then a street will be chosen where the PET is most severe during the hottest part of the day with the use of the BIO-met part of ENVI-met. In BIO-met a person can be simulated to walk through the street (Bruse & ENVI-met., 2014). By computing PET metric, the BIO-met module can help to look at the human thermal comfort (Barnstorf et al., 2023; Bruse & ENVI-met., 2014). A moving individual can have a defined speed, path, and timing (how fast the individual walks in certain parts of the model) (Barnstorf et al., 2023; Bruse & ENVI-met., 2014). Based on microclimate conditions such as air temperature, wind speed, relative humidity, and radiation exposure, PET readings are dynamically computed as the individual moves around (Barnstorf et al., 2023; Bruse & ENVI-met., 2014). An individual's clothes, metabolic rate, and degree of activity (e.g. walking, jogging, running or all together in certain parts of the route he walks) can also be modified to replicate real-world situations (Barnstorf et al., 2023; Bruse & ENVI-met., 2014).

The same weather conditions on 25 July, 2019 of the analysis will then also be used to model these three NBS scenarios. The possible effects of the NBS on the neighborhood study area's microclimate will be evaluated by comparing these two situations with regards to PET, air temperature and relative humidity.

I need to accurately represent the specific features of the components that make up the space (e.g. footpath, streets, buildings, greenery etc.) (ENVI-met GmbH, 2023a). This is needed for the microclimatic computer simulation of the urban environment comprises of a simplification of real scenarios (Barnstorf et al., 2023; ENVI-met GmbH, 2023a). The model is not an accurate imitation of reality because it does not replicate all of its complexity but it comes close to it (Barnstorf et al., 2023; ENVI-met GmbH, 2023a). I will then simulate interactions between NBS and the urban environment in order to research the NBS' potential of reducing the PET during 25 July, 2019 in the Timorplein-Zuid neighborhood. I will take into account the local weather data, such as wind direction and speed, air temperature, and the min. and max. relative humidity for the simulated day and using the simple forcing approach (Barnstorf et al., 2023; ENVI-met GmbH, 2023b). The program uses this data to model how the climatic parameters might behave over the course of a day (Barnstorf et al., 2023; ENVI-met GmbH, 2023b).

3.3.2 BIO-met

BIO-met is a biometeorological post-processing tool that computes PET and other human thermal comfort metrics in regards to the results of ENVI-met simulations (ENVI-met, 2024b). PET is a key indicator of thermal comfort in an outdoors environment (ENVI-met, 2024b). BIO-met integrates important meteorological characteristics such as air temperature, wind speed, humidity etc. to calculate PET values from ENVI-met findings (ENVI-met, 2024b). To correctly recreate people's thermal conditions I will set a "k-level 3" at 1.4 meters height, it is a human-relevant height level (Barnstorf et al., 2023). BIO-met then calculates PET values at each hour that day and will then focus on certain hours (one daytime hour and one nighttime hour) at of the day to analyze periods of extreme heat stress (Barnstorf et al., 2023). Verified PET results will be put against actual weather data to make sure models are reliable (Barnstorf et al., 2023).

The variable that will be looked at is 'static PET': *"Purely environmental based conditions PET"* (see Annex table: Thermal variables of the body during a walk) (ENVI-met GmbH, 2023). This will show the PET measured at each specific spot during the walk and will show the exact spots regarding high thermal stress.

3.3.3 Leonardo

There is a post-processing tool in ENVI-met called "Leonardo" which makes it possible to see and analyze simulation results (ENVI-met, 2024a). Leonardo can create spatial maps showing the air temperature, relative humidity and PET at different hours of the day during 25 July, 2019. I will then evaluate the influence of NBS scenarios on the microclimate and compare baseline and NBS scenarios by overlaying the findings. Leonardo will also be used to analyze PET and air temperature time series to investigate the daily cooling impact of the various NBS scenarios. I'll create legends and classifications to keep the data interpretation consistent and to make sure the visualizations align with the thermal comfort levels defined in Leonardo. And finally Leonardo will evaluate how NBS interventions affect thermal comfort which gives outcomes into how well they work to lower the PET level.

The whole workflow of the process within QGIS and ENVI-met is presented in Figure 34.

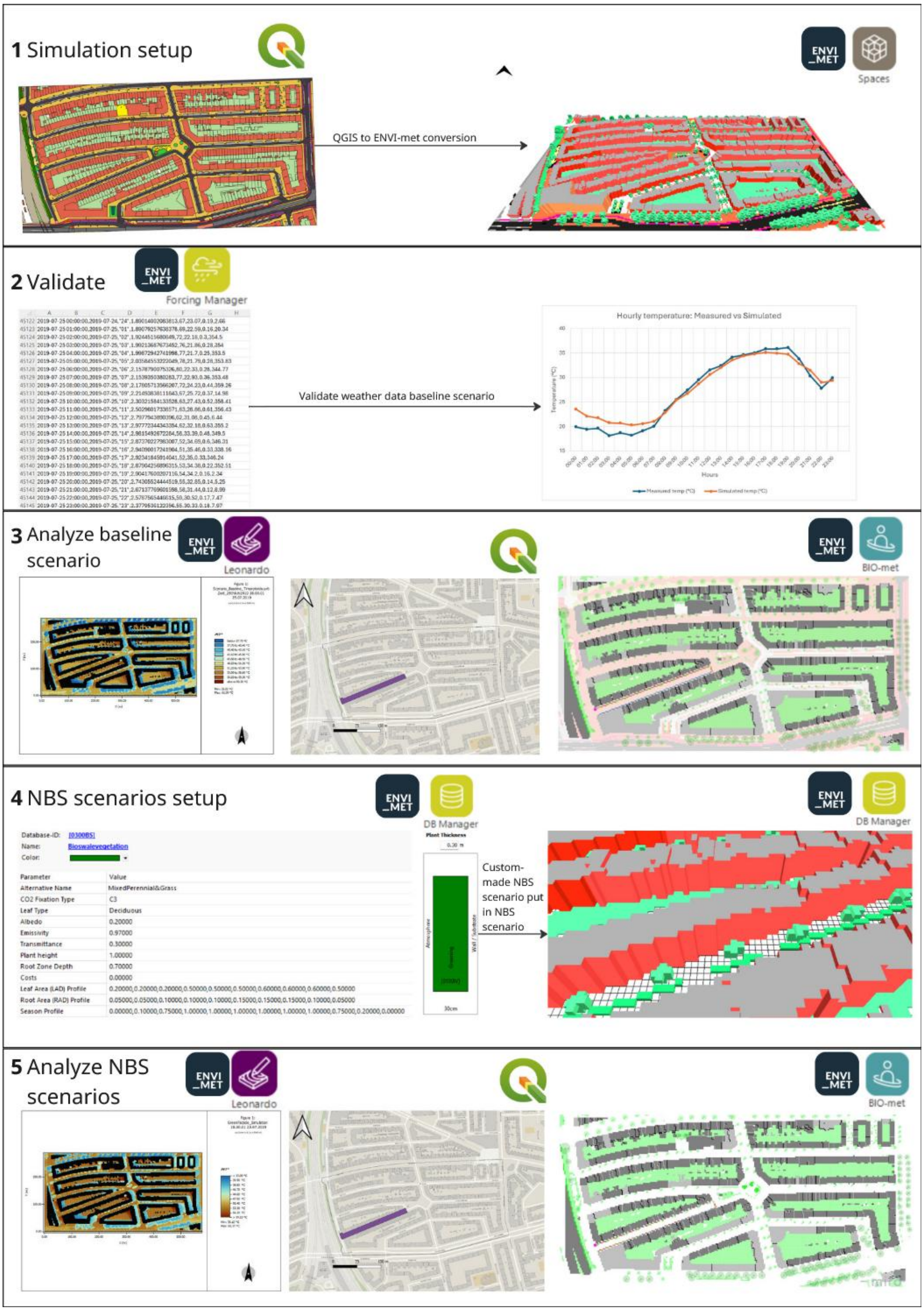


Figure 34: QGIS to ENVI-met workflow

3.4 Quantification of environmental co-benefits

3.4.1 Co-benefits quantified via ENVI-met

Temperature reduction→ By modeling changes in air temperature both before and after NBS is used.

Quantification metric: Average temperature drop (°C) of the whole Tweede Atjehstraat area after implementation of each NBS scenario and also the average temperature drop (°C) of a 2 meter bufferzone around the NBS within the street.

Carbon sequestration→ Calculating how much CO_2 is taken from the air by NBS (Martins et al., 2023).

Quantification metric: Reductions in CO_2 emissions from vegetation and CO_2 absorbed by vegetation (mg/m3) (Martins et al., 2023).

Added bioretention surface area→ Calculating how much scenario adds pervious soil to improve rainfall.

Quantification metric: Total added pervious soil as surface area in m2 (Winston et al., 2016)

3.4.2 BIO-met thermal comfort quantified

To measure the impact of NBS on human comfort, BIO-met computes these number of metrics:

Physiological Equivalent Temperature (PET)→ A thermal comfort index that translates environmental conditions into a temperature perceived by humans (Matzarakis et al., 1999).

Quantification metric: PET reduction (°C) in vegetated compared to non-vegetated areas (Matzarakis et al., 1999).

3.4.3 Bufferzone

A zone of specified size formed around the geographical elements is determined by buffer analysis (Na et al., 2024). Buffer analysis is often helpful to research the influencing area of physical objects on their surroundings (Ma et al. 2018).

I choose to calculate average values like PET within a 2-meter buffer zone around the NBS in the scenarios and compare it to the same bufferzone for the baseline scenarios. I chose this distance because the closer the area where people actually feel the most impact from these green interventions, the better (Liu et al., 2022). The strongest cooling effects from greenery are felt most strongly close to them and then drop off with distance (Liu et al., 2022). Acero et al. (2019) talk about that green walls or street plantings, give off the most meaningful thermal benefits the closer they are to the green facade. By using a narrow buffer adjacent to the NBS, I focus on those thermal benefits. It is also said that with a distance of more than three meters from the façade, thermal benefits are unlikely to be noticeable (Acero et al., 2019) So by using a small buffer it makes the outcomes of NBS effect on the microclimate more seen and also helps avoid that the strong local cooling effects blend into a larger area that averages out and then could hide these important micro-level differences (Na et al., 2024).

3.5 Statistical parameters for the model validation

3.5.1 ENVI-met model validation

Model validation needs to be done before just going through with the simulations of the NBS scenarios. Comparing any number of meteorological variables from real field data at a given time or over a period of time is called model validation (Barnstorf et al., 2023). Air temperature is often used as the main meteorological variable for validation, same goes for relative humidity (Liu et al. 2021). The accuracy of the model is evaluated by comparing the measurements of these variables to the results of the simulations (Barnstorf et al., 2023). Any number of statistical metrics that show the accuracy of the model can be drawn from this (Jamei et al. 2019; Shinzato et al. 2019; Liu et al. 2021; Lam et al. 2021; Barnstorf et al., 2023). The 'coefficient of determination R^2' and the 'Root Mean Square Error' are a few of the most used statistical metrics (Liu et al. 2021).

Only using R^2 for ENVI-met model validation could lead to misinterpretation since R^2 only evaluates general accuracy of the model (Liu et al., 2021; Willmott, 1982). The R^2 value does not confirm whether simulated and observed values align accurately and its magnitude does not always correspond to the actual differences between observed and simulated values (Liu et al., 2021; Willmott, 1982). Then using multiple statistical metrics is essential for a more complete assessment of model performance (Liu et al., 2021; Willmott, 1982).

Deviations between simulation results and field-measured values of the weather stations are frequently seen in academic studies on greenery (Liu et al., 2021). There are three primary causes for these deviations (Liu et al., 2021). One cause is that errors could be caused by flaws in the ENVI-met model itself, another issue are the differences between expected results and observed results that may result from modeling assumptions and the last one is that unsystematic errors made during experimental procedures could contribute to the deviations (Liu et al. 2021).

3.5.2 Statistical parameter - The coefficient of determination (R^2)

The coefficient of determination (R^2) is the statistical parameter that shows how well a model's predictions correlate to actual observed values (Willmott, 1982). It goes from 0 to 1, where 0 implies no correlation between the expected and actual values, and 1 represents a perfect fit, this perfect fit means that the model fully explains the variability in the observed data (Willmott, 1982). A higher R^2 value in model validation means that the simulation results closely match the measured data (Willmott, 1982).

R^2 is used to determine the extent that the simulated meteorological variables match real-world data (Liu et al. 2021), in this case for air temperature and relative humidity in ENVI-met simulations. The ENVI-met model successfully imitates temperature fluctuations in the neighborhood if the R^2 value for air temperature is high (Liu et al. 2021). In the same way, a high relative humidity R^2 means that the model correctly imitates air moisture levels (Liu et al. 2021). A lower R^2 indicates deviations, these can result from model limitations, incorrect assumptions, or unaccounted factors on the actual data (Liu et al. 2021).

3.5.3 Statistical parameter - Root Mean Square Error

The Root Mean Square Error (RMSE) is a statistical parameter for measuring the differences between simulated data and real-world data (Ayyad & Sharples, 2019). By taking the square root of the mean of squared differences, the RMSE parameter computes the average magnitude of the errors in a model's predictions (Willmott & Matsuura, 2005). Better model accuracy is shown by a lower RMSE, whilst a larger RMSE implies a larger deviation between the simulation data and real-world measured data (Willmott & Matsuura, 2005).

RMSE helps in computing the amount of errors between simulated temperatures and actual temperatures (Willmott & Matsuura, 2005) in the neighborhood when validating air temperature simulations in ENVI-met. While a high RMSE suggests possible inaccuracies, a low RMSE signifies that the ENVI-met model reliably predicts the temperature trends of the neighborhood (Willmott & Matsuura, 2005). Regarding relative humidity, RMSE assesses how accurately simulated humidity levels match real-world data for relative humidity (Willmott & Matsuura, 2005). High RMSE values for both meteorological variables point to potential errors in the model input, assumptions, or microclimate conditions not accounted for in the simulation (Liu et al., 2021).

3.6 ENVI-met model validation

The simulated data in ENVI-met did not provide an analysis option at 4 meters height (which is the height of the weatherstation), but it did provide that option of seeing the other values which the closest ones were at 3 meters and 5 meters height. So the validation of the model had to be done via linear interpolation.

A method for estimating values between two known points is "linear interpolation" and it is helpful for when you need to determine a value that lies between two measurements (Burden & Faires, 2010). Linear interpolation method can predict the temperature at 4 meters if you know the temperature at 3 and 5 meters height. Creating a straight line between the two known values is how linear interpolation works (Burden & Faires, 2010). Linear interpolation presumes that the change between two data points follows a straight-line pattern (Burden & Faires, 2010). It provides a simple method to predict or calculate values that fall between known measurements and it is assumed that there is a gradual and smooth transition between the points (Burden & Faires, 2010). This is often applied to data such as temperature and humidity in environmental research (Fassò et al., 2020). Linear interpolation is used pretty often in meteorology because it is simple and practical (Fassò et al., 2020). The only thing is that it does not always capture complex changes in atmospheric data (Fassò et al., 2020). Despite this it is still widely used to fill gaps in observations (Fassò et al., 2020). The values of air temperature and relative humidity at 4 meters of the local weatherstation D2231 were found by interpolation and by doing the interpolation it made sure that the accuracy of the model could be verified by comparing the results with data from the local weather station (D2231).

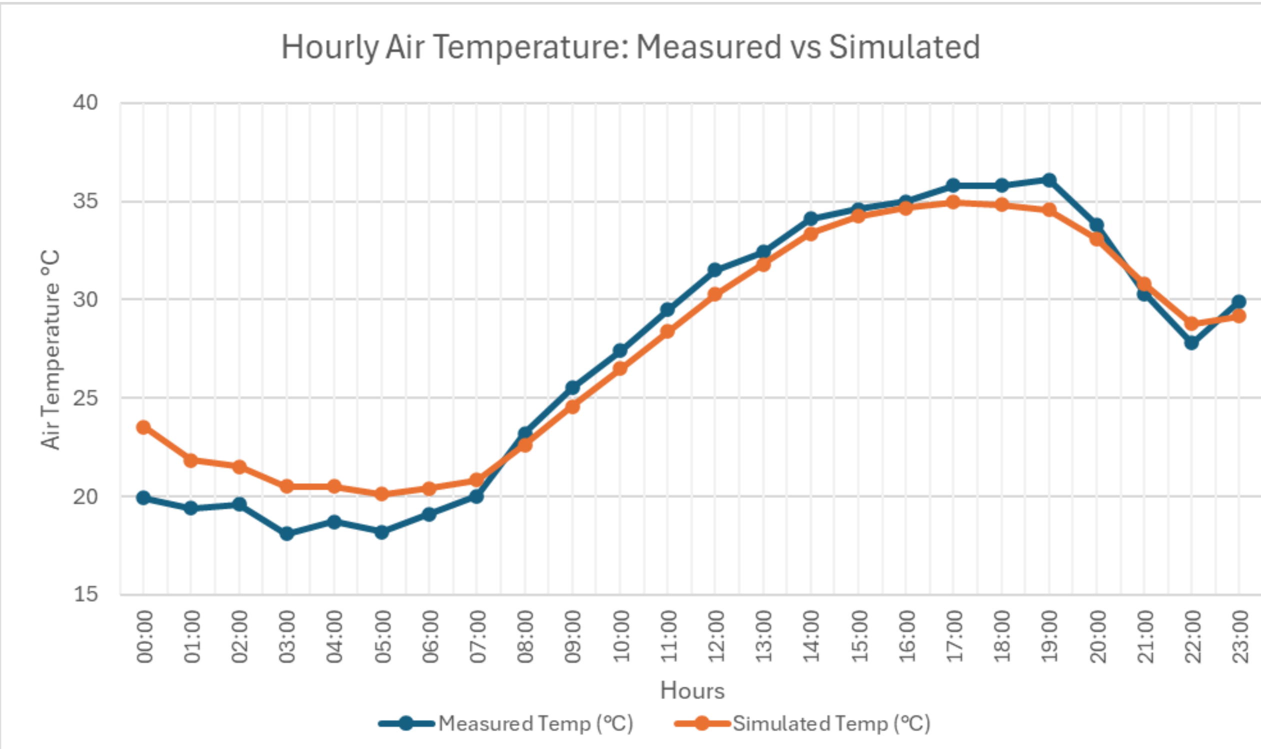
3.6.1 Temperature validation

The coefficient of determination (R^2) has an outcome of 0,977658244. So there is a strong correlation between the linear interpolated simulated ENVI-met temperature data and the real measured data on 25 July 2019. The model seems to be good at simulating air temperature by looking at the high R^2 value and is in line with other studies that showed ENVI-met to be very accurate at predicting temperature in urban environments with clearly defined surface and radiation exchanges (Ayyad & Sharples, 2019; Liu et al., 2021).

Root Mean Square Error (RMSE) outcome is 1,44 °C, the average deviation between the linear interpolated simulated ENVI-met temperature data and the real measured data on 25 July 2019.

The model overestimated the morning temperature and late evening temperature (Graph 1). This overestimation of the morning temperature and late evening was apparently also experienced by Alves et al., (2022) and Liu et al. (2018). Temperature outputs are influenced by the time-based and spatial resolution of ENVI-met simulations where the amount of nighttime cooling may be lowered by smoothed temperature profiles caused by coarse grid resolutions (Yang et al., 2013). Also by holding onto extra heat from the previous day model spin-up and initialization parameters can bias morning temperatures (Yang et al., 2013). The grid size applied for this model is 2 x 2 x 2 meters.

Simple forcing also affects the model accuracy regarding temperature where radiative forcing is the main factor influencing temperature, which results in systematic model errors that follow daily cycles (Liu et al., 2021). There may be minor biases in temperature predictions due to differences in modeling longwave and shortwave radiation (Liu et al., 2021).



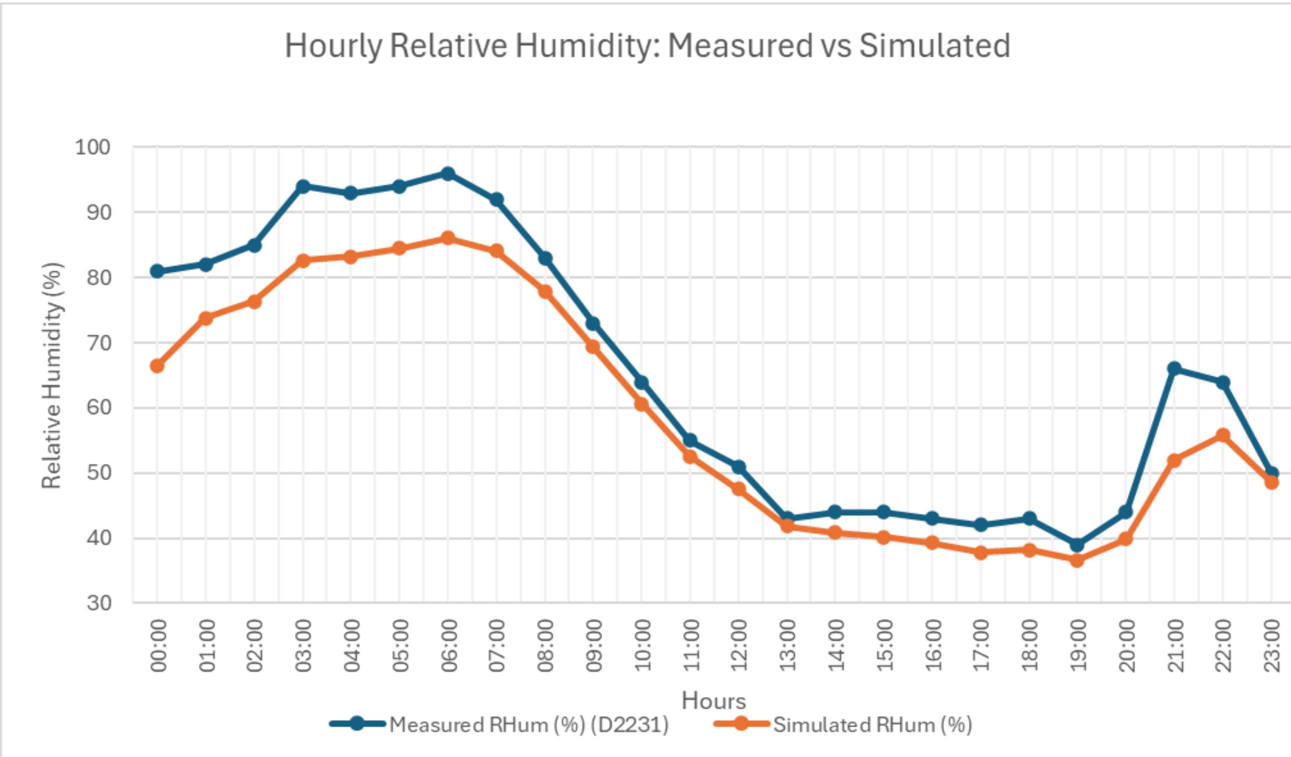
Graph 1: Measured vs Simulated air temperature

3.6.2 Relative humidity validation

The coefficient of determination (R^2) has an outcome of 0,978647743. This shows that there is also a high correlation between the linear interpolated simulated ENVI-met relative humidity data and the real measured data on 25 July 2019. Root Mean Square Error (RMSE) outcome is 7,27%, the average deviation between the linear interpolated simulated ENVI-met temperature data and the real measured data on 25 July 2019.

The relative humidity is consistently underestimated, with the highest deviation being around the late evening time and early morning hours as seen in Graph 2. Ayyad & Sharples (2019) also stated that ENVI-met tends to underestimate humidity levels and especially during nighttime hours and Yang et al., (2013) also say that ENVI-met underestimates relative humidity. The complex interactions between vegetation and the surrounding air are not accurately simulated by ENVI-met because transpiration processes are simplified in the model (Yang et al., 2013). Shading effects are not always reproduced effectively, which can cause humidity to be underestimated (Yang et al., 2013). The initial soil moisture profile in ENVI-met is usually estimated instead of being measured (Yang et al., 2013). The initial soil moisture profile of the Timorpleinbuurt-Zuid neighborhood was also estimated because no soil moisture profile data was available. Errors can be caused by this estimation, mostly if the soil moisture levels are considered to be lower than actual soil moisture levels (Yang et al., 2013). This can make it that the model could simulate drier conditions and results in relative humidity outcomes that are lower than those found in actual environmental settings (Yang et al., 2013).

Simple forcing also influences the humidity accuracy. Evaporation, atmospheric stability, and latent heat exchange all affect humidity (Liu et al., 2021). These components are needed for precise humidity modeling because of ENVI-met's sensitivity to soil moisture and water body input (Yang et al., 2013). Predictions of relative humidity can be greatly impacted by errors in these parameters (Liu et al., 2021). Therefore, big deviations in relative humidity values could result from inaccuracies of soil moisture or water bodies (Yang et al., 2013).



Graph 2: Measured vs Simulated relative humidity

3.7 NBS typology selection and configuration

Bioswales, vegetated pergolas, and green façades were chosen as NBS scenarios here not at random but for what they might do regarding heat stress mitigation and co-benefits provision. The NBS have to either take the place of paved surfaces or act as a buffer against them. Both approaches can play a role in improving microclimate conditions in an urban setting. Bioswales are systems that replace paved surfaces with pervious vegetated surfaces that improve bioretention (Winston et al., 2016; Langergraber et al., 2021). In neighborhoods like Timorpleinbuurt-Zuid where over 80% of the ground is covered with paved surfaces and where rainfall regularly is too much to handle, that substitution may offer real benefits (Cobra Groeninzicht, 2021; Gemeente Amsterdam, n.d., a). Choi et al. (2021) has also stated that this dual role of a bioswale for thermal cooling and rainwater management, as an important trait of nature-based strategies. Vegetated pergolas don not remove surfaces but instead they are above them. They are providing shade where people actually walk. They have the ability to limit incoming sunlight which can lower both surface and air temperatures (Langergraber et al., 2021). Then there are green façades. Instead of removing paved surfaces or adding overhead shade, they block incoming sunlight on a building's façade (Tan et al., 2014). Over time this can help limit thermal heat too (Tan et al., 2014). Tan et al. (2014) also say that how building façades covered in vegetation tend to stay cooler and bring surrounding air temperatures down with them. What ties these three NBS types together isn't just their individual function but also their form. They can be compact, they can be added in segments along the street and they have features that make them a good match for a dense urban environment like Timorpleinbuurt-Zuid. Because here space is limited and no NBS intervention can afford to do just one thing (Ahern, 2011). Their inclusion for NBS scenario testing is justified by literature but also based on what the site seems to need regarding thermal comfort found via the results of the baseline scenario and (environmental) co-benefits.

3.7.1 Bioswale

A bioswale is a vegetated landscape element that takes in stormwater, filters it, and infiltrates the stormwater runoff (Langergraber et al., 2021) (Figure 35). Because of the extensive impermeable surfaces, low soil permeability, and high PET within the neighborhood, bioswales can be extremely relevant in the Timorpleinbuurt-Zuid area. Bioswales improve air and surface temperatures by increasing evapotranspiration and helping soil moisture retention (Brankovic et al., 2019; Xiao et al., 2017). Next to contributing to thermal comfort, bioswales help manage stormwater (Langergraber et al., 2021). This is an important goal of the Amsterdam Climate Adaptation Strategy, by reducing the likelihood of flooding during periods of heavy rains (Gemeente Amsterdam, 2021a; Langergraber et al., 2021). They also add to the aesthetic and psychological qualities of public space and creates habitats for biodiversity (Brankovic et al., 2019). As bioswales are multipurpose interventions, they provide ecological value and climatic resilience in densely populated areas such as Timorpleinbuurt-Zuid neighborhood.

Plant species that can be used for bioswale that could grow to about 1 meters height: Knapweed (Centaurea jacea), Meadow vetchling (Lathyrus pratensis), Bugle (Ajuga reptans), Germander speedwell (Veronica chamaedrys), Rosebay willowherb (Chamerion angustifolium), Purple loosestrife (Lythrum salicaria), Flowering rush (Butomus umbellatus) (Groenblauwe Netwerken, n.d.; Amsterdam Rainproof, n.d.,b).

Figure 35: Visualization of a bioswale

3.7.2 Ground-based green façade

In the Timorpleinbuurt-Zuid neighborhood there are many streets where the total surface area of a street is relatively small. So the street layout becomes like a canyon where the building facades give off heat after being exposed to sunlight throughout the day (Calfapietra & European Commission, 2020; Susca, 2021). A ground-based green façade strategically places climbing plants or modular green systems on building walls that can provide a practical solution to urban heat (Figure 36) (Langergraber et al., 2021; Susca, 2021). High radiant heat levels and increased PET values occur in streets with narrow profiles and heat-retaining brick housing facades (Hang & Chen, 2022; Susca, 2021). By giving shade to building surfaces, vertical greenery lowers mean radiant temperature (MRT), while vegetation's evapotranspiration helps cool the surrounding air (Calfapietra & European Commission, 2020; Tan et al., 2014).So even in small areas the green façades can increase pedestrian thermal comfort by a lot (Susca, 2021). Next to making aesthetic improvements and supporting the improvement of air quality, the intervention also improves building insulation performance, which reduces energy needs (Calfapietra & European Commission, 2020). Amsterdam's Climate Adaptation Strategy, which encourages tiny, space-efficient greening initiatives that take care of several urban issues at once, is in full agreement with this (Gemeente Amsterdam, 2021a). So vertical green façades are a very flexible, multifunctional NBS that provides social and environmental co-benefits in places where there isn't much horizontal room for typical greenery (Choi et al., 2021; Langergraber et al., 2021; Kabisch et al., 2022).

Figure 36: Green facade visualization

The 'wilde bosrank' (Clematis vitalba) was chosen as the plant for the green facades in the case area (Figure 37). It makes sense both ecologically and practically with the buildings in the street being mostly built before 1940. Older masonry is more fragile so if using self-clinging climbers (e.g. ivy), it could damage the brickwork by growing into cracks or trapping moisture (Gemeente Amsterdam, 2024b). Clematis vitalba avoids that risk because it climbs by twining around a support structure like a trellis, so not the wall itself (Gemeente Amsterdam, 2024b). It is also a native species that supports local biodiversity by attracting pollinators and birds (Gemeente Amsterdam, 2024b). Clematis vitalba also maintains an airflow between the greenery and the wall, which helps prevent mold or moisture problems (Gemeente Amsterdam, 2024b). Regarding maintenance it is also manageable because you can prune it to keep it clear of windows or to fit with painting cycles (Gemeente Amsterdam, 2024b). It fits well, it contributes to cooling and biodiversity without damaging the heritage value of the houses. Green facades provide space for these animals: House sparrow, Robin, Blackbird, bats, butterflies and bumblebees (Gemeente Amsterdam, 2024b).

Figure 37: Clematis Vitalba (Gemeente Amsterdam, 2024b).

3.7.3 Vegetated pergola

A vegetated pergola is a tall green structure that gives direct shade (Figure 38) (Langergraber et al., 2021). Pergolas use vertical space while keeping accessibility and walkability (Ahmed et al., 2024). In open and sun-exposed areas vegetated pergolas help in lowering mean radiant temperature (MRT) and PET by blocking direct solar radiation and also by having evapotranspiration through its climbing plants (Kong et al., 2021; Knoll et al., 2023). Pergolas are multifunctional NBS types that can improve social contact next to their value regarding microclimate improvement (Ahmed et al., 2024; Knoll et al., 2023). The attributes of the vegetated pergola help with walkability, increase psychological well-being and support Amsterdam's goal of recovering urban space for both people and the environment (Ahmed et al., 2024; Gemeente Amsterdam, 2021a). Vegetated pergolas are a flexible solution that is also ascalable solution (Ahmed et al., 2024; Kong et al., 2021; Langergraber et al., 2021). They combine microclimate improvement with livability and inclusivity in dense urban environments as part of the city's Climate Adaptation Strategy (Ahmed et al., 2024; Kong et al., 2021; Langergraber et al., 2021; Gemeente Amsterdam, 2021a).

The common honeysuckle plant was chosen as the vegetation type to green the pergola because it is a native plant that provides habitat and food for a lot of different animal species and also has a thick vegetation layer (Figure 39) (Gemeente Amsterdam, 2024b). Vegetated pergolas provide space for these animals: Moths, Bumblebees, Wild bees, Hoverflies, Hummingbird hawk-moth and Birds (Gemeente Amsterdam, 2024b).

Figure 38: Vegetated pergola

Figure 39: Common Honeysuckle (Gemeente Amsterdam, 2024b)

4. Results

The results chapter is divided into several parts. The first part being the microclimate results of the baseline simulation of the whole neighborhood. Then the second part being a deeper analysis of the chosen street for NBS scenario testing. And the third part being the NBS scenarios' results and analysis, also results will be compared between each scenario.

4.1 Microclimate analysis Timorpleinbuurt-Zuid neighborhood

The first part of the results are the ones to address the SRQ1. Looking into the microclimate of the neighborhood and the biophysical parts influencing them.

4.1.1 Celebesstraat

Microclimate conditions

Air temperature

At night Celebesstraat holds onto warmth from the previous day. The buildings around it help trap heat, so it doesn't cool down as quickly as other streets. The shaded layout and vegetation limit radiative heat loss. It still gets cooler as the night goes on, but the middle part of the street doesn't cool down as efficiently as the rest. In the morning Celebesstraat warms up more slowly than the streets around it. The buildings and trees block the sun early on, so it takes longer for the sunlight to hit the street directly. Because of that, the air stays pretty comfortable and doesn't heat up too fast. By the afternoon Celebesstraat hits its highest temperature, around 34°C. That's pretty similar to nearby streets, but it stays a bit cooler overall. The trees and the big green area next to the train tracks help a lot with that. The average air temperature at 18:00 is about 33.98°C, the lowest in the neighborhood. It handles the heat a little better than a lot of other streets in the neighborhood. In the evening Celebesstraat starts to cool down, but not all at the same pace. The upper part near Javastraat and Balistraat holds onto the heat a bit longer. The average air temperature around the street drops to about 28.89 °C at 23:00, the lowest nighttime air temperature across the whole neighborhood.

PET

At night, PET values are comparatively higher than on other streets. In the morning, PET is still relatively high when compared to other streets, much like the air temperature and that is the case in the lower half of the street. A high level of thermal discomfort is shown by the afternoon peak of PET, which rises to approximately 49.9 °C. With multiple extreme heat hotspots, it is one of the neighborhood's hottest streets PET-wise due to the streets orientation, creating increased solar exposure and accumulated surface heat. PET measurements sharply decline in the evening, peaking at 26.39°C by 23:00. Heat is not dispersed equally throughout the street though. In comparison to the northern half, the southern half continues to be more uncomfortable and shows a slower decline.

Mean area values

Area mean air temperature at 18:00 → 33.98 °C

Area mean air temperature at 23:00 → 28.89 °C

Area mean PET at 18:00 → 49.90 °C

Area mean PET at 23:00 → 26.39 °C

4.1.2 Riouwstraat

Microclimate conditions

Air temperature

Riouwstraat starts off fairly warm at night because the brick buildings and paved surfaces soak up heat during the day and slowly release it during the night. In the first half of the morning, the temperature in the Riouwstraat is relatively high but during the second half of the morning it is relatively cooler than most streets. Riouwstraat gets noticeably hotter during the afternoon, but still relatively cooler compared to other streets. Riouwstraat starts to cool down more quickly than some of the nearby streets. It stays consistently cooler than most of the other streets in the neighborhood, but during the late evening close to midnight the temperature is relatively higher than most streets. At 23:00 the air temperature drops to 29.01°C, slightly above the area's nighttime average, which shows that while it cools fairly well it is not the best in the area.

PET

The PET values are a bit higher during the night (00:00-04:00) because the pavement and buildings are still giving off heat from earlier. It does not not feel too uncomfortable overall because there is no sunlight exposure but it is still warmer near the building facades where the heat tends to stick around longer. Riouwstraat is one of the streets with the highest average night time PET in the neighborhood. In the morning the PET values are moderate except for the left side of the left half of the street (the street is split by the Sumatrastraat, right half is on the other side of that street). At the right half of the street the buildings and the bigger trees shade some surfaces which can create thermal comfort where the PET stays below heat-stress levels through most of this period. In the afternoon the PET hits its peak at around 48.1°C, which means it is pretty uncomfortable for anyone walking around. Some spots get a bit of relief from tree shade or building shade at this time period, seriously much on the right side, but most of the street is exposed to the sun, especially where there are not much trees. By the evening the PET drops quite a bit, down to around 26.55°C by 23:00. Then it feels a lot more comfortable overall but some spots still hang onto warmth, mostly the areas on the left without much greenery or near building walls that release heat more slowly.

Mean area values

Area mean air temperature at 18:00 → 34.44 °C

Area mean air temperature at 23:00 → 29.01 °C

Area mean PET at 18:00 → 48.05 °C

Area mean PET at 23:00 → 26.55 °C

4.1.3 Sumatrastraat

Microclimate conditions

Air temperature

Sumatrastraat stays moderately warm during the night. There are not a lot of trees in the street so the heat can escape more easily during the night though there’s still a bit of lingering warmth, seen up north near Javastraat and down south where it meets Riouwstraat. In the morning the street starts to warm up steadily but not too much because the surrounding buildings and light tree cover gives off some early shade, which helps keep surfaces from heating up too quickly. Temperatures are pretty evenly spread out and it stays fairly comfortable however the open area near Eerste Atjehstraat warms up a bit faster though than the rest of the street since it gets more sun. In the afternoon the Sumatrastraat hits its peak temperatures: the intersections at Balistraat, Eerste Atjehstraat, and Insulindeweg are the hottest spots, reaching around 34.93°C by 18:00. These open street crossings don’t have much shade from buildings or trees so heat builds up there more compared to the other places in the street. In the evening the street cools down pretty quickly. Even though there aren’t many trees, the open layout and surfaces that don’t trap a ton of heat help it cool faster than more enclosed streets. By 23:00 the air temperature drops to around 28.96°C, which is on the cooler side compared to other streets, showing it actually cools off fairly well at night.

PET

At night the PET stays a bit higher than ideal, mostly because heat still lingers near building walls that slowly emit that heat, but overall the thermal stress is pretty mild. The PET starts to climb gradually in the morning just like the air temperature. There is some shade from buildings and a few trees so it stays pretty manageable thermal comfort-wise early on. In the more open spots like the crossings with Eerste Atjehstraat, the PET rises a bit faster since there is more sun exposure. It gets really uncomfortable heat-wise in during the afternoon. PET peaks at around 48.07°C by 18:00, making Sumatrastraat one of the hotter streets for pedestrians. Most of the street feels the heat during the early afternoon, around the wide junction at Eerste Atjehstraat it is the most intense. But the left side of the street gets shaded and surfaces start to cool down a bit in the late afternoon. In the evening when the air temperature and surface temperature drop it makes the PET goes down too by just above 26.32°C by 23:00. The street's open layout and lack of big tree canopies makes it cool off better than about half the other streets in the area. The only spot that stays relatively warm is near the Eerste Atjehstraat junction.

Mean area values

Area mean air temperature at 18:00 → 34.93 °C

Area mean air temperature at 23:00 → 28.96 °C

Area mean PET at 18:00 → 48.07 °C

Area mean PET at 23:00 → 26.32 °C

4.1.4 Tweede Atjehstraat

Microclimate conditions

Air temperature

Tweede Atjehstraat stays warmer at night than most other streets in the neighborhood when looking at the PET value. The early morning of the street the temperatures rise faster than in a lot of nearby streets. That is mainly because there is not much shade and the east-west layout means it gets sun pretty early during the day. Later in the morning though, the temperature evens out and becomes more similar with other streets. It starts out warmer than the other streets but Tweede Atjehstraat does not heat up as much in the afternoon compared to others. At 18:00 the average air temperature is around 34.14°C, which is actually a bit cooler than most nearby streets, aside from Celebesstraat. During the second half of the evening the street stays relatively warm because the façades and pavement keep giving off heat. At 23:00 it is still about 28.99°C. So Tweede Atjehstraat does not cool down as well compared to other streets.

PET

PET stays pretty high during the night on Tweede Atjehstraat, the heat from buildings and pavement sticks around and with not much air flow in the narrow street, it doesn't cool off easily. It actually ends up having the highest nighttime PET value in the neighborhood. In the morning it is more of the same, the PET is the highest during the first half of the morning, seen in the upper part of the street where there is barely any shade. And as the sun gets stronger the heat builds up quickly but PET really peak in the afternoon. Even though the air temperature is not the hottest compared to other streets, PET almost hits 53°C by 18:00. That is mostly because of the sun hitting a lot of the bare surfaces because it has very little tree cover, and the narrow street layout can make it feel way hotter than it actually is. At 23:00, PET drops to around 28.1°C, but it is still high. There are places in the street that cool off better but most of the street stays warm near buildings and pavement that were in the sun all day. It also ends the day with the highest PET in the evening, showing just how much heat this street traps.

Mean area values

Area mean air temperature at 18:00 → 34.14 °C

Area mean air temperature at 23:00 → 28.99 °C

Area mean PET at 18:00 → 52.98 °C

Area mean PET at 23:00 → 28.11 °C

4.1.5 Eerste Atjehstraat

Microclimate conditions

Air temperature

In the night the Eerste Atjehstraat stays fairly warm as can be seen in the western end of the street near Celebesstraat. During the morning the sides of the streets swap the average heat pattern, the eastern side becomes hotter than the western side of the street. The eastern half is comparatively hotter than a lot of the other streets in the neighborhood. In the afternoon this stays about the same regarding the street halves' heat pattern with the left side being relatively cooler than the eastern side. Air temperature peaks in the afternoon, hitting around 35.05°C by 18:00. And that makes Eerste Atjehstraat the hottest street in the neighborhood with regards to air temperature. The open square near Sumatrastraat and the eastern half of the street show higher heat levels due to limited tree coverage and stronger solar exposure. Meanwhile the western portion of the Eerste Atjehstraat is slightly cooler thanks to partial shading from trees and nearby buildings. In the evening the cooling begins but it is uneven in the street halves. During the first half of the evening the eastern end is still hotter than the western side but the western end of the street holds onto more heat halfway through the evening. By 23:00 the street-wide average temperature drops to about 29.00°C, placing it in the middle range for evening temperatures among the streets analyzed.

PET

The Eerste Atjehstraat stays relatively cooler PET-wise during the night than the other streets in the neighborhood. Only the western side next to the Celebesstraat stays a bit warmer. PET keeps increasing of course during the morning, with the least amount of thermal comfort near the Tweede Atjehstraat and also again centered around the open Sumatrastraat intersection during the first half of the morning. The closer it gets to noon the way ir becomes hotter across the whole street. Thermal stress is highest in the afternoon the PET reaches at around 49.94°C by 18:00. This is among the higher PET levels for the neighborhood although not the highest level but its neighboring street (Tweede Atjehstraat). The Sumatrastraat intersection area again is the most thermally uncomfortable zone but it also has some cooler spots from the greenery at the square. Meanwhile the shaded areas on the bottom halves of the street offer some thermal relief, though overall the thermal discomfort remains high throughout the street. PET drops notably by evening, falling to about 25.36°C by 23:00. During the evening one pocket of heat at the Sumatra intersection stays relatively hot.

Mean area values

Area mean air temperature at 18:00 → 35.05 °C

Area mean air temperature at 23:00 → 29.00 °C

Area mean PET at 18:00 → 49.94 °C

Area mean PET at 23:00 → 25.36 °C

4.1.6 Balistraat

Microclimate conditions

Air temperature

Balistraat is also one of the warmer streets during the night. Parts of the street retain heat, mostly the western section near Celebesstraat. Balistraat then also stays as one of the warmest streets in the morning only the eastern end near the Benkoelenstraat en Langkatstraat stays relatively cooler. In the afternoon the Balistraat's temperature increase to about 34.96°C by 18:00 which places it among the warmer streets but it is still slightly below Eerste Atjehstraat and Langkatstraat. Open areas around intersections heat up more, these intersections are at the Sumatrastraat intersection and near the Langkatstraat and Benkoelenstraat. The western halve of the street is cooler than the eastern end. In the evening the street halves swap their cooler sides with now the western part becoming warmer again and the eastern part cooling down more. By 23:00 the air temperature drops to around 29.00°C.

PET

At night the PET levels on Eerste Atjehstraat are relatively low, on the east side compared to other streets nearby. In the morning the west side stays a bit cooler, while the east side near Benkoelenstraat and Langkatstraat starts to feel pretty thermally uncomfortable as heat builds up there specifically. In the afternoon the PET is about average overall but the street has more cooler spots scattered around. It peaks at around 48.14°C around 18:00, which means there's still a lot of heat stress, near the open intersections where there's little shade is it peaks. PET drops off nicely in the evening: at 23:00, it is down to around 25.34°C, which is actually the lowest evening PET of all the streets in the neighborhood.

Mean area values

Area mean air temperature at 18:00 → 34.96 °C

Area mean air temperature at 23:00 → 29.00 °C

Area mean PET at 18:00 → 48.14 °C

Area mean PET at 23:00 → 25.34 °C

4.1.7 Benkoelenstraat

Microclimate conditions

Air temperature

Benkoelenstraat is one of the streets in the neighborhood with the lowest average nighttime temperature. During the morning the Benkoelenstraat is warmer than other streets, except for the adjacent Langkatstraat which has almost the same buildup. In the afternoon the air temperature rises to about 34.89°C by 18:00, having an average temperature among the streets. In the first half of the evening the street is a bit cooler than the other streets but in the second half it starts to overtake the nighttime air temperature of the other streets. This makes the Benkoelenstraat having the second-highest evening temperature in the area at 29.09°C at 23:00.

PET

During the nighttime the Benkoelenstraat has the highest average PET. Even the case until halfway through the morning when it then starts to swap, then it is becoming one of the cooler streets PET-wise in the neighborhood. In contrast to its relatively high air temperature, PET peaks as the lowest at 18:00, being 45.85°C, which is less than most other streets with even slightly cooler air temperatures.In the evening the PET is 27.18°C by 23:00, making it have the second highest PET level of all streets.

Mean area values

Area mean air temperature at 18:00 → 34.89 °C

Area mean air temperature at 23:00 → 29.09 °C

Area mean PET at 18:00 → 45.85 °C

Area mean PET at 23:00 → 27.18 °C

4.1.8 Langkatstraat

Microclimate conditions

Air temperature

Langkatstraat has a relatively average nighttime temperature. Langkatstraat is the warmest street temperature-wise in the morning. In the afternoon the street stays warm. By 18:00 the air temperature peaks at 35.00°C, the second highest in the neighborhood behind the Eerste Atjehstraat. In the evening, Langkatstraat is even the hottest street. At 23:00, temperatures are still at 29.14°C, the highest evening value in the area.

PET

Langkatstraat has one of the highest average nighttime PET next to Benkoelenstraat and Celebesstraat. PET during the first half of the morning is comparatively higher than other streets but during the second half of the morning it starts to swap. At 18:00 the PET temperature reaches 46,55°C, the second lowest amount after the adjacent Benkoelenstraat. PET decreases a lot during the evening but it is still 26.7°C, one of the highest PET in the area at 23:00.

Mean area values

Area mean air temperature at 18:00 → 35.00 °C

Area mean air temperature at 23:00 → 29.14 °C

Area mean PET at 18:00 → 46.55 °C

Area mean PET at 23:00 → 26.69 °C

4.1.9 Whole neighborhood street comparison

After showing the average PET and air temperature of each street at 18:00 and 23:00, they are compared and ranked. Table 2 ranks the seven streets of the neighborhood by their mean air temperature and PET at 18:00. It shows how street design and greenery shape evening heat stress.

At 18:00

Street	Air temperature (°C) at 18:00	PET (°C) at 18:00
Sumatrastraat	34.93387673947388 °C	48.072847232625584 °C
Balistraat	34.96496658917427 °C	48.14210483187894 °C
Eerste Atjehstraat	35.053363846114756 °C	49.93654309799782 °C
Tweede Atjehstraat	34.13960065427552 °C	52.97891251082273 °C
Riouwstraat	34.44218922814304 °C	48.05347695240101 °C
Celebesstraat	33.98265634100546 °C	49.89673524300478 °C
Benkoelenstraat	34.8859160620452 °C	45.8479120962730 4 °C
Langkatstraat	35.00416283399301 °C	46.5492918010561 °C

Street	Insights
Sumatrastraat	High daytime air temperature and PET because of sparse young tree canopy.
Balistraat	Third highest air temperature and average PET, above average amount of trees helps moderate air temperature.
Eerste Atjehstraat	**Highest air temperature** and second highest PET thanks to partial tree coverage and large open area.
Tweede Atjehstraat	Lower air temperature, but **highest PET,** narrow canyon effect traps heat.
Riouwstraat	Third lowest air temperature and average PET, average amount of vegetation and materials.
Celebesstraat	**Coolest air temperature** due to a high amount of greenery bordering the street, but PET is third highest.
Benkoelenstraat	Average air temperature, but **lowest PET** because of moderation by vegetation and high amount of tree shading and vegetation reducing radiant heat.
Langkatstraat	Second highest air temperature but second lowest PET due to dense tree canopy and vegetation reducing radiant heat.

Table 2: Neighborhood average Air temperature and PET at 18:00

Table 3 shows the same as Table 2: seven streets by their mean air temperature and PET, but then at 23:00. This displays how street layout and greenery influence how much heat each street holds onto.

At 23:00

Street	Air temperature (°C) at 23:00	PET (°C) at 23:00
Sumatrastraat	28.964198995623548 °C	26.320399179607765 °C
Balistraat	29.000864770778367 °C	25.343992127298122 °C
Eerste Atjehstraat	29.003088041747557 °C	25.3597207712674 7 °C
Tweede Atjehstraat	28.99570034102178 °C	28.114502215303506 °C
Riouwstraat	29.010985110633793 °C	26.547621100746778 °C
Celebesstraat	28.888033609642385 °C	26.388939654547222 °C
Benkoelenstraat	29.090274207199677 °C	27.178880769995196 °C
Langkatstraat	29.137820701837043 °C	26.68538067395375 °C

Street	Insights
Sumatrastraat	Second lowest nighttime air temperature and slighty below average nighttime PET because this street due to its openness to the sky can lose its radiant heat effectively.
Balistraat	Third lowest nighttime air temperature and **lowest nighttime PET** because of high tree density.
Eerste Atjehstraat	Average nighttime air temperature and second lowest nighttime PET due to having an open central area where heat can escape and because of big greenery areas.
Tweede Atjehstraat	Average nighttime temperature but the **highest nighttime PET**, because heat is trapped due to a narrow canyon effect layout.
Riouwstraat	Above average nighttime air temperature and above average nighttime PET due to balanced mix of trees and urban materials.
Celebesstraat	**Coolest nighttime air temperature** and third lowest nighttime PET due to less tree canopy coverage so radiant heat can escape better.
Benkoelenstraat	Second highest nighttime air temperature and PET because of dense canopy trapping humidity and radiant heat.
Langkatstraat	**Highest nighttime air temperature** and third highest nighttime PET due to dense canopy trapping humidity and radiant heat.

Table 3: Neighborhood average Air temperature and PET at 23:00

Tweede Atjehstraat has the highest average mean PET during the hottest hour of the day and the nighttime. This means that the Tweede Atjehstraat will be chosen to test the NBS intervention scenarios. So the detailed geometry and microclimate analysis of the Tweede Atjehstraat will be next to inform the NBS scenario setup before presenting the performance results of the scenarios.

4.2 Detailed analysis of the Tweede Atjehstraat

In this part of the results a more in-depth analysis of the Tweede Atjehstraat regarding PET results at 18:00 and street layout and biophysical features to inform the design of the three NBS scenarios will be done.

4.2.1 Scenario Baseline

PET Analysis

PET analysis of the street consists of a cool zone analysis and a hot zone analysis. These will be compared with the physical dimensions of the street and the surface layers of the buildings and the street itself (sub-chapter 4.3).

Cool zones

Certain sections on the upper part of the street have lighter PET spots that match the sidewalk zones that are covered by trees (Figure 40). Tree canopies provide some cooling through evapotranspiration and shade. The sunlight is intercepted by trees, and this directly affects PET. Some colder PET narrow strips can be found close to building facades. This can be explained by shadows cast by buildings, seen in the lower half of the street, showing the blue spots (barely visible). This creates a small area of cooler air, providing some relief.

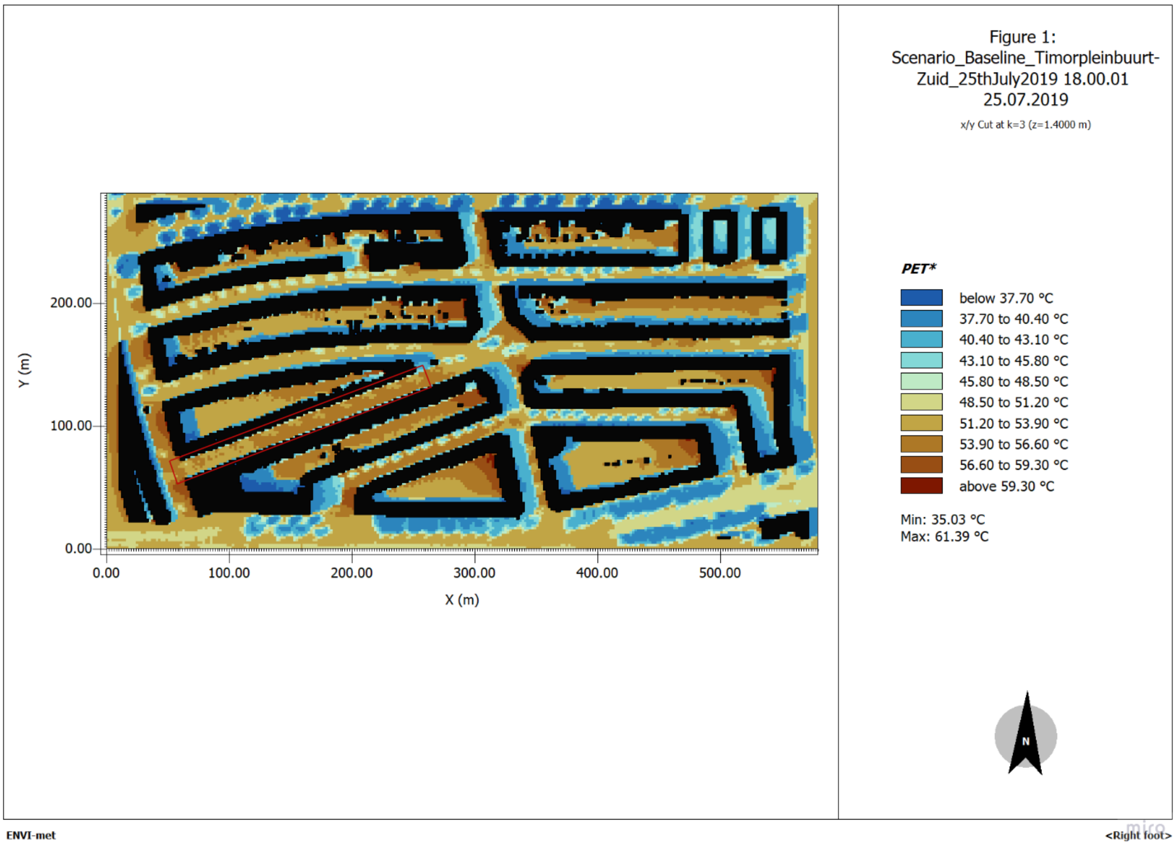


Figure 40: Baseline scenario neighborhood PET map at 18:00, red rectangle shows the Tweede Atjehstraat

Hot zones

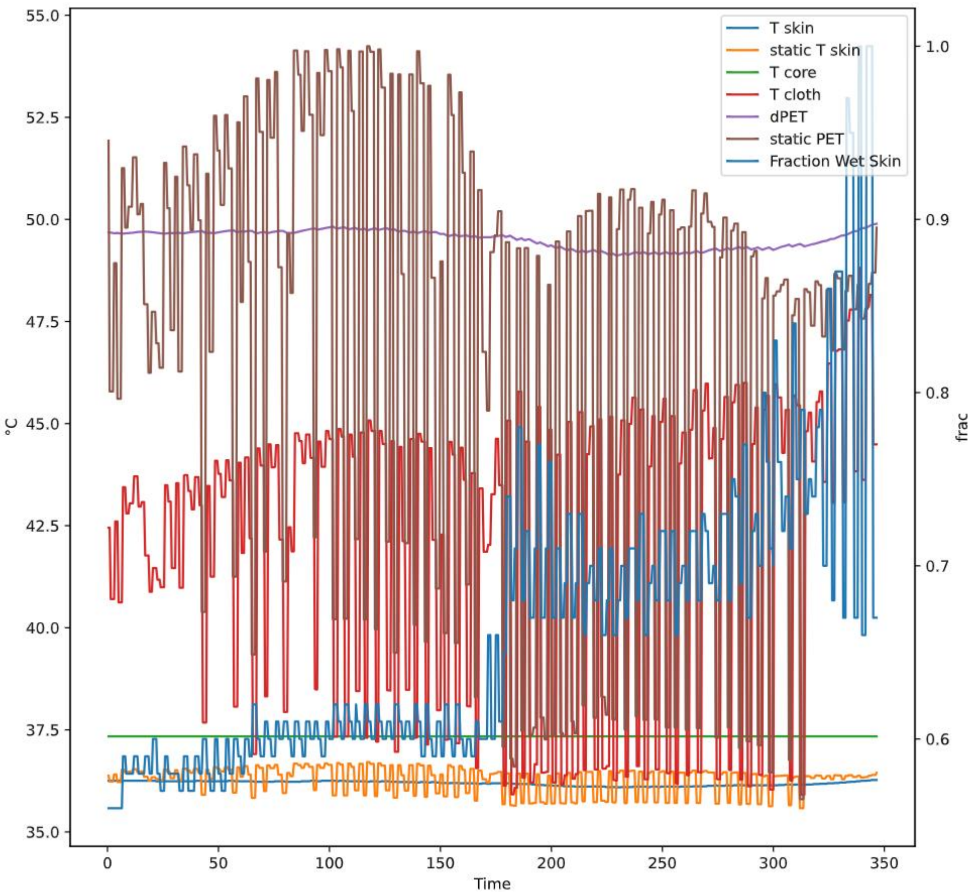
The brownish zones are the hottest parts of the street during this part of the day. These areas are building facades and paved surface areas. They emit radiant heat because of their exposure to sunlight during the day. They are also not giving off shade during this part of the day. Also the wider, open parts of the street exposed to direct solar radiation for extended periods (during midday to the afternoon) are the hottest.

Static PET walk

For the static PET walk a 'Default Male, Summer Clothing' is used (Table 2). Table 2 shows several thermal comfort indicators during a walk along a route that passes the sidewalk on both streets at 18:00. Graph 3 maps the neighborhood's static PET levels at 18:00. The colored path is the walking route and the legend classifies the static PET values from 'below 37.65 °C' (dark blue) to 'above 52.40 °C' (dark brown) (Figure 41). The route reveals hot spots (brown spots) in the Tweede Atjehstraat, contrasted by cooler areas (blue spots and green spots). Most cooler spots are either found in the shade of the buildings or near trees.

Figure 41: Scenario baseline PET walk at 18:00

Graph 3 shows the actual values of the several thermal comfort indicators that are measured during the walking sequence. Here there will be focus on the 'static PET' line in the graph. Graph 3 shows how the different body temperature metrics and thermal comfort indicators evolve over time during the simulated heat-stress event. The blue line is the actual skin temperature. The orange line is the "static" (baseline) value. The green line is the (constant) core temperature. The red line is the clothing surface temperature. The two PET indices are the dynamic PET (purple line)f and static PET (brown line). The fraction of wet skin is the light blue line. You can see that when skin and clothing heat up, the PET rises above comfort thresholds and evaporative cooling (wet skin fraction) increases.



Graph 3: Baseline scenario PET walk graph at 18:00

4.3 NBS scenario design

4.3.1 Street layout

The street width total is 15 m. The width consists of several surface layers which are (Figure 42):

- Upper sidewalk width: 5.15 m
- Lower sidewalk width: 2.35 m
- Upper parking area width: 2 m
- Lower parking are width: 2 m
- Road width: 3.5 m

The parking lots of the upper row are respectively 70.18 m, 16.55 m, 56.41 m and 30.77 m long. The parking lots of the lower row are respectively 95.24 m and 96.85 m long (Figure 42).

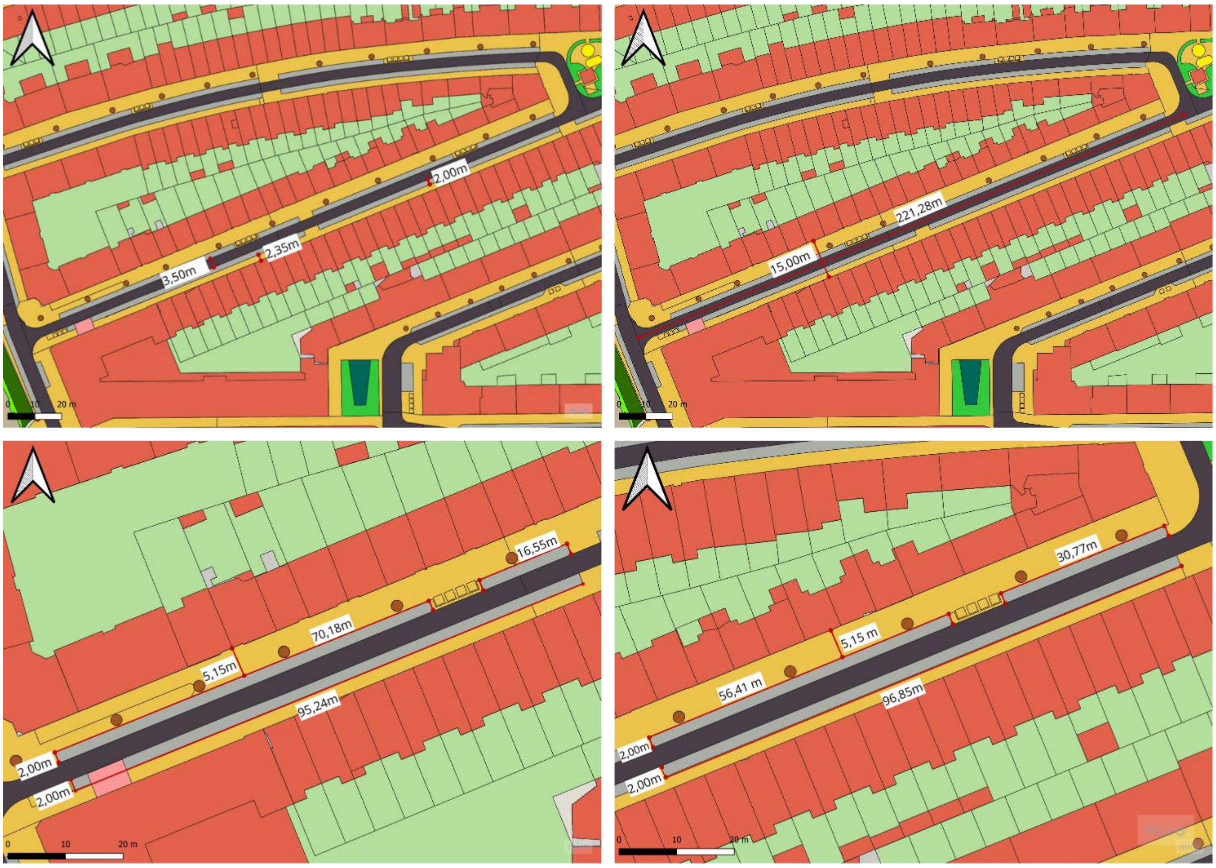


Figure 42: Street dimensions of several surface layers

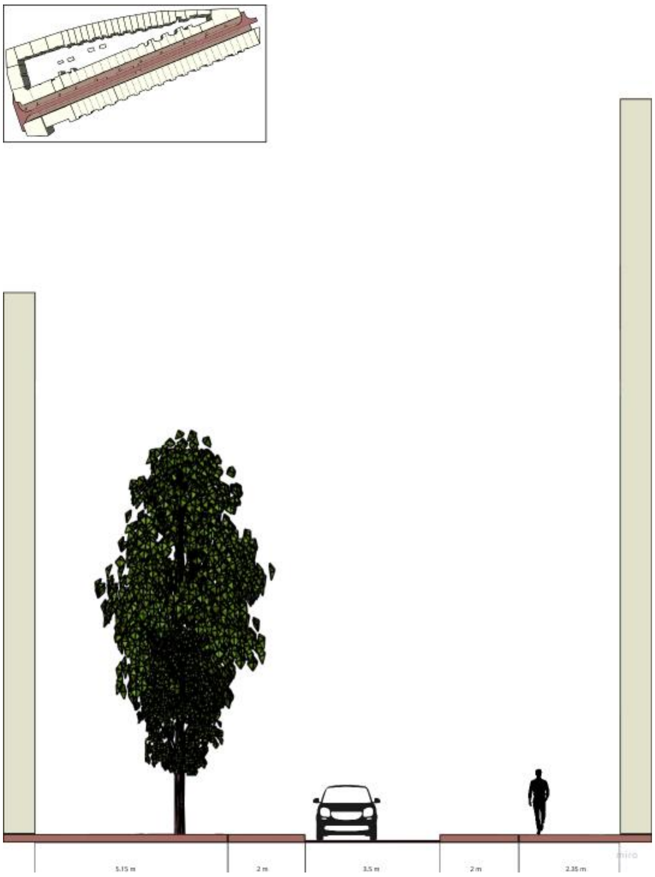


Figure 43: Cross-section Tweede Atjehstraat Baseline scenario

4.3.2 Design strategies for the microclimate of the Tweede Atjehstraat

So by looking at the PET map of the baseline scenario (Figure 40), and the static PET route in the street with thermal comfort graph (Figure 41 and Graph 3) and comparing it with the street layout map with dimensions (Figure 42) and cross-section of the Tweede Atjehstraat (Figure 43), there are several painpoints regarding PET. So there are several surface layers that need to be tackled and it shows the value of microclimatic design by these cooler zones in the street at 18:00 (shade and evapotranspiration via trees). The features of the street that need to be tackled in several ways:

- Limit paved surfaces that store heat. One can do this by targeting the heat spots and replacing the paved surfaces with green surfaces, so implement ground based greenery (e.g., bioswales, green pergolas NBS types).
- Increase the continuity of vegetated canopy that blocks incoming sunlight from reaching the street's paved surfaces (e.g. vegetated pergolas NBS types).
- To make the most of building façades by using vertical greening that limit radiant heat by blocking incoming sunlight on the building facade (e.g. green façades NBS type).

Scenario Bioswale

Setup

Setup chapter contains the setup of the street layout after implementation of the Bioswale scenario in the Tweede Atjehstraat (Figure 44) and includes the ENVI-met NBS typology setup in ENVI-met DB.

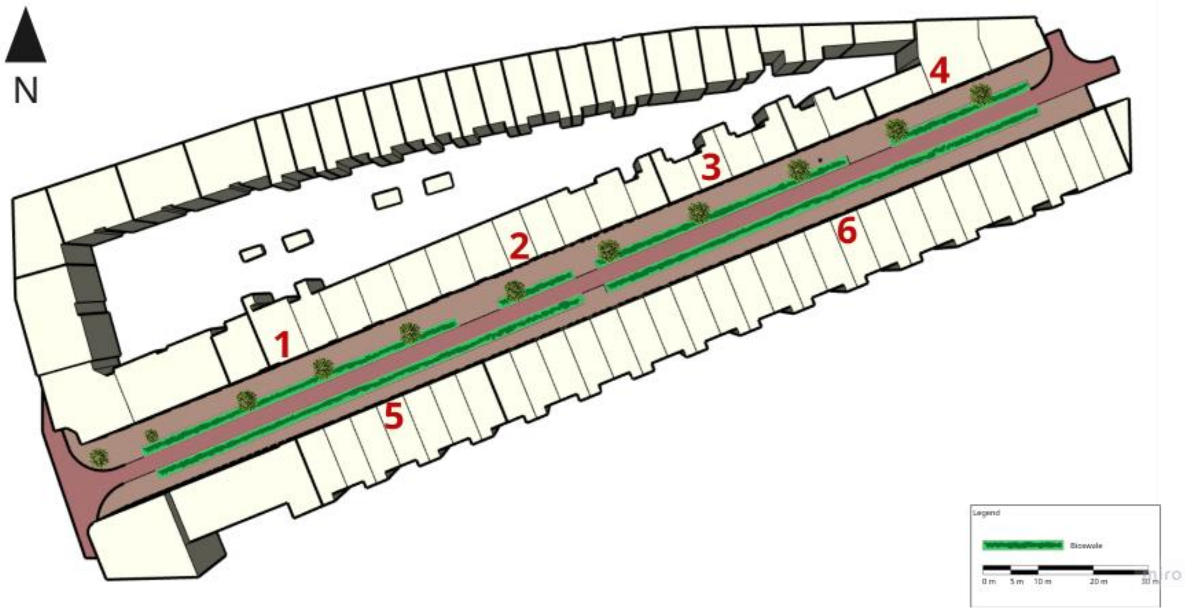


Figure 44: Layout Tweede Atjehstraat Bioswale scenario

Street layout

Tweede Atjehstraat's 15 m cross-section has two 2 meter wide parking areas, a 3.5 m wide road and sidewalks of 5.15 m (upper) and 2.35 m (lower) width (Figure 45).

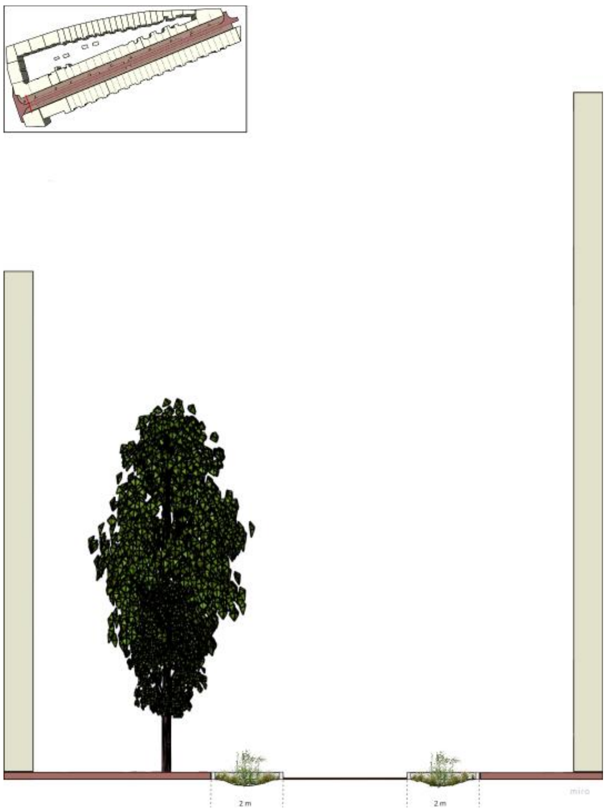


Figure 45: Cross-section Tweede Atjehstraat Bioswale scenario

The only unpaved areas are the 11 tree pits (~3.14 m² each) in the upper part of the street, and some small facade gardens. By replacing the parking lanes with bioswales, it adds 732.01 m² of extra bioretention area and can help with the street's rainwater problem. The parking strips lie directly upslope of the storm-drain inlets. This lets the bioswales capture some rainwater and infiltrate it locally instead of transferring it into the sewer system directly and helps relieving pressure from the storm-drain inlets (Davis et al., 2001). Because the bioswales are placed on the former parking areas it also keeps the road and sidewalk free.

Dimensions of bioswales (example in Figure 46):

1: 70.18 meters x 2 meters

2: 16.55 meters x 2 meters

3: 56.41 meters x 2 meters

4: 30.77 meters x 2 meters

5: 95.24 meters x 2 meters

6: 96.85 meters x 2 meters

Figure 46: Example of the dimensions of a Bioswale implemented in the Tweede Atjehstraat

ENVI-met setup

The "Hedge dense, 1m" is used as the stand-in for the bioswale vegetation in the ENVI-met model (Figure 47), because a dense vegetation along its length, like more densely vegetated bioswales, needs to be imitated and there is no specific bioswale option in ENVI-met (Figure 72).

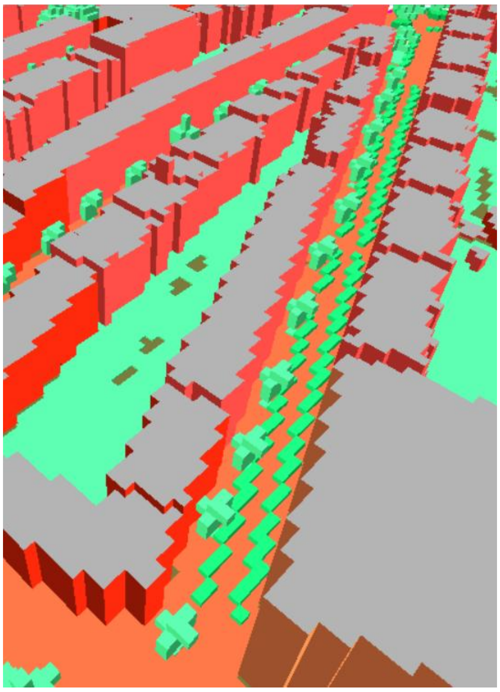


Figure 47: ENVI-met Spaces Bioswale Scenario

The albedo value of 0.2 means that 20% of sunlight bounces off. An emissivity value of 0.97 lets leaves radiate heat effectively at night. A transmittance of 0.3 is about letting light through the canopy. The bioswale is 1m tall with roots reaching 0.7m deep. The series of numbers in Leaf Area Density (LAD) and Root Area Density (RAD) imitate foliage and roots layer by layer and the seasonal profile's monthly values show if there is plant foliage activity up or down through the year. It is deciduous vegetation so it loses its leaves during the winter.

Scenario Green Façade

Setup

Setup chapter contains the setup of the street layout after implementation of the NBS (Figure 48) and includes the ENVI-met NBS typology setup in ENVI-met DB.

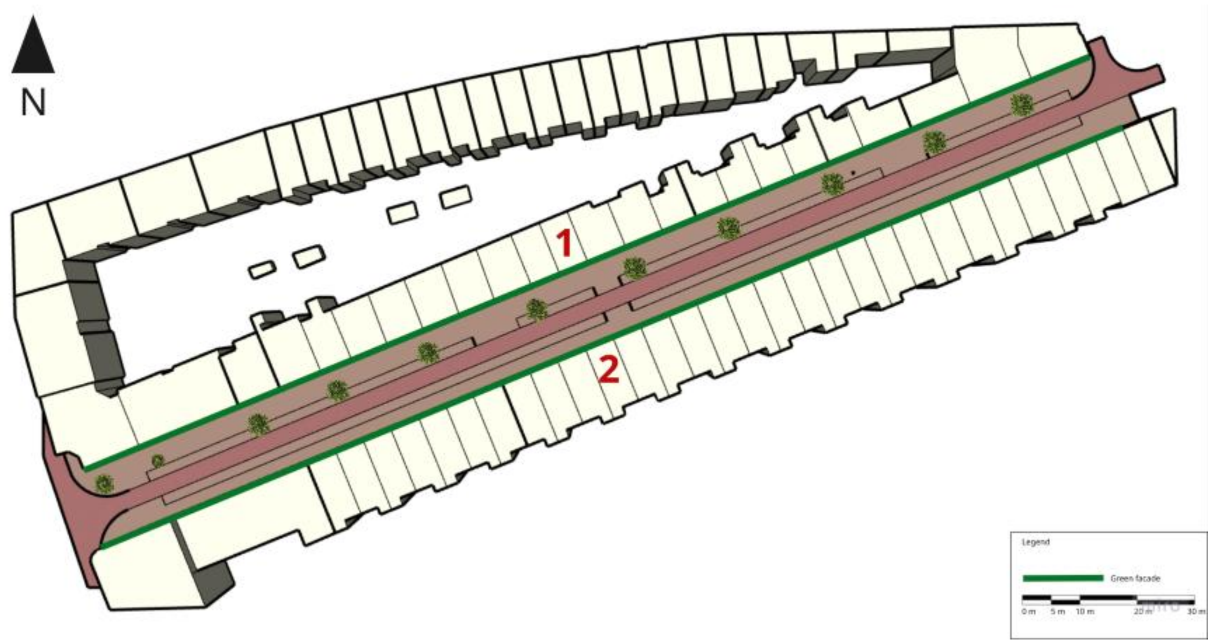
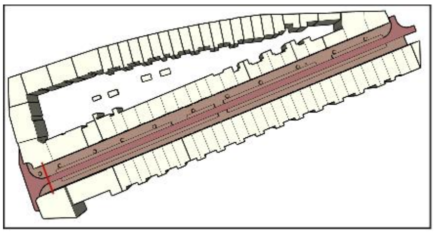


Figure 48: Layout Tweede Atjehstraat Green Façade scenario

Street layout

The continuous unshaded brick façades of the buildings are four stories high on both sides of the Tweede Atjehstraat (Figure 49) (including the roof with attic makes it 5 stories high but that is not counted because it is a sloped facade).



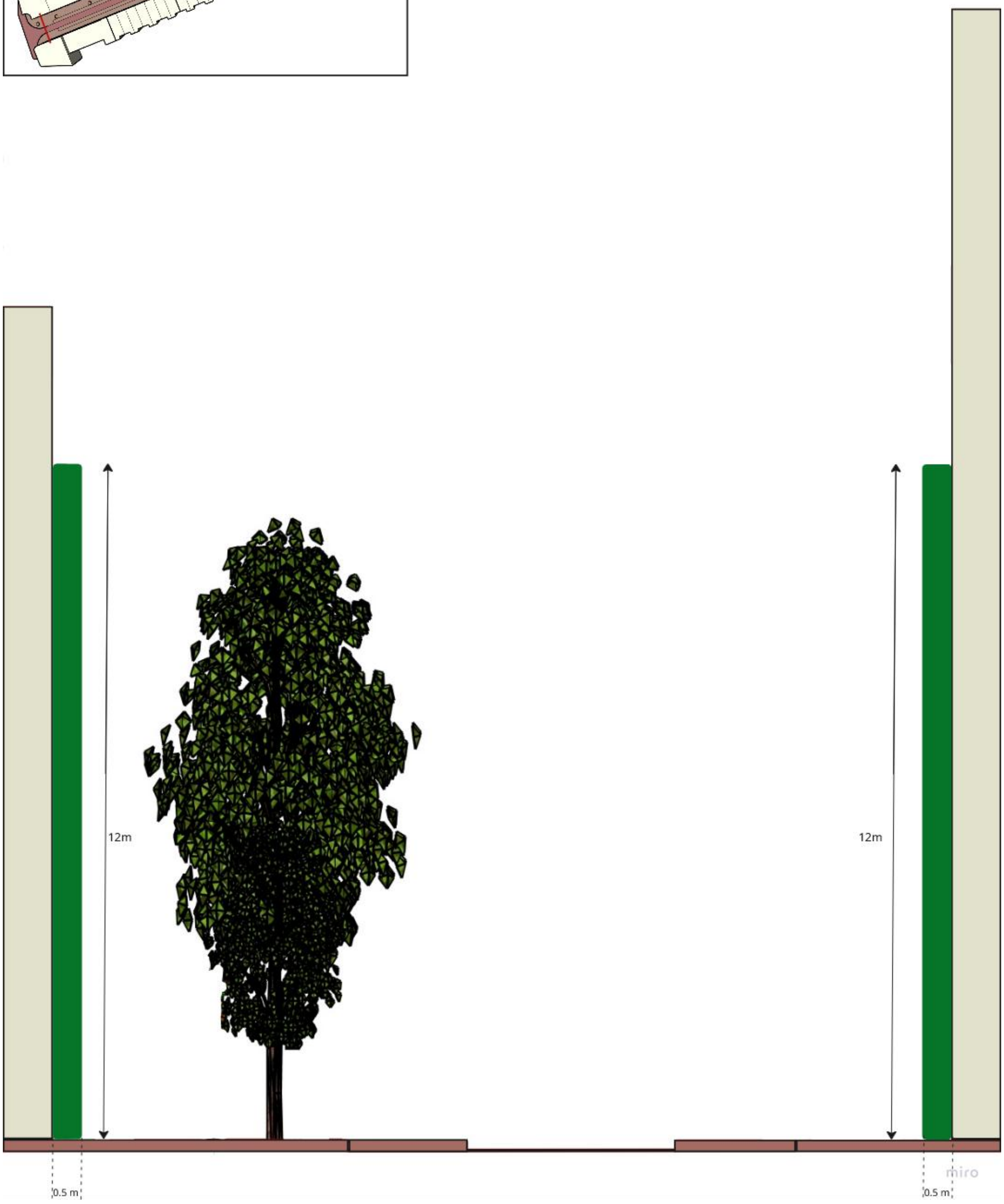


Figure 49: Cross-section Tweede Atjehstraat Green Façade scenario

Ground-based green façades are planted in small facade gardens at the base of each building so that no street or sidewalk space is used. By putting the plant climber supports off the facade the masonry can mostly remain intact. This could also be stated as a semi-unpaved surface by covering up vertical paved surfaces (building facades).

Dimensions of the green façades (example in Figure 50).

Upper row: 204,11 meters x 2 meters x 12 meters

Lower row: 204,11 meters x 2 meters x 12 meters

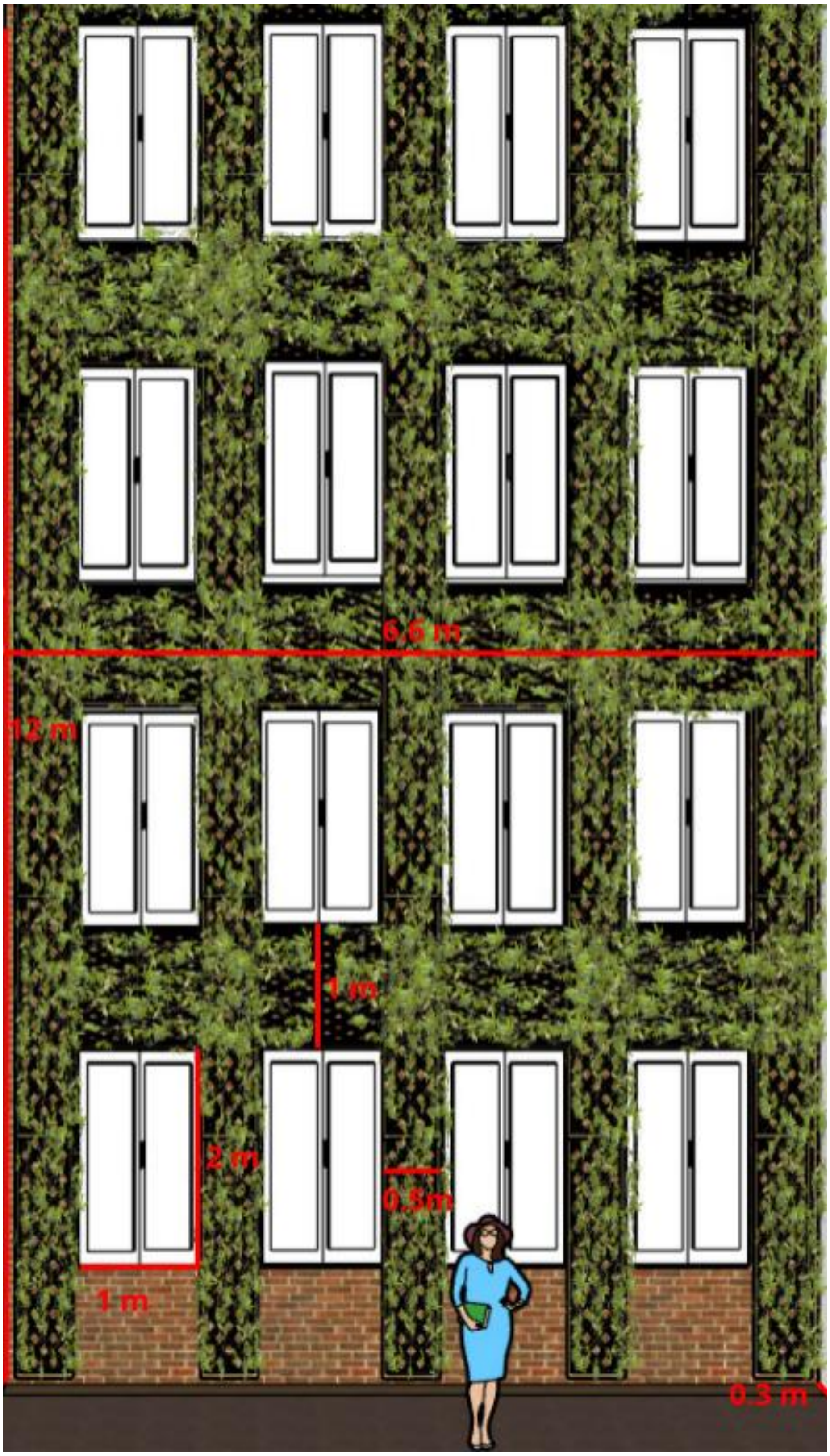


Figure 50: Example of the dimensions of a Green Façade implemented in the Tweede Atjehstraat

ENVI-met setup

To create and simulate the Clematis vitalba on brick walls in ENVI-met Spaces (Figure 51), a custom ENVI-met greening facade was made (Figure 74). The plant thickness: 0.60 m, size for a more pruned plant, Clematis vitalba can at least be 1 (Esveld Shop, n.d.) so that it does not protrude into pedestrian space (sidewalk) too much. The Leaf Area Index (LAI): 5.0 m²/m², a bit on the high end but need to make it reflect the dense and layered vegetation of Clematis vitalba (Gemeente Amsterdam, 2024b; De Bock et al., 2023). The Leaf Angle Distribution (LAD): Was put at 0.70, based on Li et al., (2019). They used Ivy (Hedera helix) to test, same as in for my research because it comes closest to resembling the type of plant that is used.

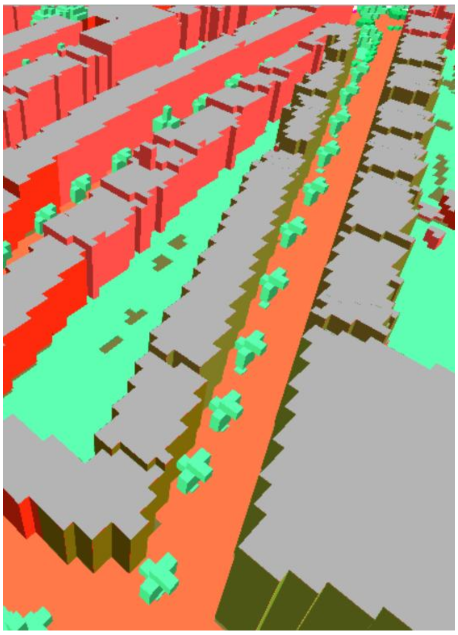


Figure 51: ENVI-met Spaces Green Façade scenario

Scenario Vegetated Pergola

Setup

Setup chapter contains the setup of the street layout after implementation of the NBS (Figure 52) and includes the ENVI-met NBS typology setup in ENVI-met DB.

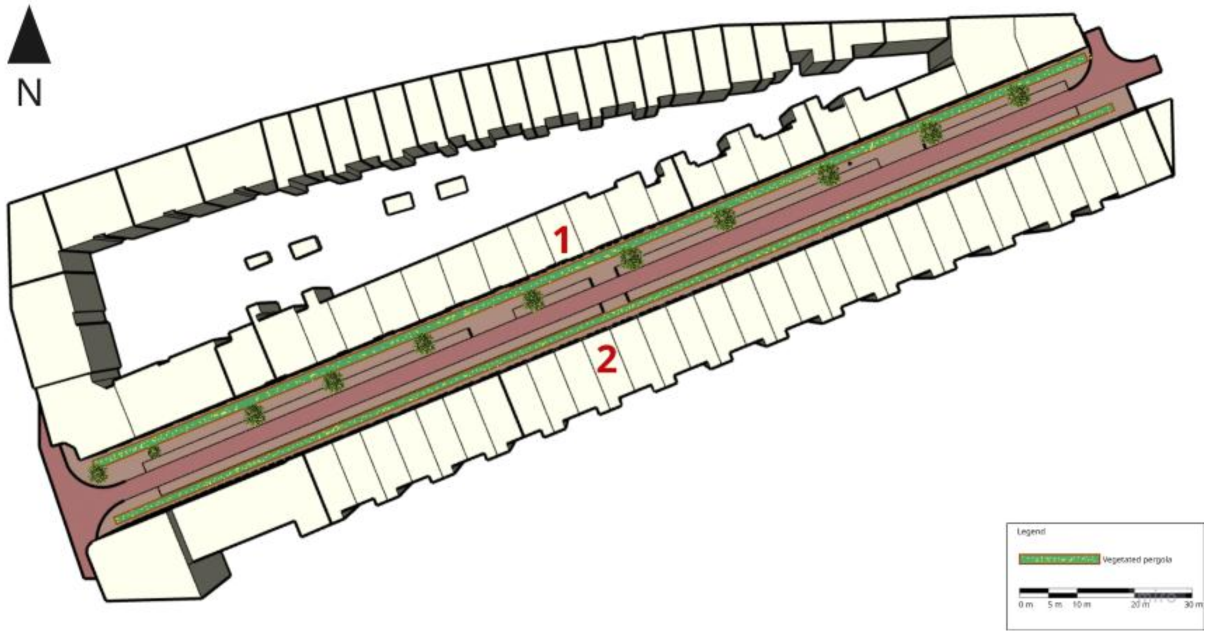


Figure 52: Layout Tweede Atjehstraat Vegetated Pergola scenario

Street layout

Tweede Atjehstraat has trees that lower PET via shade and evapotranspiration, due to their canopy they lower intense solar exposure on the sidewalk. To simulate something similar to a tree by providing shade and evapotranspiration is a vegetated pergola. This pergola will be across the full 206.0 m block length on both sides of the street to add a continuous overhead canopy that intercepts direct solar radiation, reduces MRT and provides evapotranspiration from the vine layer (Kong et al., 2021; Knoll et al., 2023).

The pergola is located on both sidewalks (Figure 53). The pergola on the upper sidewalk is 2 meters wide with one side of the long side is rooted in the tree pits.

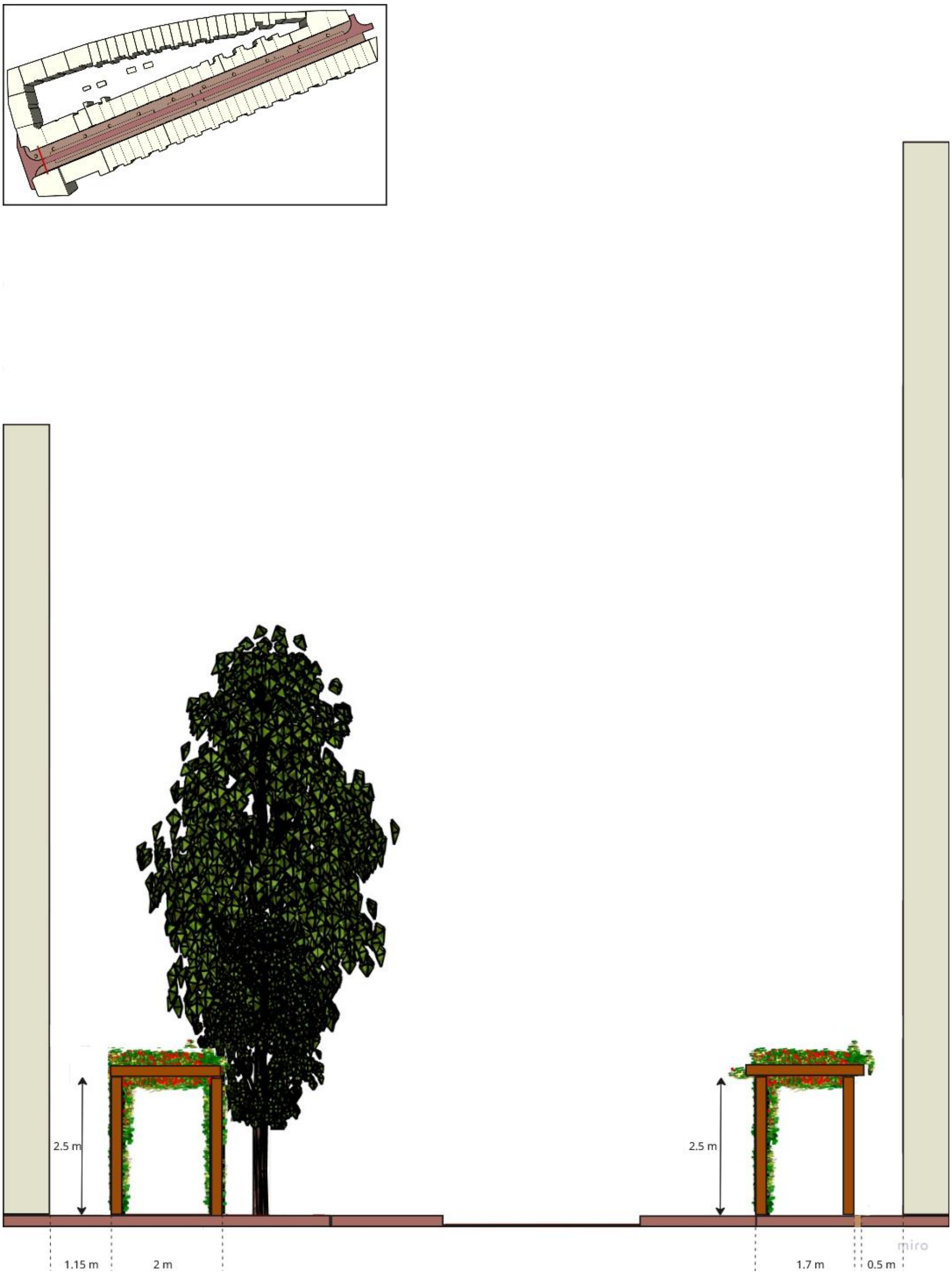


Figure 53: Cross-section Tweede Atjehstraat Vegetated Pergola scenario

This makes sure that there is at least 1,15 meters space between the building facade and the pergola. The pergola on the lower sidewalk is less wide, being 1,7 meters due to space constraints, because the sidewalk itself is just 2,35 meters wide and there should be some clearance from the facade of the building for sightlines and also some space for the honeysuckle to root in (0,35 meters) because there are no tree pits on this side to root in. This and the walking space under the pergolas itself maintains walking space albeit a bit reduced because of the support beams but at least it keeps the street free for traffic. The pergola itself is 2.5 m so that anyone can walk under. On top of the pergola is the 1 m dense honeysuckle vine layer, mounted into the tree pit (upper side) or off the curbside (lower side).

Dimensions of the Vegetated pergolas (example in Figure 54).

Upper row: 206 meters x 2 meters x 2,5 meters

Lower row: 206 meters x 1,7 meters x 2,5 meters

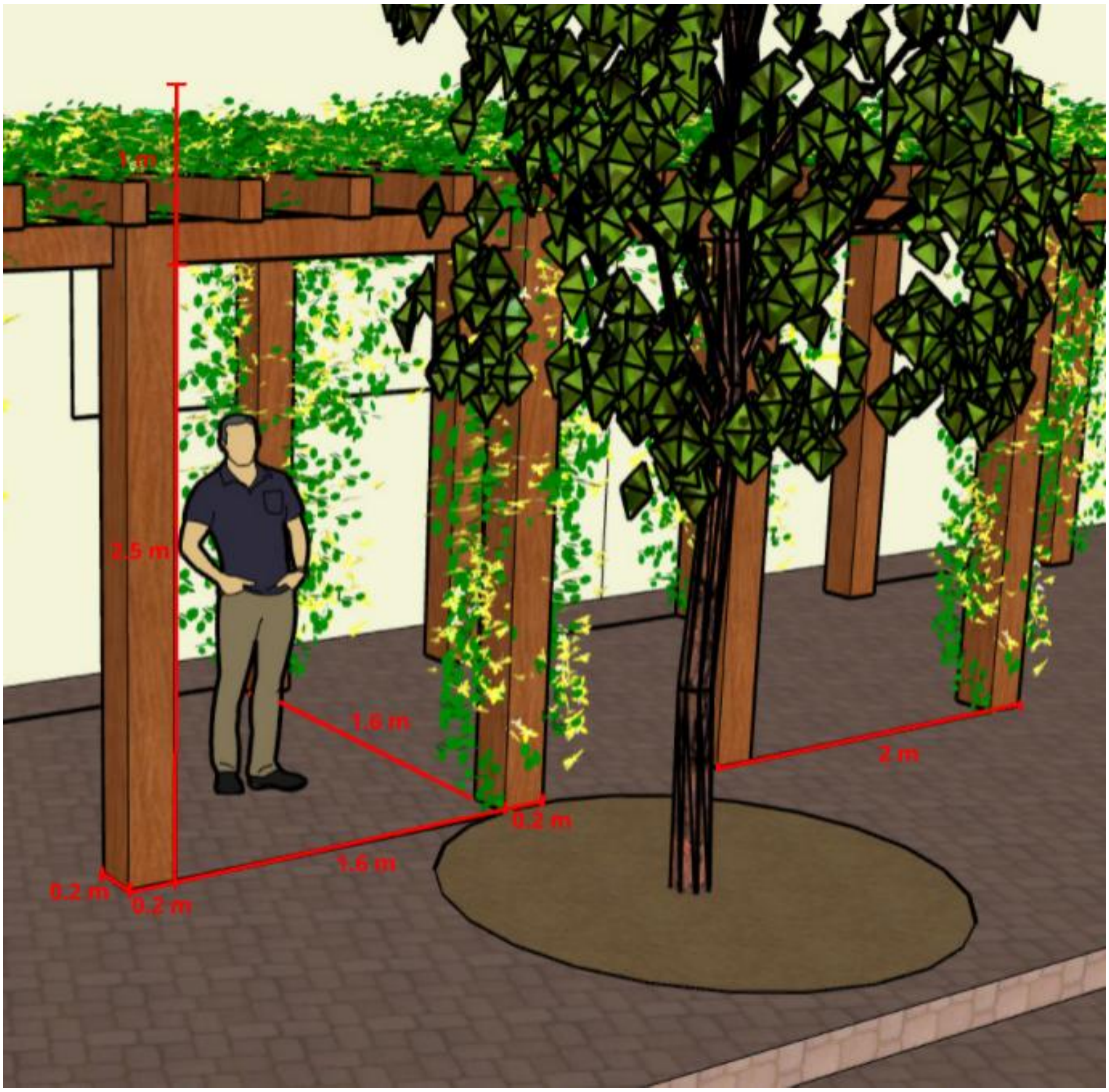


Figure 54: Example of the dimensions of a Vegetated Pergola implemented in the Tweede Atjehstraat

ENVI-met setup

To model a 2.5 m-high pergola with 1 m of honeysuckle (Lonicera periclymenum) in ENVI-met Spaces (Figure 55), a custom dense hedge 1m was modified (Figure 76).

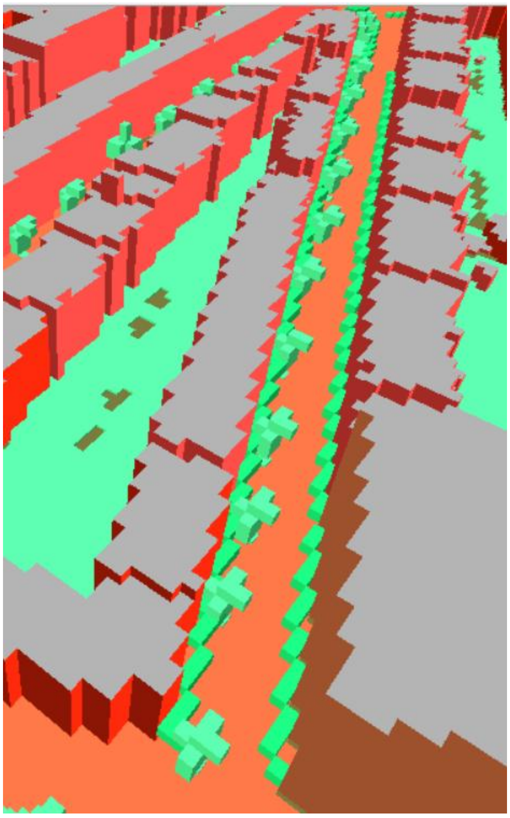


Figure 55: ENVI-met Spaces Vegetated Pergola scenario

Custom specifications:

The plant height is 3.5 m (basically including structure and vine reach). The root zone depth is 1.0 m (standard for a hedge dense in ENVI-met). The LAD profile is [0,0,0,0,0,0,1.0,1.0,1.0]. Only the top three canopy layers (one layer is 0,35m thick, so 3 x 0,35 =1,05 meters) to simulate the 1 meter thick vine cover on top of a 2.5 m pergola structure. The idea on how to create a pergola in ENVI-met came from the ENVI-met forum (Onnoter & Tim, 2023).

4.3 Results: Microclimate, co-benefits and trade-offs

In this part of the results, the design outputs of the NBS scenarios are created and are simulated and their output will be looked at regarding microclimate conditions, such as PET at 18:00 and 23:00 for the whole street and bufferzones, thermal comfort walk at 18:00, the CO2 sequestration at 18:00, the added bioretention surface area (m2) and the trade-offs.

4.3.1 Scenario Bioswale

Microclimate performance

Looking at the ENVI-met PET map at 18:00 of the Tweede Atjehstraat, most of the area has high PET, exceeding 53.90 °C (Figure 56). But by transforming these parking strips into bioswales, you will get six linear beds (to see them located in the ENVI-met Leonardo map see Figure 73 in the Annex). As you can see when comparing with the baseline PET map you can see a narrow strip of more lightly colored zones on the lower side of the street, overlapping with the bioswales' location (between 51.20-53.90 °C). But you can also see on the upper side of the street the impact of them. Notably on the left side of the upper side of the street you see several smaller spots of light brown colors, ranging from 48.50-51.20 °C.

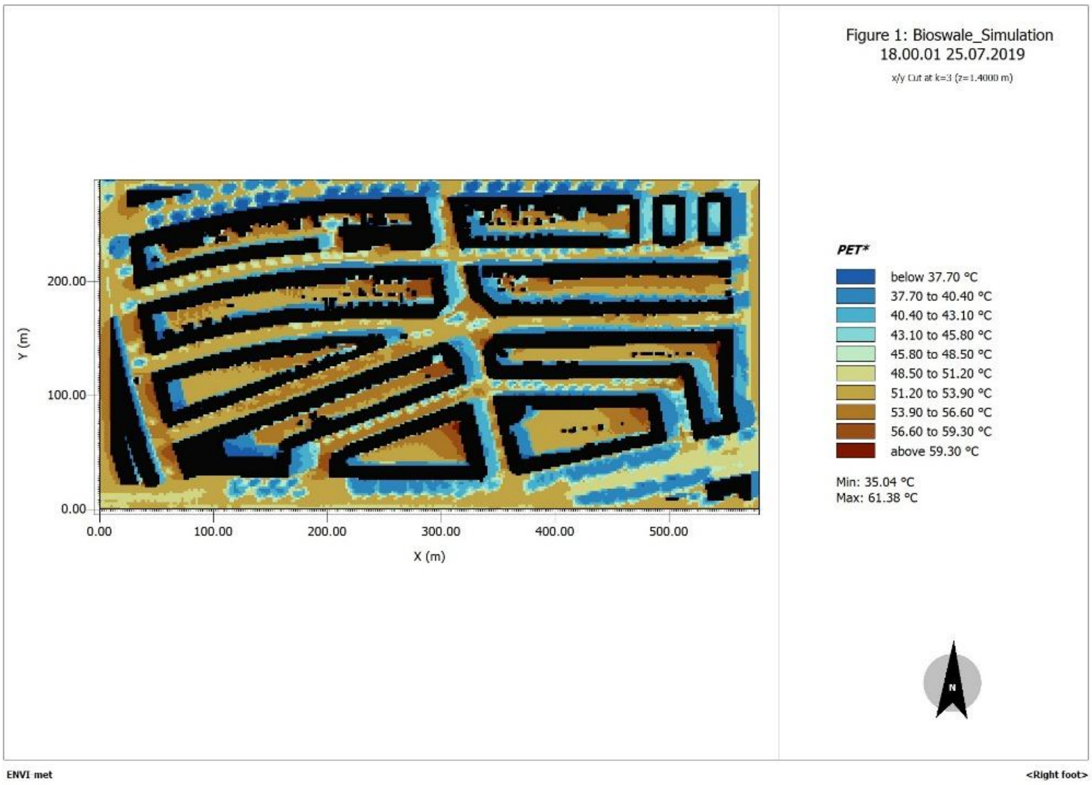


Figure 56: Bioswale scenario Neighborhood PET map at 18:00

Air temperature and PET

The values of the air temperature and PET tables of the whole street will be compared in the analysis of this bioswale scenario chapter.

Table 3 shows the results of the Bioswale scenario regarding air temperature reduction of the whole street.

Time	Before Intervention	After Intervention	Δ (°C)
18:00	34.14 °C	34.07 °C	–0.07 °C
23:00	28.996 °C	28.947 °C	–0.049 °C

Table 3: Temperature reduction whole street

Table 4 shows the results of the Bioswale scenario regarding PET reduction of the whole street.

Time	Before Intervention	After Intervention	Δ (°C)
18:00	52.979 °C	52.729 °C	–0.250 °C
23:00	28.115 °C	27.829 °C	–0.285 °C

Table 4: PET reduction whole street

Bioswale bufferzone comparison

The tables posted here with the results of the bufferzones regarding air temperature and the PET will be discussed in the analysis at the end of this Bioswale scenario chapter.

Table 5 shows the results of the Bioswale scenario regarding air temperature reduction of the bufferzones.

Row	Time	Baseline (°C)	Bioswale (°C)	Δ (°C)
Upper	18:00	34.16 °C	34.10 °C	–0.06 °C
	23:00	29.00 °C	28.95 °C	–0.05 °C
Lower	18:00	34.12 °C	34.04 °C	–0.08 °C

	23:00	28.99 °C	28.94 °C	–0.05 °C

Table 5: Air temperature comparison bufferzones

Table 6 shows the results of the Bioswale scenario regarding PET reduction of the bufferzones.

Row	**Time**	**Baseline (°C)**	**Bioswale (°C)**	**Δ (°C)**
Upper	18:00	53.85 °C	53.67 °C	–0.18 °C
	23:00	27.94 °C	27.66 °C	–0.28 °C
Lower	18:00	52.71 °C	52.35 °C	–0.36 °C
	23:00	28.09 °C	27.72 °C	–0.37 °C

Table 6: PET table comparison bufferzones

Thermal comfort walk

Figure 57 and Figure 58 show the route during the bioswale scenario at 18:00. Because every route is walked on the sidewalk within 2 meters distance of the NBS implemented, the exact route must be placed in the baseline scenario (Figure 59) to see the comparison in thermal values with the same route but then walked in the baseline scenario.

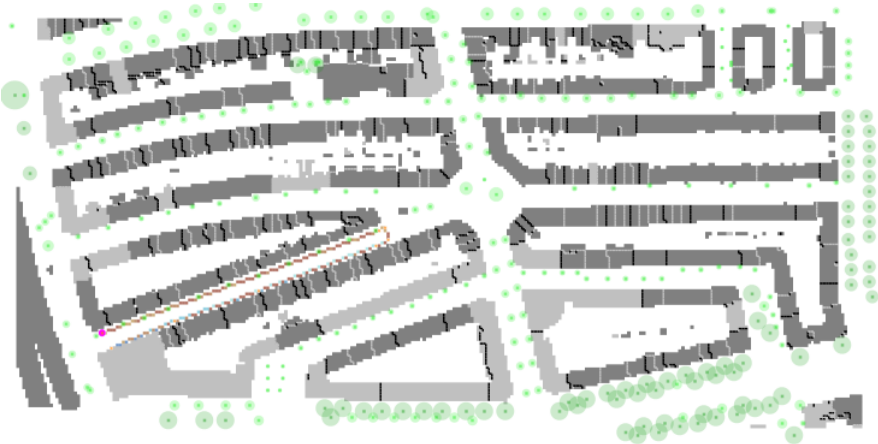


Figure 57: Bioswale scenario PET walk at 18:00 (excluding bioswale from the visualization so you can see the PET outcome)

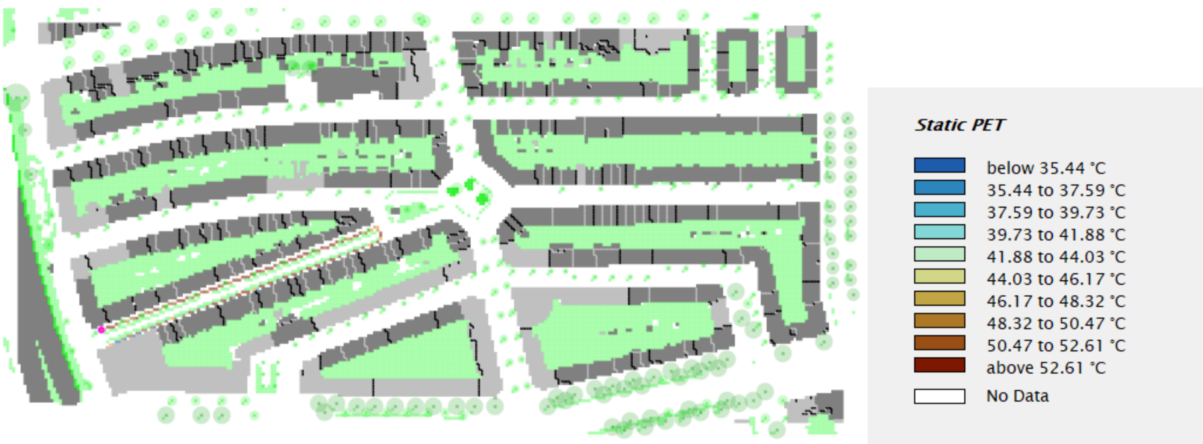
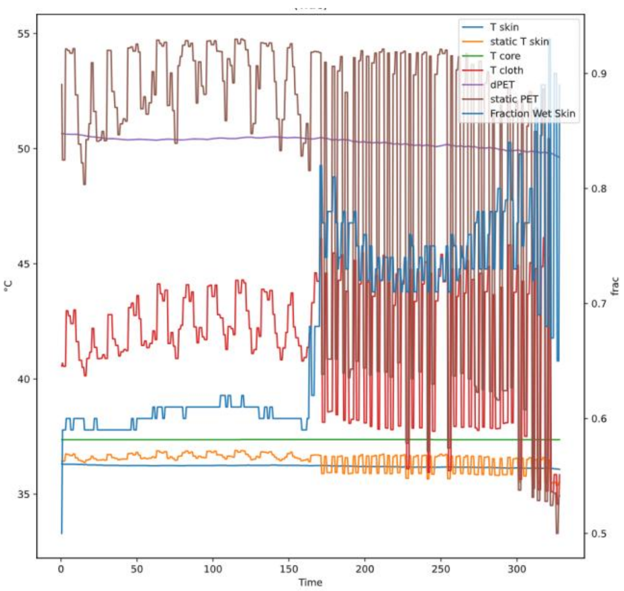


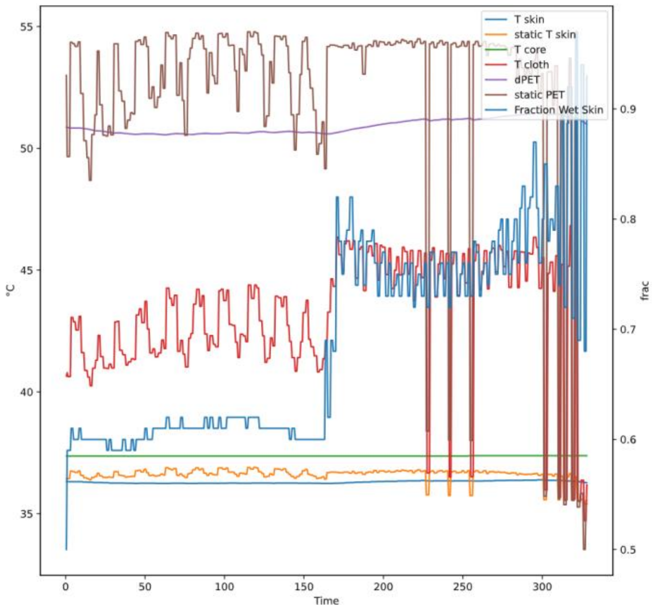
Figure 58: Bioswale scenario PET walk at 18:00 (including bioswale)

Figure 59: Baseline scenario PET walk Bioswale route at 18:00



Graph 4: Bioswale scenario PET walk graph at 18:00

The brown "static PET" lines from the two plots barely move in the street-tree section of the route (0-175 s) when you align the graphs. Both the baseline and bioswale runs peak at around 54 °C in direct sunlight during that first half, and then drop to about 50 °C under the tree canopy. The baseline drops into the mid-30 °C, reaching around 35 °C at its greatest shade, when you turn around into the north-facing wall (lower side of the street) (175-350 s) (Graph 5). The bioswale line also drops slightly, reaching about 34 °C at its lowest. In contrast the sunny-wall (upper side of the street) peaks remain really constant. The addition of the bioswale NBS in this setting reduces the temperature variations you experience throughout the route by approximately 1 °C at the coolest spots (Graph 4).



Graph 5: Baseline scenario PET walk graph Bioswale route at 18:00

Environmental co-benefits

Part of the environmental co-benefits are CO_2 sequestration and added bioretention surface area.

CO_2 sequestration (mg/m³)

In table 7 you have the values of the different bioswale rows and the whole street regarding CO_2 sequestration. Lower row of the bioswales have a higher amount of CO_2 sequestration.

In table 7 you got the uptake of CO2 of the whole street and bufferzones at 18:00.

Location	**Baseline CO_2 (mg/m³)**	**Bioswale CO_2 (mg/m³)**	**Δ (mg/m³)**
Upper row	719,65	719,39	–0,2612
Lower row	719,65	719,37	–0,2876
Whole street	719,66	719,42	–0,2416

Table 7: Bioswale scenario CO2 uptake whole street and bufferzones at 18:00

In Figure 60 you can see that the most uptake of CO2 corresponds to the area where the bioswales are located. With an absolute difference of CO2 uptake compared to the baseline scenario of 0.33-0.37 mg/m³.

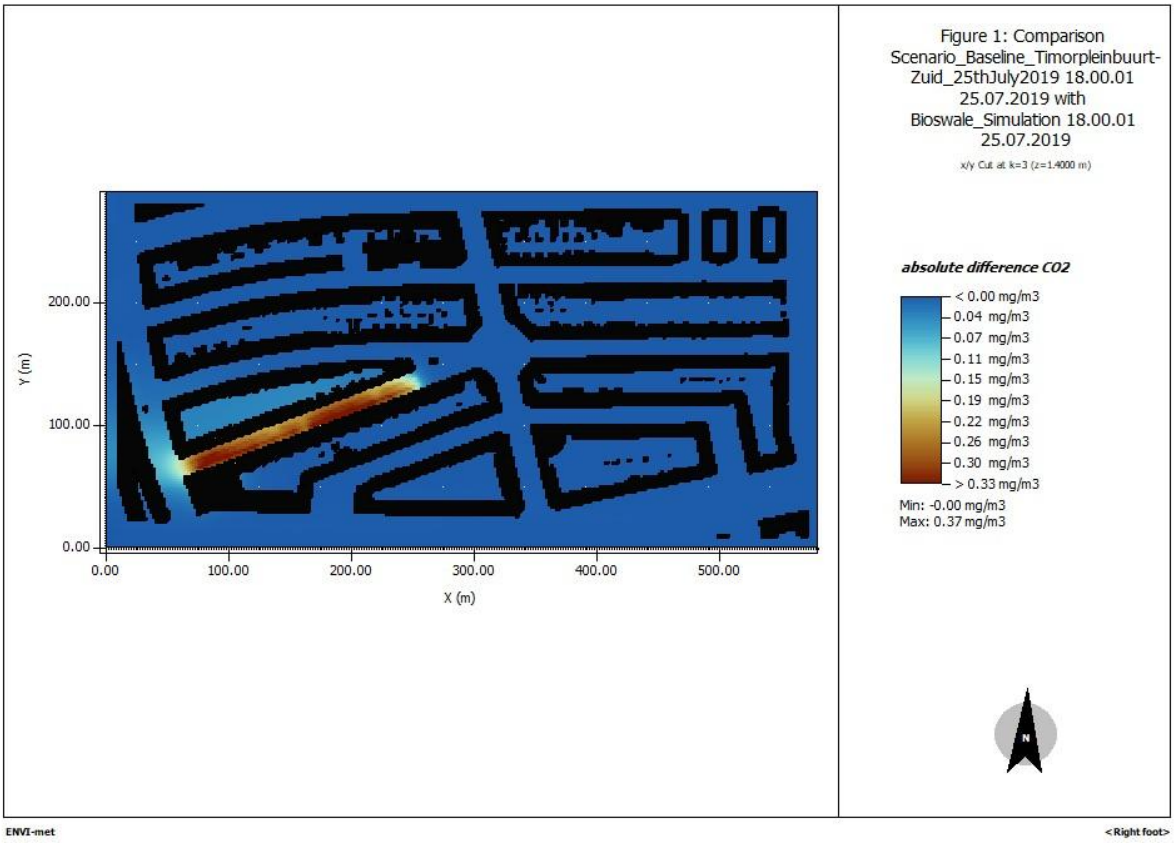


Figure 60: CO2 sequestration Bioswale scenario

Bioretention surface area

The upper row of bioswale strips is made up of four separate strips that are 70.18 m, 16.55 m, 56.41 m, and 30.77 m long (Figure 61). They replace the parking area in the street and each strip is 2 m wide. The lower row has two strips of 95.24 m and 96.85 m also being 2 m wide each. So it adds all together 732.01 m2 of biorention surface area.

Social & Well-being co-benefits

Increase in vegetated area

Parking lots have been used as places where bioswale could be implemented.

Square meters of each bioswale:

Upper part of the street:

- 140,36 m2

- 33,1 m2

- 112,82 m2

- 61,54 m2

Lower part of the street:

- 190,48 m2

- 193,71 m2

Total square meters added of vegetated area= 732,01m2

Tweede Atjehstraat total square meters: 3369,312 m2

Trade-offs

Implementation cost (€/year): € 15.1m2 x 732.01 m2= € 11053,35 year

Ground space requirement: High, takes up all the parking space.

Impact on access/use: 732,01 m2 of parking space lost, does not interfere with the walking area.

Vegetation effects on visibility and potential safety: No effect on visibility.

Analysis

The bioswale scenario generated small microclimate benefits: at 18:00 the street's mean air temperature went from 34.14 °C to 34.07 °C (-0.07 °C) and at 23:00 from 28.996 °C to 28.947 °C (-0.049 °C), while the PET dropped by 0.25 °C at 18:00 (52.979 °C to 52.729 °C) and by 0.285 °C at 23:00 (28.115 °C to 27.829 °C). In the two-meter buffer immediately adjacent to the bioswale strips air temperature cooled by 0.06 °C (upper row) and 0.08 °C (lower row) at 18:00 (both about 0.05 °C at 23:00) and PET fell by up to 0.36 °C in the lower row at 18:00 and by 0.37 °C at 23:00. The CO_2 concentrations across the street dropped by 0.2416 mg/m³ (719.66 mg/m³ to 719.42 mg/m³), with a little bit larger reductions in the buffer zones (-0.2612 mg/m³ upper, -0.2876 mg/m³ lower). The bioswale scenario adds 732.01 m² of bioretention area (which is about 21.73% of street area, street surface area=3369.31 m2). The bioswales added 732.01 m² of planted area. This helps with mental well-being, aesthetics and brings pollinator habitat. Trade-offs would be the loss of parking space and the high total implementation costs (if the municipality takes care of the street instead of the residents). No effect on visibility because of low height of vegetation.

4.3.2 Scenario Green Façade

Microclimate performance

Looking at the ENVI-met PET map at 18:00 of the green façade scenario you can see that in the Tweede Atjehstraat most of the area has a high PET (exceeding 53.00 °C) (Figure 61) than the baseline scenario (Figure 40). By adding these green façades you will get two facades in the street on both building rows that cool locally (to see them located in the ENVI-met Leonardo map see Figure 75 in the Annex). But what you see when comparing with the baseline PET map you can see a more darker blue narrow strip on the lower side of the street, corresponding with the green façades' locations on the lower side of the street (between 35.00-38.00 °C) and for the baseline it is around 40.40-43.10 °C. The colors of the legend are the same but each have a different temperature range, that's why it can look like it is warmer after the implementation of the scenario, even though the PET is a bit lower. On the upper side of the street the PET level at the wall was about 40.40-48.50 °C, while the PET level of the green façade is about 35.00-47.00 °C.

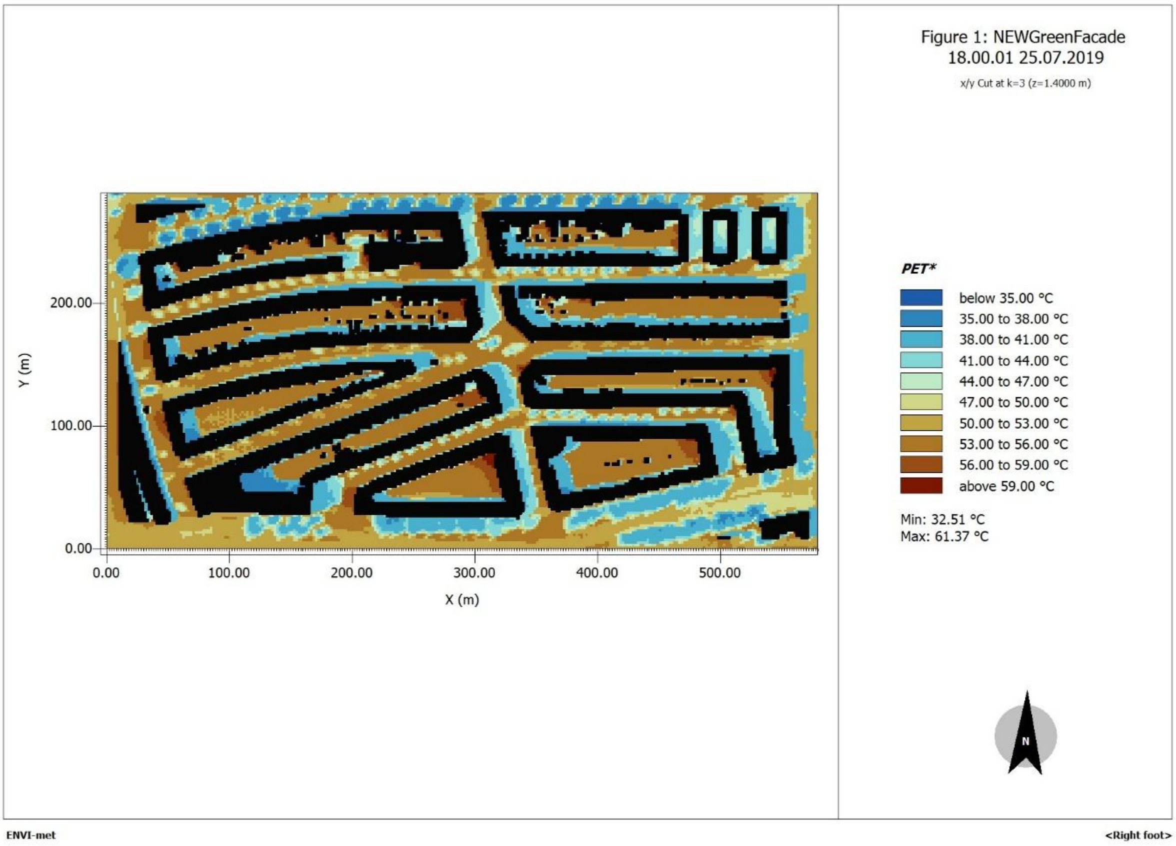


Figure 61: Green Façade scenario PET map at 18:00

Air temperature and PET

The values of the air temperature and PET tables of the whole street will be compared in the analysis of this Green Façade scenario chapter.

Table 8 shows the results of the Green Façade scenario regarding air temperature reduction of the whole street.

Time	Baseline (°C)	Green Facade (°C)	Δ (°C)
18:00	34.140	33.687	–0.453
23:00	28.996	28.799	–0.197

Table 8: Temperature reduction whole street Green Façade scenario

Table 9 shows the results of the Green Façade scenario regarding PET reduction of the whole street.

Time	Baseline (°C)	Green Facade (°C)	Δ (°C)
18:00	52.979	51.716	–1.263
23:00	28.115	26.947	–1.169

Table 9: PET reduction whole street Green Façade scenario

Green façade bufferzone comparison

The tables posted here with the results of the bufferzones regarding air temperature and the PET will be discussed in the analysis at the end of this Green façade scenario chapter.

Table 10 shows the results of the Green façade scenario regarding air temperature reduction of the bufferzones.

Row	Time	Baseline (°C)	Green Façade (°C)	Δ (°C)
Upper	18:00	34.195 °C	33.732 °C	–0.463 °C
	23:00	29.003 °C	28.804 °C	–0.199 °C
Lower	18:00	34.099 °C	33.647 °C	–0.452 °C
	23:00	28.987 °C	28.787 °C	–0.200 °C

Table 10: Air temperature table comparison bufferzones

Table 11 shows the results of the Green façade scenario regarding PET reduction of the bufferzones.

Row	Time	Baseline (°C)	Green Façade (°C)	Δ (°C)
Upper	18:00	49.815 °C	46.813 °C	–3.002 °C
	23:00	29.353 °C	27.849 °C	–1.504 °C
Lower	18:00	50.716 °C	49.022 °C	–1.694 °C
	23:00	28.588 °C	27.334 °C	–1.254 °C

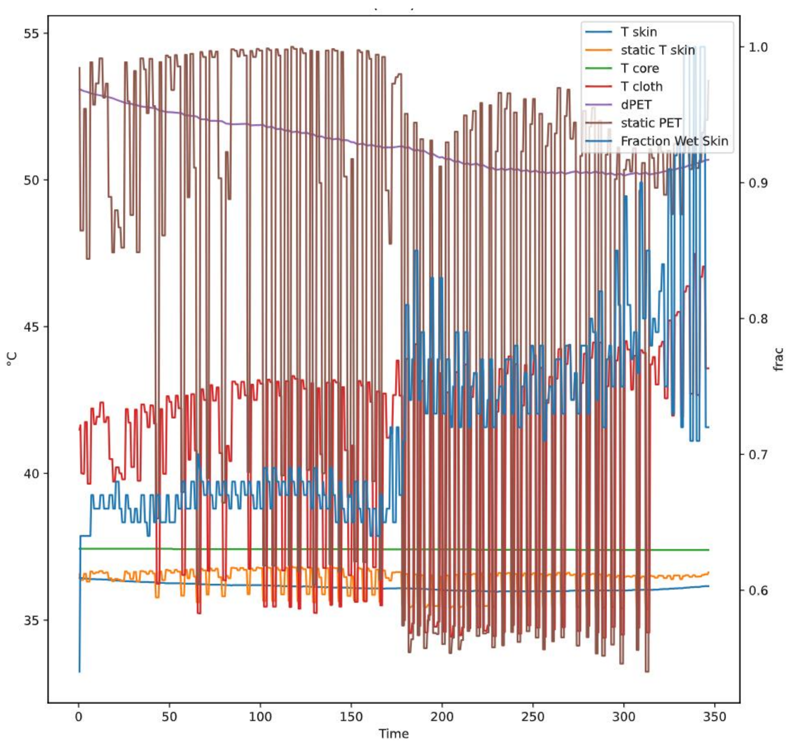
Table 11: PET table comparison bufferzones

Thermal comfort walk

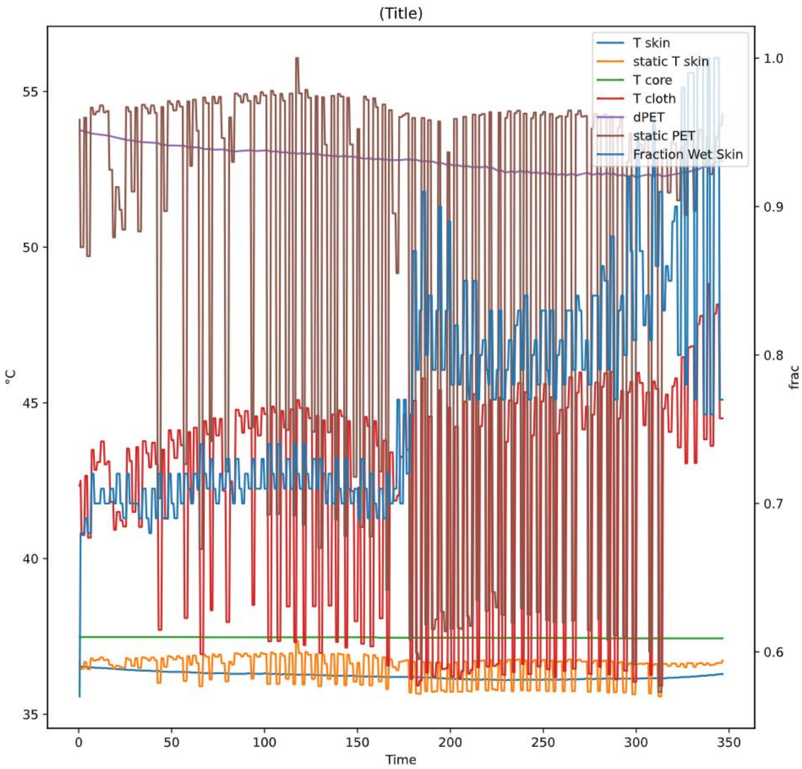
Figure 62 shows the static PET route in BIO-met. As you can see on both sides the blue spots are the parts during the route where you are within 2 meters of the wall and experience a lower static PET.

Figure 62: Green facade scenario PET walk at 18:00

In the baseline scenario the static PET only cools to an average of 41 °C under the street trees (Graph 7) but when the green façade is added, the temperature drops to about 37 °C (Graph 6). The coolest static PET is at around 37.5 °C when there is no vegetation next to the north-facing wall, and it falls to about 33.5 °C when there is vegetation. The green façade in both shaded areas provides considerably deeper thermal comfort by removing about 4 °C from the lowest static PET points.



Graph 6: Green façade scenario PET walk graph at 18:00



Graph 7: Baseline PET walk graph with Green Facade route at 18:00

Environmental co-benefits

Part of the environmental co-benefits are CO_2 sequestration and added bioretention surface area.

CO_2 sequestration (mg/m^3)

Outcomes average CO2 sequestration whole street are not available because a green façade modeled in ENVI-met does not provide a calculation of CO2 sequestration (Bruse et al., 2023).

Bioretention surface area

A green facade does not directly add a lot of surface area, but by holding water in the plant's canopy and delaying the throughflow to the plant's bottom connected to the soil, it can intercept rainfall and delay rain water surface runoff (Tiwary et al., 2018). This helps delay rain discharge and thus helps with a better rain water capture by the adjacent tree pits and facade garden which can lower peak surface flows a little (Gemeente Amsterdam, n.d., b).

In this scenario the narrow beds at the ground level of the building facades on both sides of the street are planted with green façades. These beds only have direct rainfall so there is no surface rainwater flow from the pavement or roofs, because the adjacent sidewalk slopes toward the road. This makes it that you have to calculate the amount of rainwater that falls on the planted area directly and seeps in to the soil to determine their runoff-reduction.

A façade garden can be 45-60 cm wide but then has to have at least 2 meters of walking space available adjacent to it (Gemeente Amsterdam n.d.). That's possible for the sidewalk width of the upper half (5,15 m) but not for the sidewalk on the lower half of the street (2,35 m). So there only a façade garden of 35 cm is possible. Net planted lengths are 160.07 m (upper) and 143.65 m (lower) after deducting the unplanted doors (29 × 1.825 m = 52.93 m on the upper side, 38 × 1.825 m = 69.35 m on the lower side). The ground-level façade gardens add 122.31 m² of added bioretention (permeable soil) area (equal to about 3.63% of street area).

Social & Well-being co-benefits

Increase in vegetated area

Upper row

Buildings in the street on the upper row are on average 15 meters high, including the attic floor that is in the roof. The plant will be maintained at a height of 12 meters max. Because there won't be a trellis there to attach to. The row of buildings is about 213 meters long. So having a continuous green façade across the whole row would be an area of 12x213=2556 m2 (including the windows and doors).

Subtracting the doors:

Each block has two adjacent doors so 1.825 m wide by 2.00 m high (standard door height). Upper row has about 29 blocks which makes the total door area be 29×(1.825×2.00)=105.9m2

Subtracting the windows:

Ground floor has 2 windows , floors 1–3: 3 windows each. So the total windows per block = 2 + (3×3)= 11 windows per block. Assume each window size is 1m wide × 2m high=2 m². Window area per block = 11×2.00= 22.0 m². Total window area: 29×22.0=638.0m2

Planted façade area:

=2556−105.9−638=1812.1m2

Lower row

Buildings in the street on the lower row are on average 16,5 meters high, including the attic floor that is in the roof. The plant will be maintained at a height of 13,5 meters max. Because there won't be a trellis there to attach to. So having a continuous green façade across the whole row would be an area of 13.50×213=2875.5m2 (including the windows and doors).

Subtracting the doors:

Each block has two adjacent doors so 1.825 m wide by 2.00 m high (standard door height). Lower row has about 38 blocks which makes the total door area be 38×(1.825×2.00)=138.7m2

Subtracting the windows:

Ground floor has 2 windows , floors 1–3: 3 windows each. So the total windows per block = 2 + (3×3)= 11 windows per block. Assume each window size is 1m wide × 2m high=2 m². Window area per block = 11×2.00= 22.0 m². Total window area: 38×22.0=836.0 m2

Planted façade area:

2875.5−138.7−836=1900.8 m2.

Total increase in vegetated area

1812.1+1900.8=3712.9 m2

Trade-offs

Implementation cost (€/year): € 10 m2 x 1900.8 m2= € 19008 year

Ground space requirement: Low, only the facade gardens in the street will be needed.

Impact on access/use: Minimal interference, green façade does not obstruct the walking area.

Vegetation effects on visibility and potential safety: Could block views from the window, can reduce perception of safety.

Analysis

The green façade scenario helped with cooling. At 18:00 the street's mean air temperature lowered from 34.14 °C to 33.69 °C (-0.453 °C) and at 23:00 from 28.996 °C to 28.799 °C (-0.197 °C). PET fell by 1.263 °C at 18:00 (52.979 °C to 51.716 °C) and by 1.169 °C at 23:00 (28.115 °C to 26.947 °C). In the two-meter buffer zone alongside the walls, the air temperatures cooled by 0.463 °C (upper) and 0.452 °C (lower) at 18:00 (0.199 °C and 0.200 °C at 23:00). In the buffer zones PET dropped by up to 3.002 °C at 18:00 (upper) and 1.694 °C (lower), at 23:00 there was a PET relief of 1.504 °C and 1.254 °C respectively. The intervention had no measurable impact of CO_2 sequestration because of those because the ENVI-met program doesn't have parameters to calculate the CO_2 sequestration of a green facade (Bruse et al., 2023). The green facades adds 122.31 m² of bioretention area (3.63% of street area) via the façade gardens. The green façades add 3712.9 m² of vertical planting with no loss of parking space. This scenario improves the street-level greenery, biodiversity habitat, and building shading. Trade-offs and the high total implementation costs yearly. Could block views from the window which could reduce perception of safety for people.

4.3.3 Scenario Vegetated Pergola

Microclimate performance

In Figure 63 you can see the PET level at 18:00 after the implementation of the pergola NBS type. On both sidewalks of the street you can see a noticeable drop in PET (light blue strip on the sidewalk) (to see them located in the ENVI-met Leonardo map see Figure 77 in the Annex). With the PET levels corresponding to the pergola area but in the baseline scenario being around 48.50-53.90 °C while the PET level in the same area in the vegetated Pergola scenario being 39.60-48.00 °C which is a significant drop.

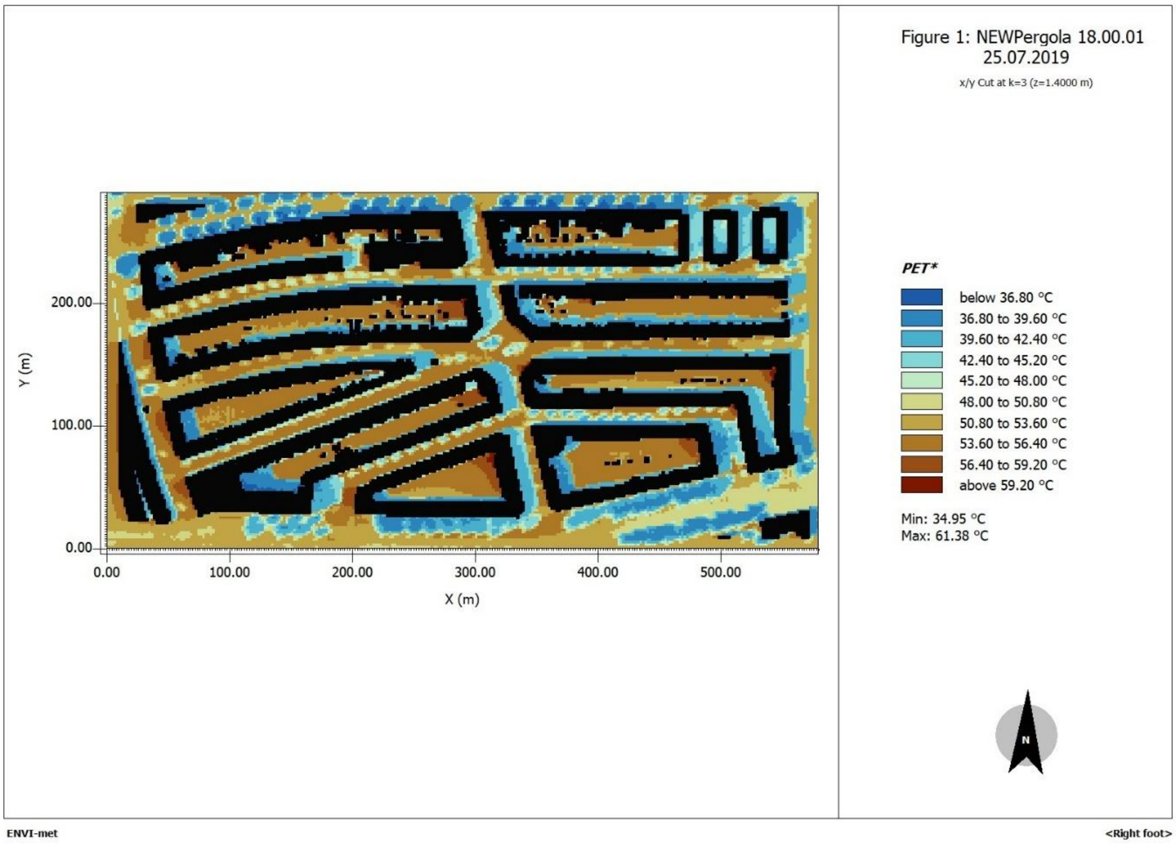


Figure 63: Pergola scenario PET map at 18:00

Air temperature and PET

The values of the air temperature and PET tables of the whole street will be compared in the analysis of this Vegetated Pergola scenario chapter.

Table 12 shows the results of the Vegetated Pergola scenario regarding air temperature reduction of the whole street.

Time	**Baseline (°C)**	**Pergola (°C)**	**Δ (°C)**
18:00	34.140	34.081	–0.059
23:00	28.996	28.969	–0.027

Table 12: Temperature reduction whole street

Table 13 shows the results of the Vegetated Pergola scenario regarding PET reduction of the whole street.

Time	**Baseline (°C)**	**Pergola (°C)**	**Δ (°C)**
18:00	52.979	50.932	–2.047
23:00	28.115	27.909	–0.206

Table 13: PET reduction whole street

Pergola bufferzone comparison

The tables posted here with the results of the bufferzones regarding air temperature and the PET will be discussed in the analysis at the end of this Vegetated Pergola scenario chapter.

Table 14 shows the results of the Vegetated Pergola scenario regarding air temperature reduction of the bufferzones.

Row	Time	Baseline (°C)	Pergola (°C)	Δ (°C)
Upper	18:00	34.176	34.109	–0.067
	23:00	29.003	28.975	–0.028
Lower	18:00	34.100	34.037	–0.063
	23:00	28.990	28.962	–0.028

Table 14: Air temperature table comparison bufferzones

Table 15 shows the results of the Vegetated Pergola scenario regarding PET reduction of the bufferzones.

Row	Time	Baseline (°C)	Pergola (°C)	Δ (°C)
Upper	18:00	51.933	47.579	–4.354
	23:00	28.760	28.552	–0.208
Lower	18:00	51.786	49.366	–2.420
	23:00	28.321	28.141	–0.180

Table 15: PET temperature table comparison bufferzones

Thermal comfort walk

As you can see in Figure 64 and 65, most of the part of the BIO-met route is light blue and only when you are not directly under the pergola it is way warmer (brown spots). After implementation of the pergola you can see that the pergola in the upper and lower row reduce the PET by at least 6 °C. Unfortunately the static PET walk graph was not possible to generate because of no Python plugin availability within the WUR PC. Check the Limitations for explanation of it.

Figure 64: Pergola scenario PET walk at 18:00 (without the pergola visible)

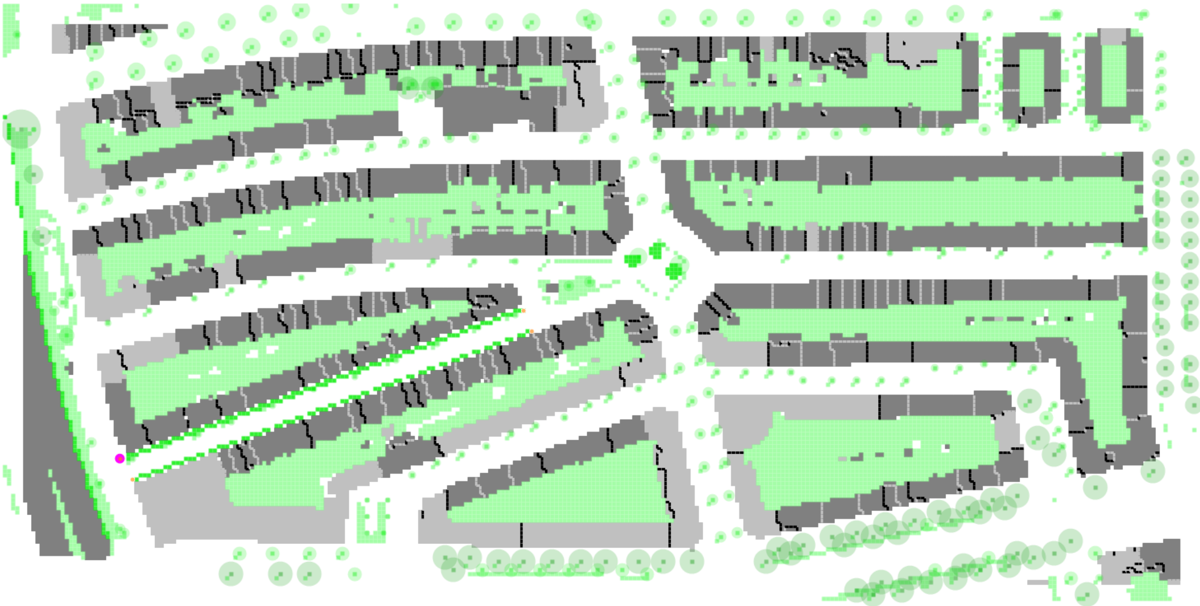


Figure 65: Pergola scenario PET walk (cannot see the PET level because it is located under the Vegetated Pergola).

Environmental co-benefits

Part of the environmental co-benefits are CO_2 sequestration and added bioretention area.

CO_2 sequestration (mg/ m³)

In Figure 66 you can see the CO2 sequestration of the pergola scenario compared to the baseline scenario. It shows a clear extra CO2 uptake after the implementation of 0-0.22 mg/ m³.

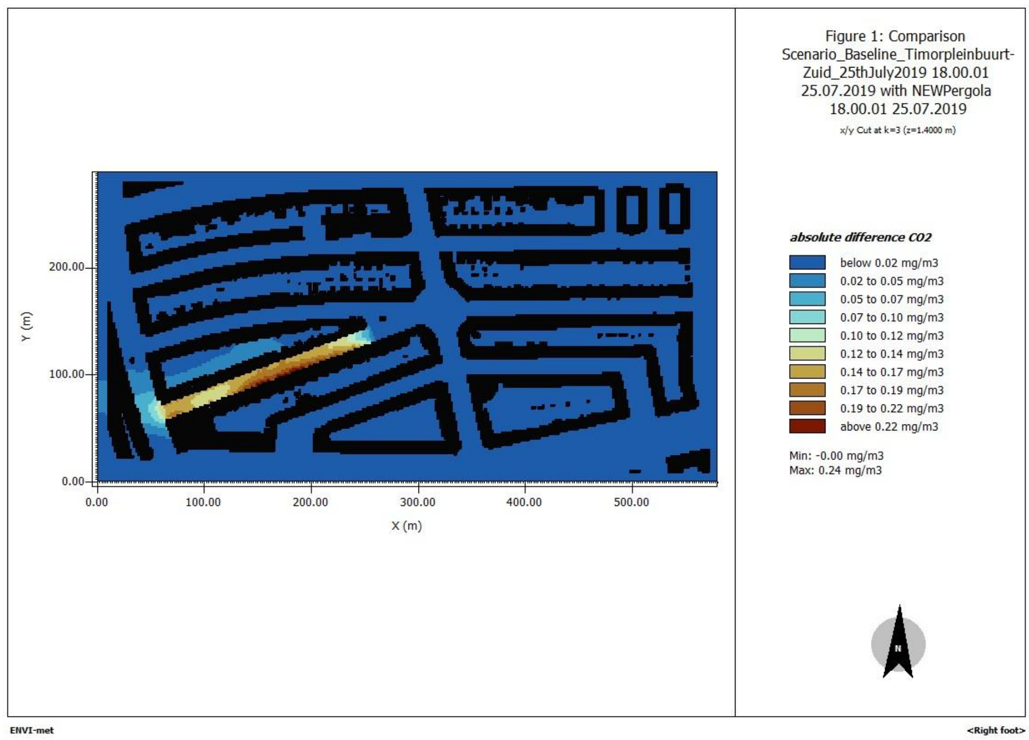


Figure 66: Pergola scenario CO2 uptake at 18:00

In table 16 it shows the values of the uptake of CO2 of the different pergola rows and the whole street. Lower row of the pergola has a higher amount of CO_2 sequestration. In Figure 66 you can see that the most uptake of CO2 corresponds to the area where the bioswales are located.

Location	Baseline CO_2 (mg/m³)	Pergola CO_2 (mg/m³)	Δ (mg/m³)
Upper row	719,744	719,639	–0.1052
Lower row	719,685	719,535	–0.1504
Whole street	719,661	719,521	–0.1398

Table 16: Vegetated Pergola scenario CO2 uptake whole street and bufferzones at 18:00

Bioretention surface area

Beneath and next to the pergola on the building-facing side of the lower row is a 0.35 m-wide soil strip runs 206 m. It could function a bit similarly to a green façade regarding catching -and slowing down rainwater drops flow (Tiwary et al., 2018). This helps delay rain discharge and then helps with a better rain water capture by the adjacent tree pits which can lower peak surface rainwater flows a little bit (Tiwary et al., 2018).The greenery growing on the facade in the upper row is rooted in the tree pit. But the lower row is rooted into a soil strip. In the pergola scenario a narrow 0.15 m-wide soil strip runs 206 m on the sidewalk next to the base of the pergola side facing the building and this is the only area of bioretention surface area added in the scenario which brings it to 30.9 m2.

Social & Well-being co-benefits

Total increase in vegetated area

Upper row pergola: 2mx 206 m= 412 m2

Lower row pergola: 1,7m x 206m= 350,2 m2

Total increase in vegetated area: 762,2 m2

Trade-offs

Implementation cost (€/year): € 100,7 m2 x 762,2 m2= €76753,54 year

Ground space requirement: Medium, only the poles use the ground space

Impact on access/use: Limits functional walking area on both sides of the street by a bit.

Vegetation effects on visibility and potential safety: Overhead structure may reduce perceived openness and block views, can reduce perception of safety.

Analysis

The vegetated pergola scenario brought some cooling in the street. At 18:00 the mean air temperature reduced from 34.14 °C to 34.08 °C (-0.059 °C) and at 23:00 from 28.996 °C to 28.969 °C (-0.027 °C). PET lowered by 2.047 °C at 18:00 (52.979 °C to 50.932 °C) and by 0.206 °C at 23:00 (28.115 °C to 27.909 °C). In the 2 m buffer around and under the pergola, the air temperature cooled by 0.067 °C (upper row) and 0.063 °C (lower row) at 18:00 (and about 0.028 °C at both rows at 23:00). In this buffer zone the PET dropped by up to 4.354 °C (upper) and 2.420 °C (lower) at 18:00, with at 23:00 a drop off of 0.208 °C (upper) and 0.180 °C (lower). CO_2 levels dropped by 0.1398 mg/m³ on average (719.661 mg/m³ to 719.521 mg/m³) and with buffer-zone drops of 0.1052 mg/m³ (upper) and 0.1504 mg/m³ (lower). The soil strip at the pergola of the lower row added 30.9 m2 of added bioretention surface area which is about 0.92% of the total Tweede Atjehstraat street surface. The vegetated structure adds 762.2 m² of planted area (412 m² upper row, 350.2 m² lower row). Parking spaces still available. The pergola itself creates a shaded structure that can reduce perceived openness and block views because of the vegetated roof which could reduce perception of safety.

4.3.4 NBS scenarios compared

In this part of the results the three NBS scenarios will be compared to each other.

The green façade scenario has the strongest whole street-scale cooling (air temperature-wise) both at 18:00 (−0.45 °C air, −1.26 °C PET at 18:00) and at 23:00 (−0.20 °C air, −1.17 °C PET at 23:00), compared with the bioswale's relatively low −0.07 °C air/−0.25 °C PET (18:00) and −0.05 °C air/−0.29 °C PET (23:00) and the pergola's −0.06 °C air/−2.05°C PET (18:00) and −0.03 °C air/−0.21 °C PET (23:00), only the average PET lowering at 18:00 of the pergola is higher than the green facade scenario.

Table 17: Air temperature of the Tweede Atjehstraat in the baseline scenario and the NBS scenarios at 18:00 and 23:00

Time	Baseline (°C)	Bioswale (°C)	Green Façade (°C)	Pergola (°C)
18:00	34.14 °C	34.07 °C	33.69 °C	34.08 °C
23:00	29.00 °C	28.95 °C	28.80 °C	28.97 °C

Table 18: PET of the Tweede Atjehstraat in the baseline scenario and the NBS scenarios at 18:00 and 23:00

Time	Baseline (°C)	Bioswale (°C)	Green Façade (°C)	Pergola (°C)
18:00	52.98 °C	52.73 °C	51.72 °C	50.93 °C
23:00	28.11 °C	27.83 °C	26.95 °C	27.91 °C

Also in the buffer zones the pergola wins regarding thermal relief (up to −4.35 °C PET at Upper row and −0.21 °C PET at Lower row at 18:00), the façade follows up (−3.00 °C PET Upper row/−1.50 °C PET Lower row at 18:00) and the bioswale is the lowest (−0.36 °C PET Upper Row/−0.37 °C PET at Lower row at 18:00). Within the 2 m buffer zone at 23:00, the green façade scenario has the strongest PET thermal relief in both rows, lowering PET by −1.50 °C in the Upper row and −1.25 °C in the Lower row. The bioswale comes in second with modest cooling (−0.28 °C Upper row, −0.37 °C Lower row), while the pergola again offers the least amount of thermal relief (−0.21 °C Upper row, −0.18 °C Lower row).

Table 19: Air temperature reduction of the 2 meter bufferzone of the NBS scenarios compared to the baseline scenario at 18:00 and 23:00 in the Tweede Atjehstraat

Row	Time	Bioswale (°C)	Δ vs base (°C)	Green Façade (°C)	Δ vs base (°C)2	Pergola (°C)	Δ vs base (°C)3
Upper	18:00	34.10 °C	–0.06 °C	33.73 °C	–0.46 °C	34.11 °C	–0.07 °C
	23:00	28.95 °C	–0.05 °C	28.80 °C	–0.20 °C	28.98 °C	–0.03 °C
Lower	18:00	34.04 °C	–0.08 °C	33.65 °C	–0.45 °C	34.04 °C	–0.06 °C
	23:00	28.94 °C	–0.05 °C	28.79 °C	–0.20 °C	28.96 °C	–0.03 °C

Table 20: PET reduction of the 2 meter bufferzone of the NBS scenarios compared to the baseline scenario at 18:00 and 23:00 in the Tweede Atjehstraat

Row	Time	Bioswale (°C)	Δ vs base (°C)	Green Façade (°C)	Δ vs base (°C)2	Pergola (°C)	Δ vs base (°C)3
Upper	18:00	53.67 °C	–0.18 °C	46.81 °C	–3.00 °C	47.58 °C	–4.35 °C
	23:00	27.66 °C	–0.28 °C	27.85 °C	–1.50 °C	28.55 °C	–0.21 °C
Lower	18:00	52.35 °C	–0.36 °C	49.02 °C	–1.69 °C	49.37 °C	–2.42 °C
	23:00	27.72 °C	–0.37 °C	27.33 °C	–1.25 °C	28.14 °C	–0.18 °C

In CO_2 uptake at 18:00, bioswale (−0.242 mg/m³) and pergola (−0.140 mg/m³) reduce concentrations modestly, unfortunately there is no data available for the CO2 level reduction of the green facade scenario.

Table 21: CO2 level Tweede Atjehstraat and its CO2 sequestration of the NBS scenarios compared to the baseline scenario (at 18:00)

Scenario	**Baseline**	**Bioswale**	**Green Façade**	**Pergola**
CO_2	719.66 mg/m³	719.42 mg/m³	n.d.	719.52 mg/m³
Δ vs. Base	n.a.	–0.24 mg/m³	n.d.	–0.14 mg/m³

Table 22: CO2 level of the 2 meter bufferzone and its CO2 sequestration of the NBS scenarios compared to the baseline scenario (at 18:00) in the Tweede Atjehstraat

Row	**Bioswale (mg/m³)**	**Δ vs baseline (mg/m³)**	**Green Façade (mg/m³)**	**Pergola (mg/m³)**	**Δ vs baseline (mg/m³)**
Upper	71.938.638	–0.26122	n.d.	71.963.903	–0.10520
Lower	71.936.680	–0.28763	n.d.	71.953.505	–0.15037

Regarding the added bioretention surface area, bioswale scenario bring 732.01 m² (21.73% of street area), green façades bring 122.31 m² (3.63%) and pergolas bring 30.9 m² (0.92%).

Table 23: Total added bioretention surface area (m²) and share of street of the NBS scenarios

Scenario	**Upper** (m2)	**Lower** (m2)	**Total** (m2 and %)
Bioswale	347.82	384.18	732.01 m2 and 21.73%
Green Façade	72.0315	50.2775	122.31 m2 and 3.63%
Pergola	0	30.9	30.9 m2 and 0.92%

Regarding greenery the façade covers 3712.9 m² of vertical greenery versus 762.2 m² (pergola) and 732.0 m² (bioswale).

Table 24: Combined table of the NBS scenarios' PET reduction, CO2 sequestration, added bioretention surface area and newly added vegetated area of the whole street (Tweede Atjehstraat) compared to the baseline scenario

Metric	**Bioswale**	**Green Façade**	**Pergola**
Whole street air cooling (18:00)	–0.07 °C	–0.453 °C	–0.059 °C
Whole street PET drop (18:00)	–0.25 °C	–1.263 °C	–2.047 °C
Whole street CO_2 concentration drop (18:00)	–0.242 mg/m³	n.d.	–0.140 mg/m³
Added bioretention surface area	732.01 m2	122.31 m2	30.9 m2
Newly vegetated area	732.01 m²	3712.9 m²	762.2 m²

In the table below you see the bufferzones of the NBS scenarios compared at 18:00.

Table 25: Combined table of the NBS scenarios' bufferzone (2 meters wide) PET reduction at 18:00 and CO2 sequestration at 18:00, compared to the baseline scenario

Scenario	**PET buffer-zone Δ (°C) at 18:00**	**CO_2 buffer-zone Δ (mg/m³) at 18:00**
Bioswale	–0.27 °C	–0.274 mg/m³
Green Façade	–2.35 °C	n.d.
Pergola	–3.39 °C	–0.128 mg/m³

The trade-offs of each NBS scenario are in Table 26 where they are also compared to each other. PET reduction around the bioswale scenario is lowest while the one of the vegetated pergola is the highest and the green façade is moderate. Added bioretention surface area of the bioswale scenario definitely is the highest and much lower for the pergola scenario and the green façade scenario. The CO2 uptake for the bioswale is the highest compared to the vegetated pergola which is lowest and the green façade could not be calculated. The amount of vegetated area added street-wise is moderate for the bioswale because it only replaces the parking lots, the green facade (which covers the whole building facades on both sides) and the vegetated pergola which covers both sidewalks on each side of the street are high because they cover a larger surface area. But the ground space requirement of the bioswales are obviously higher because they are implemented in the ground surface while the pergolas only have connection to the surface via the vertical wooden beams which is less than the bioswale, and the green façade is across the length of both sides but is of course only rooted in the small façade garden area along the buildings' length of the street. Implementation costs of the vegetated pergola scenario is the highest (€100.7/m²/year) compared to the bioswale (€15.1/m²/year) or green façade scenario (€10/m²/year). The impact on use of the street is that the bioswales take up the space of the parking lots so cars cannot be parked here and the vegetated pergola can limit the walking area because of its beams but the green façade would not interfere much because it takes up a smaller area of the ground surface compared to the other scenarios. Bioswale's vegetation does not grow high enough to have a limit on the visibility of the street. Pergolas can block sight with their beams and their overhead structure filled with vegetation which can reduce perception of safety. Same with the green façade which if it grows thick it can block views from the windows looking outside which can reduce perception of safety.

Trade-Off Criterion	Bioswale	Pergola	Green Façade
PET reduction	Low	High	Moderate
Bioretention surface area added	High	Low	Low
CO2 uptake	High	Low	n.d.
Vegetated area added	High	High	High
Ground space requirement	High	Moderate	Low
Implementation cost (€/m²/year)	15,1	100,7	10
Impact on access/use	Reduces parking	May obstruct overhead access, limits walking width	Minimal interference with space
Vegetation effects on visibility and safety	No effect on visibility	Overhead structure may reduce perceived openness and block views, can reduce perception of safety	Could block views from the window, can reduce perception of safety

Table 26: Trade-offs between the NBS scenarios: Cost and perceived safety are literature-informed, PET reduction, bioretention surface area, CO2 sequestration, added vegetated area, impact on access/use are study results.

5. Discussion

5.1 How the microclimate conditions vary across Timorpleinbuurt-Zuid during a hot summer day and the biophysical features influencing these variations

To see how the different microclimate conditions across Timorpleinbuurt-Zuid on July 25, 2019, the process began with a 24 hour ENVI-met microclimate simulation of that day. Some notable local variations in air temperature and PET at 18:00 were found in the model's result. More visible than the average air temperature, which ranged between 33.98°C and 35.05°C, was the spread in average PET between the different streets in the neighborhood. In shaded zones, vegetated zones, the PET values could drop to around 45.85°C. But in the unshaded parts of the streets the PET could reach as high as 52.98°C at 18:00.

PET is sensitive to biophysical features, such as tree cover, building facades and surface materials, because these influence shading, albedo, and wind exposure (which make up PET) (Matzarakis et al., 1999; Höppe, 1999; Hidayati et al., 2021). While streets like Tweede Atjehstraat that have little vegetation and primarily impervious surfaces suffered more from heat stress than streets like Benkoelenstraat, which have a higher density of trees and more open pavement. Benkoelenstraat had the lowest PET at 18:00.

Tree density had a big influence on the microclimate of the streets in the neighborhood and it could be seen in comparison to the similarly orientated but less tree planted streets, because the Langkatstraat and

Benkoelenstraat that had continuous canopies and vegetated verges had noticeably lower PET values at 18:00 and as seen in Figure 36 (all the blue or lighter colored circular shapes in the streets). This demonstrates the cooling effects of shade and evapotranspiration during the day, also seen in the literature on ENVI-met microclimate simulation of the effect of urban vegetation (Tsoka et al., 2018; Liu et al., 2021).

The way a street was oriented affected the solar radiation exposure due to their extended sun exposure, so east-west oriented streets, like Tweede Atjehstraat, had greater afternoon and evening PET. This is also in line with research done by Ali-Toudert & Mayer (2007) who found that street direction and openness have a big impact on thermal stress levels. Surface materials can also play a role. Common surface materials in the neighborhood are red brick pavers that retained heat better than vegetated ground. Air temperature buildup was lower at 18:00 in Celebestraat which has the most vegetated surface area in the neighborhood compared to a street with a similar north-south orientation (Sumatrastraat, which has no green surfaces, just trees) which was almost 1 °C hotter.

The results of the PET and air temperature spread are aligned with other research on urban heat islands and microclimate variation. Regarding the performance of shaded versus sun exposed places and the reported PET variability of it is consistent with what ENVI-met has been used to show for others (Acero & Herranz-Pascual, 2015). But being too covered by trees can also be a disbenefit because the heat stored during the day cannot escape easily at night because the tree canopies block the radiated heat, as seen in the Benkoelenstraat and Langkatstraat's air temperature and PET baseline results at 23:00 (both streets and both nighttime air temperature values being the highest and the PET values being the second highest and third highest in the neighborhood). This is also said by Zhao et al., 2023 but unfortunately no academic ENVI-met studies could be found to confirm that during the evening and nighttime the tree canopies within ENVI-met perform the same way regarding heat trapping which can make spots under or near trees warmer.

The ENVI-met program was useful for showing the microclimate of the neighborhood, but its model assumptions have some flaws and the reason is that ENVI-met simplifies facade reflectivity and atmospheric forcing (Huttner & Bruse, 2009). All of these being simplified may affect the accuracy of results mentioned by Tsoka et al. (2018) and Liu et al. (2021). Further research might improve reliability when you also use thermal imaging next to local sensor data to validate scenarios (Tsoka et al.,2018; Liu et al., 2021). But still the model successfully reflected important patterns of microclimate variation throughout the neighborhood (Graph 1 and Graph 2), with a coefficient of determination (R^2) having an outcome of 0,977658244 and the root mean square error having a value of 1,44 °C. This has given it a strong foundation to analyze the viability of the custom created NBS scenarios.

5.2 Custom-designed NBS interventions most effective in reducing PET in Timorpleinbuurt-Zuid and the additional co-benefits they provide

Pergola, green façade, and bioswale were the three NBS scenarios that were tested. Looking at the 2-meter buffer zones (Upper and Lower) and the whole of the Tweede Atjehstraat, the pergola scenario had the greatest PET decrease at 18:00. At 50.93°C, the pergola scenario's PET was 2.05°C lower than the baseline and lower than that of the bioswale (52.73°C) and green façade (51.72°C). With a PET drop of 4.35°C in the upper buffer zone and 2.42°C in the lower buffer zone, pergolas likewise performed better than the other scenarios when examining the buffer zone data (Table 20). However extreme heat stress remained in the whole street and the bufferzones across the street at 18:00. Despite this improvement the PET values in all the three NBS scenarios stayed well over the 41°C limit (52.73 °C for the bioswale scenario, 51.72 °C for the green façade scenario and 50.93 °C for the vegetated pergola scenario). But the relative effectiveness of the pergola scenario compared to the other two scenarios decreased around 23:00, then temperatures decrease because of no sun radiation. In comparison to the green façade and bioswale it demonstrated the smallest PET decreases at 23:00 for both the street-level data (-0.20°C) and the buffer zones (-0.21°C upper, -0.18°C lower). Probably due to the fact that pergolas work best during daylight hours when the sun is active since they mainly provide shade and lower direct solar radiation (Katsoulas et al., 2016). There does not seem to be an ENVI-met academic study that looks specifically at how vegetated pergolas affect nighttime temperatures, but you could see in this one that they might work in a similar way to tree canopies, because by blocking the warm air of going up they limit longwave radiation loss (Ali-Toudert & Mayer, 2007). Zhao et al. (2023) found that simulated trees had this effect and that they reduced nighttime airflow and kept heat near the ground by blocking upward air movement and thus blocking the cooling process. The green façade and bioswale scenarios on the other hand have more open street layout and vegetated surfaces which likely do not block impervious surfaces heat release to the sky which can result in more effective cooling at night (Ali-Toudert & Mayer, 2007). So the design form and structure of the NBS and what type of NBS affects when cooling happens and how strong it is because some NBS types work best late in the afternoon and other NBS measures work better at night in reducing PET, so by using several NBS types and layouts it helps keep the thermal conditions comfortable across both the late afternoon and the evening.

Important to mention is that a modeling limitation affects the interpretation of the BIO-met dynamic thermal comfort walk: it was not always possible to place the simulated person right next to the implemented NBS, like walking beneath the pergola, next to the bioswale, or next to the green façade because of this ENVI-met model's 2x2x2 meter grid resolution. So then when those NBS are encountered up close or directly underneath then the PET levels recorded in the route could not always accurately reflect the cooling effect of those NBS typologies, so some cooling effects seen in static PET points may appear smaller in the walk-based simulation. But still the use of dynamic simulations in this study helps to close a methodological gap in NBS research, specifically the lack of use of dynamic, walk-based PET modeling so far (only Tousi et al. (2025) could be found implementing a dynamic thermal comfort walk in research, modeling a part of Athens and analyzing it via scenarios) and that adds to the goal of more accurate evaluations of pedestrian thermal experience in urban settings improved by NBS scenarios.

The ENVI-met simulations also had important environmental co-benefits that each of the custom created NBS scenarios provided, next to PET reduction. The bioswale scenario had the most consistent decreases in CO_2 levels across the whole Tweede Atjehstraat and the two bufferzones that were tested in terms of carbon sequestration. In comparison to the baseline, bioswales decreased the concentration of CO_2 at street level by −0.24 mg/m³ (Table 21) and they did even better in the 2-meter bufferzones (Table 22). It had a CO_2 decrease of −0.28763 mg/m³ in the lower row and −0.26122 mg/m³ in the upper row. Pergolas reduced less CO_2: −0.10520 mg/m³ (upper) and −0.15037 mg/m³ (lower) and −0.14 mg/m³ for the whole street. The modeling restrictions of ENVI-met forced the pergola to be imitated as a hedge where the first 2,5 meters had no vegetation but the last 0,5 meters had vegetation and also planted over a sidewalk with impermeable surface materials, potentially limiting root & soil interaction. So the root zone was not completely modeled in soil. This could mean that the CO_2 sequestration capacity could maybe be underestimated. The green facades have been shown to help with CO_2 sequestration in real life (Jozay et al., 2024) but the model could not provide data for that scenario, making it impossible to evaluate the CO_2 effect of the green façade. The data indicated that bioswales are most successful at reducing local CO_2 concentrations. Pergolas also help sequestrating CO_2 but their influence is more restricted, perhaps because of modeling limitations as well as design features, so bioswales offer a more stronger ecosystem service when carbon sequestration is the main target.

The bioswale scenario did so much better than the other scenarios in terms of adding bioretention surface area to help with rainwater in the street. Compared to just 122.31 m2 added in the green façade scenario and 30.9 m2 added in the pergola scenario, the bioswale scenario had way more bioretention surface area (732.01 m2). This is to be expected as bioswales are made exactly to deal with rainwater, which makes them very efficient comparatively when it is raining intensely. The green façade scenario, which added 3,712.9 m² of greenery to the street, so nearly five times more than the pergola (762.2 m²) and bioswale (732 m²) interventions, produced the biggest benefit regarding the increase in vegetated area since the scenarios focused on mitigating PET at the hottest areas of the street, which included the sidewalk, so the NBS interventions were either placed adjacent to or directly over the sidewalk to reduce the amount of heat absorbed by impervious surfaces. This was done by removing impermeable surfaces completely as done in the bioswale scenario, which replaced heat-retaining pavement with plants and permeable soil, or it was done by blocking incoming sunlight on the sidewalk, such as with pergolas shading the sidewalk, or by blocking incoming sunlight on the building facades in the green façades scenario. A big vegetated surface area does not always translate into the best cooling or hydrological performance or CO_2 sequestration. The results likely showed that having greenery that gives off shade is one of the most important factors in reducing PET in urban environments during the daytime. These findings indicate that whereas pergolas had the greatest effect on lowering PET during periods of extreme warmth, bioswales and green façades provide more co-benefits in terms of adding bioretention surface area and carbon sequestration. And again this shows the value of having a multifunctional NBS approach where integrating several NBS types might improve the variety of ecosystem services provided.

Hansen et al. (2017) have created categories of ecosystem services that can be used to frame the co-benefits found in literature and calculated in the ENVI-met simulations (PET, CO2 sequestration) or calculated itself (bioretention surface area added). These are directly supported by the NBS functions evaluated in this study and include provisioning, regulating, supporting, and cultural services. Each of the three NBS scenarios: vegetated pergola, green façade, and bioswale, made a contribution to these services: PET, rainwater management and CO2 to regulating services, added greenery for potential habitat for animals to habitat services and comfort and streetscape quality to cultural services (Hansen et al., 2017).

The bioswale scenario did the best in terms of regulating services. It lowered CO_2 levels and can deal with precipitation with the added bioretention surface area a lot when looking at the green façade and vegetated pergola scenario and it had the highest potential for carbon sequestration across the street and upper buffer zones and lower buffer zones. By providing sun protection in the areas of the street most exposed to heat, the pergola also helped to regulate services by minimizing PET most efficiently at the hottest time of the day, which was at 18:00. The green façade didn’t regulate temperature or manage stormwater as well as other methods, but it did slightly reduce PET and added vertical greenery that helps buffer temperature on building surfaces.

The green façade scenario had the most obvious effect on 'supporting ecosystem services', which promote long-term ecosystem functioning (e.g. plant growth, habitat potential) (Hansen et al., 2017). It increased the amount of newly added vegetated area by a lot compared to the pergola (762.2 m^2) and bioswale (732 m^2) treatments, adding 3,712.9 m^2 and this extra green space increases opportunities for biodiversity support in dense urban areas (Langergraber et al., 2021; Gemeente Amsterdam, 2024b). The bioswale also supported these habitat services by replacing impervious surfaces with vegetated, soil-based systems that improve soil structure and microbial activity (Chen et al., 2023; Brodsky et al., 2019) and the vegetated pergola has a canopy cover that provides space for biodiversity which are part of the support services (Hansen et al., 2017; Gemeente Amsterdam, 2024b).

Even if they are not specifically simulated in this thesis (which is not possible due to limitation of plant species choice), the habitat services are important when it comes to multifunctional NBS, but they could at least be gotten from literature (plant species and potential animals attracted to these species). Green façades, pergolas and bioswales can create a habitat for beneficial insects and pollinators because of the choice of native plants as their vegetational structure (Hansen et al., 2017). Using layered greenery in the dense urban areas is helpful and it can also fit well with the bigger citywide goals of the municipality to make urban spaces greener and accessible, more climate-adaptive to rainwater and heat, and also increase the biodiversity potential.

All the three NBS scenarios provided cultural ecosystem services: potentially better public spaces, better visual quality and potential psychological comfort for residents. This can be important in socially vulnerable neighborhoods like Timorpleinbuurt-Zuid. The pergola increased thermal outdoor comfort by improving shade and more walkability because of increased thermal comfort. The bioswale scenario can make the street feel greener and more welcoming by improving the visual identity of urban space, the green façade scenario improve the look of building facades and give the built environment a more natural ‘look’ (Branković et al., 2019; Neto et al., 2021). These cultural benefits thus aligned with the goals like social justice cohesiveness and health & social wellbeing (Figure 6) (Bona et al., 2022).

The total amount of ecosystem services and the types of ecosystem services that are delivered by each NBS scenario varied. Viewing them through the ecosystem services perspectives’ framework showed their multifunctionality: Bioswales did do the best in regulating services, green façades in habitat services, pergolas in thermal comfort and cultural services and all to provisioning services.

When considering the multifunctionality of the three specially created NBS scenarios, the findings indicate that no single NBS intervention performed better than the others in every category, backing the idea that multifunctionality in urban design requires a mix of complementing strategies/NBS types. The pergola scenario produced the greatest temperature and PET reduction throughout the Tweede Atjehstraat and both buffer zones, minimizing PET at the warmest time of the day (18:00). Thus it is particularly valuable for immediate thermal comfort and cultural ecosystem services, such as improving walkability and outdoor usability in hot weather. Its physical construction probably reduced sky exposure which is why it had the least effect on nighttime PET and a relatively low contribution to stormwater management and CO_2 sequestration.

The bioswale scenario was notable for its regulating and habitat services (native plant species diversity), definitely its ability to take up carbon and reduce rainwater because here it really outperformed the other two NBS scenarios. It covers 21.73% of the street for rainwater reduction and providing the largest CO_2 reduction in both the street and both the buffer zones. Due to open sky exposure and soil-based evapotranspiration, its cooling impact was more equally spread throughout the day and even at night even though it did not produce a big PET decrease at 18:00.

The green façade scenario outdid the other two interventions regarding added vegetated area in the street: almost five times as much greenery (total surface area) and this helps support long-term habitat services like biodiversity, plant productivity and urban ecological resilience (Hansen et al., 2017; Somarakis et al., 2019). The green façade model did not generate any CO_2 sequestration data for this scenario. Research shows that façades may also make a great contribution in this area. Its PET decrease was second highest and somewhat constant throughout the day and night.

The results confirm the thoughts Alves et al. (2024) and Hansen & Pauleit (2014) who say that multifunctionality involves more than just stacking benefits, it involves understanding where trade-offs arise and how NBS work in together. Integration of the NBS scenarios into one scenario were not modeled in this study. The results could suggest that strategically and spatially integrating multiple NBS types could result in more resilient outcomes (e.g. bioswale and green façade).

The goal of reducing PET determines which NBS scenario is the "best" because the focus here is mostly PET reduction, so the pergola would be best option for thermal comfort. More benefits are provided by bioswales regarding environmental regulation and the green facade is a good fit in between.

The results of this study mostly align with what has been seen in other urban climate and NBS effectiveness studies regarding the different strengths of each NBS intervention. For example the (ENVI-met modeling) results demonstrate that bioswales provided a range of environmental advantages, including addition of area for rainwater capture, a decrease in CO_2 concentrations, and a moderate improvement in thermal comfort. This performance aligns with example studies such as the Gdańsk rain garden research, which shown that rain gardens, a type of bioswale, can at the same time improve infiltration, reduce heat stress, and increase biodiversity (Kasprzyk et al., 2022).

Similar to the ENVI-met model of Yilmaz et al. (2023) where design scenarios with (tree) canopies increased thermal comfort on pedestrian routes, the cooling effect of the pergola canopy on the upper sidewalk (that can mimic a flat tree canopy cover) during afternoon heat, lined up with regards to having shade as the main temperature lowering option. However my results also point out the drawbacks of shade focused designs (with regards to canopies), such as decreased cooling at night, which are associated with lower sky view factor and minimal evapotranspiration, Zhao et al. (2023) observed this while examining microclimatic behavior in dense urban morphologies.

The ENVI-met model did not produce CO2 sequestration data for the green façade but its contribution to spatial greening and possible future benefits are consistent with both simulation and empirical results because vertical greening systems can lower building surface temperatures, improve air quality, and function as passive cooling buffers, according to (Manso & Castro-Gomes, 2015).

What is also consistent of my results with regards to the literature on multifunctionality is the observation that no single NBS type can have the most optimal benefits with regards to PET reduction, CO2 sequestration and rainfall. Hansen & Pauleit (2014) say that in multifunctionality planning that the significance of understanding trade-offs and the synergies is really important. The objective is to balance ecosystem service delivery rather than maximizing a single outcome (Hansen & Pauleit, 2014). Alves et al. (2024) state that in the same way that ignoring multifunctionality in the early planning phases of NBS design can make it happen that the single-objective NBS interventions will perform poorly over time. This study supports the idea. Each NBS interv ention focused on one particular aspect of the environmental needs of the street. By integrating the three scenarios (if that scenario had been modeled) could have produced results that were even more multifunctional.

5.3 The key trade-offs by implementing multifunctional NBS in Timorpleinbuurt-Zuid

The effectiveness and integration of multifunctional NBS in Timorpleinbuurt-Zuid are influenced by a number of key trade-offs. The neighborhood's high urban density with more than 80% of its surfaces impervious is one of its main spatial challenges (Cobra Groeninzicht, 2021). The bioswales did good at adding bioretention surface area for rainwater capture and infiltration. However they take up a lot of ground space and in this case replace parking space, which makes it challenging to implement them without compromising with the functions of the space. Even though they need a little amount of ground surface area the pergolas can block overhead access and obstruct the sidewalks with their beams. This is case on both sides of the street where their beams are attached to the sidewalk instead of being partly attached to the buildings' facade. Green façades on the other hand require almost no ground space and interfere less with sidewalk accessibility, but they may obstruct window views, which can lower the perception of safety (Choi et al., 2021). Pergola in this scenario has great daytime PET reduction but nearly no added bioretention surface area, whilst the bioswale scenario score poorly on PET reduction. Green façade scenario provides minimal bioretention surface area but at least provides moderate PET reduction. So finding a solution that finds a balance between cost and multifunctionality is challenging.

Parking and sidewalks in this scenario will be sacrificed when the space is repurposed as bioswales. NBS are frequently seen as long-term cost-effective (European Commission, 2015). There can be a lot of variation in maintenance expenses though. Pergolas can cost up to €100.7/m²/year, bioswales only cost €15.1/m²/year and green facades even less at €10/m²/year (Di Pirro et al., 2023; Panduro et al., 2024). This can make it difficult to pay for their widespread use. The tested measures are Type-3 NBS (Eggermont et al., 2015), so trade-offs and maintenance demands are expected, which supports the advice of having a combined package of NBS scenarios rather than one NBS measure on its own.

Some of the outputs of the results were compared to the trade-offs and main attributes of high quality urban nature Bulkeley et al. (2023), with the pergolas gave a significant amount of PET relief in the bufferzones at 18:00, green façades had more consistent nighttime cooling and bioswales were the most efficient for bioretention rainwater potential and CO_2, but no NBS scenario on its own beat the other NBS scenarios across every indicator. Thus this is indicating that using a combination of NBS measurements is more beneficial than using just one NBS type. The findings also varied at bioretention added surface area, across the buffer zones, and between the two sides of the street, indicating that placement should adapt to these local differences. The Timorpleinbuurt-Zuid has little vegetation, is very vulnerable to heat and has significant rainwater problems. Due to this, it is a suitable and necessary site for NBS, and placing the measures on both sides of streets, like the Tweede Atjehstraat, ensures that the benefits are distributed more fairly. The conclusion when interpreting the scenarios you could say that NBS cannot be seen as divided greening attempts because their effects on the rainwater capturing potential and heat are dependent upon their integration with the broader street system (which includes drainage, building form, and surfaces). This backs up Bulkeley et al.'s (2023) that high-quality NBS needs to address underlying drivers rather than symptoms, respond to local context, promote equity, and provide multiple benefits. The scenarios are small scale and do not include community in the design process but they provide multiple benefits and respond to local context equity in a sense, so when these scenarios are upscaled for a whole neighborhood and include the community then it would be fully high quality urban nature provision (Bulkeley et al., 2023).

Safety and visibility are the two main problems from a social perspective. Because of their overhead structure the pergolas may block sky view factor and so then it can reduce a sense of security (Choi et al., 2021). Similar problems are that green façades can likewise make looking from the inside of a building to outside less visible because of a potential thick green facade. Since vulnerable populations like the elderly may be more susceptible to changes in accessibility and perceived safety, these NBS could add problems (Choi et al., 2021). In this regard only bioswales seem to not block street view.

Even though things as multifunctionality, community engagement, and resilience to climate-related challenges are the main components of both NBS and Ecosystem-Based Adaptation (EBA) frameworks, putting these ideas into reality is not easy. In particular the NBS's potential effectiveness within the larger EBA framework may be limited by trade-offs between cooling effect, cost, usage of space, and whether or not people in the area of the intended NBS will actually accept the adjustments (Kabisch et al., 2016; Cohen-Shacham et al., 2019; Choi et al., 2021; Cortinovis et al., 2022). Cohen-Shacham et al. (2019) say that successful interventions must be in line with both ecological function and community context. Ecological function was added by looking at which plant species are local to the Netherlands, which benefits native wildlife and also if their structure could provide habitat/benefits for animals. Also the study looked at the spatial layout and microclimate needs of the place (ENVI-met simulation), however community context was left out because in the process of creating these NBS scenarios, feedback from the community was not considered. So these NBS could provide limited benefits or even unanticipated negative effects, such as decreased safety or low public approval, because they were not reviewed by the community of the Tweede Atjehstraat and Timorpleinbuurt-Zuid neighborhood.

5.4 Methodological reflection and limitations

A Research for Design approach was used during the process. No generic tests of NBS were run, but the interventions were shaped for the Tweede Atjehstraat itself. Bioswales, green façades, and pergolas were drawn with actual dimensions, positioned in the street and put in a masterplan. These design sketches were then translated and placed into ENVI-met, where their potential effects could be tested.

The effects of multifunctional NBS scenarios on Timorpleinbuurt-Zuid's urban microclimate and thermal comfort using ENVI-met as a modeling tool were looked at. The ability of ENVI-met to simulate and evaluate various NBS scenarios with spatial and time related precision is one of the programs main advantages. It is great for looking at the potential effects of certain design interventions like green walls, trees, green strips etc. on the local urban microclimate under heat stress since it makes it possible to clearly evaluate microclimatic variables like air temperature, PET etc.

A limitation of ENVI-met is that it provides comprehensive microclimate data but its models are only able to approximate microclimate behavior, so it does not completely reflect it. This means that even when you give all the exact weather parameter values regarding hourly temperature, relative humidity, wind speed, cloudiness etc. that the output values will then either be overestimated or underestimated (Alves et al., 2022; Liu et al., 2018).

The exact values of the simulated temperature at the height of the local weatherstation of the neighborhood (4 meters above the soil) for model validation was done with linear interpolation because we could not get the exact simulated values for relative humidity and air temperature. So this means you validate the model based on data at 4 meters interpolated and not the exact simulated values at that height.

That ENVI-met could not simulate the uptake of CO_2 for the green façade scenario was a big limitation. The greening layer apparently does not provide input directly into the CO_2 sub-model and the output statistics do not include relevant vegetation processes (Bruse et al., 2023). This means that there is no contribution to CO_2 sequestration in the simulation from the green facade scenario and so then it also then cannot be properly judged comparatively to the other NBS scenarios. Olivieri et al. (2012) had to model green façades as custom trees in order to get around this limitation. But this is not the best solution.

Also some of the simulations were done on a WUR PC without the required Python plug-in for BIO-met for PET walk chart generation. So the pergola scenario was not able to be included into the BIO-met static PET walk comparison. This could not be done on my own PC afterwards because the ENVI-met workspace could not be moved to the personal laptop.

The analysis focused only on two time points: 18:00 and 23:00. A more deeper understanding of thermal behavior and microclimate impact after the implementation of the NBS scenarios would have been possible with a 24-hour or a multiple day simulation. Another thing is that the spatial focus was on buffer zones surrounding the interventions rather than precise measurement locations beneath or adjacent to them. This decision decreased spatial precision regarding microclimate values such as PET but helped generalize findings in a way to see the average impact around a whole NBS typology.

Due to the grid size of the spatial resolution of the model being 2x2x2 meters instead of 1x1x1 meters, not every spatial detail can be accurately represented. For example if a green strip does not make up the majority of a 2x2x2 meters grid it won't be shown within the ENVI-met Spaces model and thus not be included within the simulation process. Another thing was that no windows were created which if put in the model could add a more closer to reality output. The roofs were modeled as flat while most buildings in the neighborhood actually have a sloped roof. A way I could have created a more detailed street is if I would have adjusted the roofs manually myself. This was not possible to do in the QGIS environment before importing it into ENVI-met.

I did not include looking at other important thermal indicators for analysis of the street(s) which are the mean radiant temperature and the wind speed. Other factors that were not looked at but could also be analyzed for future research to analyze the street is the percentage of open space in a street, how narrow it is, looking at the building height etc.

Stakeholder participation was not included in this study. The choice of NBS typologies was made without the neighborhood residents' input. No expert interviews (landscape architects, urban climate adaptation experts) were done to get opinions on maintenance, aesthetics, placement or spatial viability of the NBS scenarios, these are based on literature study and study of the street and neighborhood itself. There was no iterative process so no extra testing, modifying, and improving of design scenarios. These exclusions can limit the social - and governance relevance of the outcomes. Cost analyses did not account for lifecycle costs, so they were restricted to only maintenance + implementation costs.

The ecosystem approach was not completely used in the way it was intended. But it used the interactions between NBS and the urban system and combining multiple benefits (multifunctionality). Involving stakeholders (residents, municipality), receiving feedback (from experts in the field of urban ecology, urban climate, urban planners/landscape architects) and having an iterational process, and assessing various trade-offs or co-benefits (social, ecological, and economic) are also part of the ecosystem approach. But they were not all included. The reason for this was the limited time and scope of this thesis.

6. Conclusion

The Timorpleinbuurt-Zuid neighborhood of Amsterdam was looked at to see how well multifunctional NBS reduced heat stress with the NBS being the bioswales, vegetated pergolas, and green façades. The scenarios were modeled using ENVI-met simulations to look at their output regarding reducing air temperature and PET while also taking trade-offs and co-benefits into consideration.

The green façade scenario provided the most consistent street-scale cooling out of the three scenarios. It decreased the air temperature by −0.45 °C and PET by −1.26 °C at 18:00 and −0.20 °C and PET by −1.17 °C at 23:00. The pergola performed badly in terms of air temperature decrease and evening PET results, but it had a better average PET reduction at 18:00 (−2.05 °C). On both metrics the bioswale had the least amount of effect.

But in the buffer zones, pergolas had the greatest thermal relief at 18:00: PET dropped by up to −4.35 °C in the upper row and −0.21 °C in the lower row. So it has good localized cooling directly beneath or next to the structure. The green façades had −3.00 °C for the upper row and −1.50 °C for the lower row respectively. But at

23:00 the green façades performed best again, cooling PET by −1.50 °C and −1.25 °C in the upper and lower rows.

On CO_2 sequestration the bioswales and pergolas showed modest reductions at 18:00: −0.242 mg/m³ and −0.140 mg/m³ respectively. Unfortunately though the green façade scenario did not have CO_2 data. The bioswale did a whole lot better than the others in terms of dealing with rainwater. It is providing 732.01 m2 of added bioretention area compared to the green façade 122.31 m2 and the vegetated pergola 30.9 m2.

Green façades had the maximum amount of greenery in terms of vegetated area. It had 3712.9 m² of vertical vegetation compared to 762.2 m² for pergolas and 732.0 m² for bioswales.

These results show that no NBS option is superior in every indicator category, every scenario has different advantages. The pergolas did really well in concentrated PET reduction inside buffer zones during the day, bioswales had the most effective rainwater capture potential and highest CO_2 uptake and green façades provided the most consistent cooling at both times and also for the whole street and bufferzones. However purely looking at PET is a different story. Only in specific areas did the pergola scenario have the greatest PET reduction at 18:00. By 23:00 their effectiveness had really decreased. Also they have poor performance in the lowest buffer row, with a minimal reduction of −0.21 °C. The green façade scenario on the other hand has the highest overall PET reduction by 23:00. It maintains consistent output in both buffer rows and provides a solid PET reduction across the entire street at both 18:00 and 23:00. This is important because heat stress can still affect thermal comfort later in the evening. So overall the green façade is the most reliable and well-balanced choice for lowering PET over time and space of these three scenarios.

In line with the principles for effective NBS the results direct towards the idea to bring a mixed (different NBS types) and context-sensitive package that targets multiple benefits and prioritizes and places NBS types where the residents of the street and neighborhood are most affected, these would be the areas in the street where they are exposed to a high PET level the most.

There were two research gaps tackled. One gap tackled was about the question of integration, instead of looking at just a single indicator outcome, the analysis brought together thermal comfort, air temperature, CO_2 sequestration, and added bioretention surface area, while also looking at the trade-offs and the trade-offs between them. Another gap tackled was one that is more about the method. By trying out the relatively newly added BIO-met dynamic walk tool (in literature), it could be explored how people might actually feel conditions while moving around and not just by standing still in a place. This tool has almost not been used in NBS scenario testing research (yet). So the thesis fills a gap by contributing both methodological and applied insights into multifunctional urban NBS design.

An option for future research it is an idea to do an iterative design process which will make ENVI-met modeling of the NBS scenarios iterative if you include feedback rounds as qualitative methods like interviews with experts or with residents of the neighborhoods where these NBS would be implemented. This kind of mixed-method setup could have insights into thermal performance and other co-benefits and into how people actually perceive and accept the different NBS types. Testing the NBS scenarios in other neighborhoods and cities would also show how well the results here regarding microclimate improvement found here apply in different urban contexts and environments. It is worth running simulations across different seasons so not just in the summer and in a heat wave scenario to understand how these NBS do perform throughout the year and not just during the hottest day ever recorded in Amsterdam. Also for future studies it should measure microclimate indicators over full 24 hour cycles and test combined NBS scenarios to tackle multiple issues within a street simultaneously (for example, combining green façade and bioswales to tackle both heat stress and rainwater capturing potential at a high level). Considering the expected lifespans of these NBS scenarios regarding long-term costs might help create a better cost-benefit picture, though these outcomes will likely vary depending on the urban context and costs may increase/decrease over time. Plant species selection for the NBS types should be looked at with closer attention because it can influence allergen levels (Cariñanos et al., 2019). And also while canopy structures such as pergolas bring shade, maybe by breaking them up especially in these less wide streets it could increase nighttime cooling by not trapping the heat being under the pergola canopy.

The research done contributed to urban climate adaptability field and climatic resilience science field by giving urban ecologists, urban planners & landscape architects specific benchmarks for NBS designs and scenarios on thermal relief (air temperature and PET reduction), CO2 uptake measured at pedestrian level at two relevant times of the day at the warmest hours during daytime and nighttime (18:00 and 23:00) and basic rainwater capture potential by looking at the added bioretention surface area. Another contribution to the field is showing the microclimate benefits of buffer zones around the NBS at the human height level (1.4 meters) since it is a more detailed overview of the PET and CO2 uptake at and around the exact location where people walk instead of just looking at the effects on the whole street. All the insights from the research done support the design of multifunctional NBS adapted for environmental performance.

7. References

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8. Appendix

Table

Street	Vegetation type and density	Land cover classification	Surface permeability	Surface materials	Impervious surface coverage	Building façade characteristics
Sumatrastraat	Young trees along both sidewalks (limited canopy), nearby mature trees at the square of Eerste Atjehstraat, low amount of green verges	Tree pits, light concrete paving, red tiles, small asphalt strip (bike lane)	Extremely low, tree pits and small green verges, minimum infiltration	Red brick, light concrete tiles, small red asphalt trip (bike lane)	High, mostly paved with few permeable elements	Brick buildings (burned and reinforced),
Balistraat	High tree density with large crowns, partial canopy, greenest near Benkoelenstraat & Langkatstraat, medium amount of green verges	Red brick paving and red concrete tiles, many tree pits, some small green verge areas, tree pits	Low, some permeable areas (tree pits, verges) especially near Benkoelenstraat and Langkatstraat	Red brick, red concrete stone, light grey concrete	High, but a bit less impervious cover than other streets due to higher vegetation presence	Brick façades (burned)
Eerste Atjehstraat	Uneven tree distribution, more consistent canopy in the western part, sparse in the east, medium amount of green verges	Tree pits, red brick paving (west), concrete tiles (east), small green verges, paved square area near Sumatrastraat	Low, moderate infiltration at square and green verges and tree pits	Red brick paving, red concrete stone	High overall but more balanced near central square, less greenery in eastern section	Brick façades (burned and reinforced),
Tweede Atjehstraat	Trees on one side only, sparse crown coverage, low amount of green verges	Red brick paving and tree pits along sidewalks, small green verge areas	Extremely low, minimal infiltration via tree pits and green verges	Red brick paving, red concrete stone	High, mostly paved except for tree pits and small green patches	Brick façade (burned) mid-rise façades
Riouwstraat	Moderate, trees on both sides only in one section (right half), small amount of green verges	Light concrete tiles, red bricks, small green verges, tree pits	Extremely low, tree pits and very small vegetated areas and small green verges offer minimal infiltration	Light concrete tiles, small red asphalt strip (bike lane)	High, mostly paved, with small pockets of green and one playground	Mix of brick façades (reinforced) and white concrete
Celebesstraat	Moderate tree density, well-dispersed, adjacent elevated green zone (not accessible), small amount of green verges	Red brick, sand, light concrete pavements, vegetated soil, narrow green verges	Low, provided by tree pits, green verges, and a playground	Red brick, concrete tiles	Moderate to high, reduced by adjacent green zone. Street itself has a high impervious coverage	Brick façades (reinforced & aerated)
Benkoelenstraat	High tree density, medium amount of green verges	Red brick paving, small green verges, and vegetated zones	Medium, extensive tree pits, green verges, and permeable vegetated zones	Red brick tiles	Moderate, lower than average due to narrow width, vegetated edges, and small paved area	Brick façades (burned)
Langkatstraat	High tree density, medium amount of green verges	Red brick tiles, open vegetated areas	Medium, extensive tree pits, green verges, and permeable vegetated zones	Red brick tiles	Moderate, narrow street width + vegetation + open surfaces reduce impervious area	Brick façades (burned)

Table 1: Biophysical features description of all the streets in the Timorpleinbuurt-Zuid neighborhood

Variable	Explanation
T_skin	Temperature at the skin. It rises with radiant heat and metabolic strain
static T_skin	Baseline skin temp without physiological reaction
T_core	Core body temperature
T_cloth	Clothing surface temperature. It varies with external heat and sweat evaporation
dPET	Subjective thermal stress including body response
static PET	Purely environmental based conditions PET (based on the sun, temperature, humidity, wind)
Fraction Wet Skin	How much skin is sweating. For example 0.8 indicates strong thermal stress

Table: Thermal variables of the body during a walk (ENVI-met GmbH, 2023)

Plant species for NBS scenarios

Bioswale

Plant species that can be used for bioswale that could grow to about 1 meters height: Knapweed (Centaurea jacea), Meadow vetchling (Lathyrus pratensis), Bugle (Ajuga reptans), Germander speedwell (Veronica chamaedrys), Rosebay willowherb (Chamerion angustifolium), Purple loosestrife (Lythrum salicaria), Flowering rush (Butomus umbellatus) (Groenblauwe Netwerken, n.d.; Amsterdam Rainproof, n.d.,b).

Green Façade

Figure 37: Clematis Vitalba (Gemeente Amsterdam, 2024b).

Vegetated Pergola

Figure 39: Common Honeysuckle (Gemeente Amsterdam, 2024b)

ENVI-met to QGIS plugin details

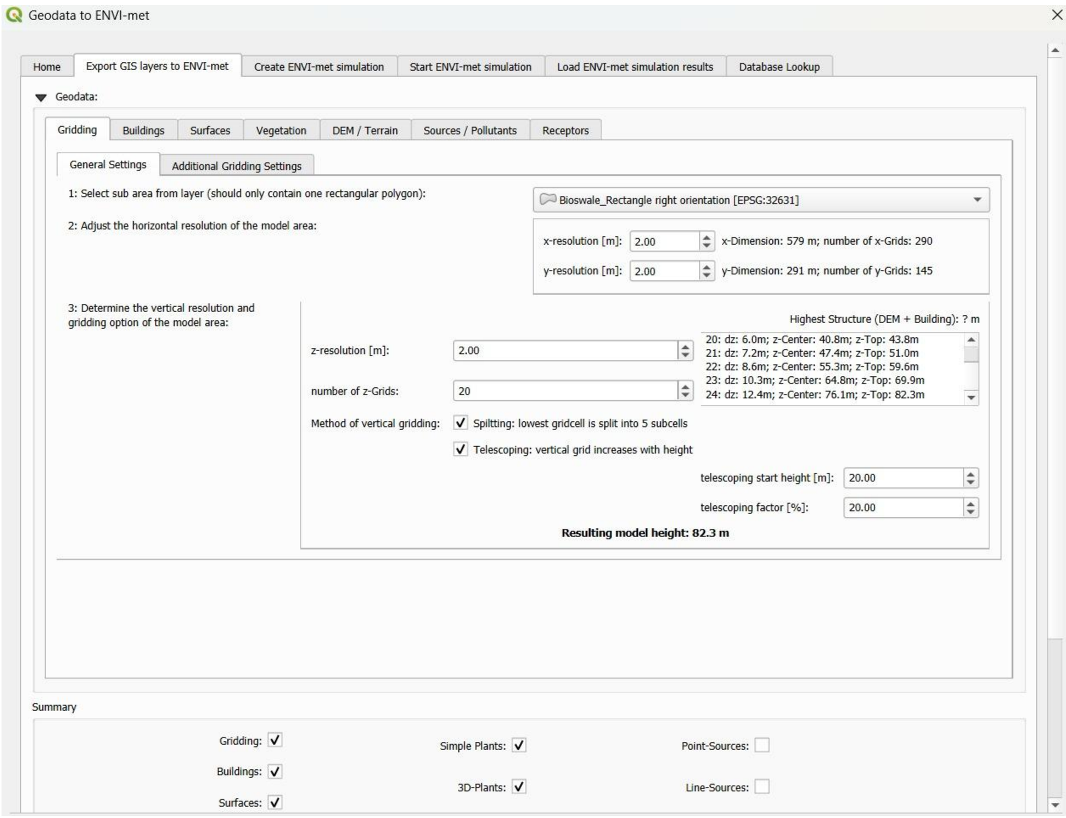


Figure 67: Gridding settings QGIS to ENVI-met plugin

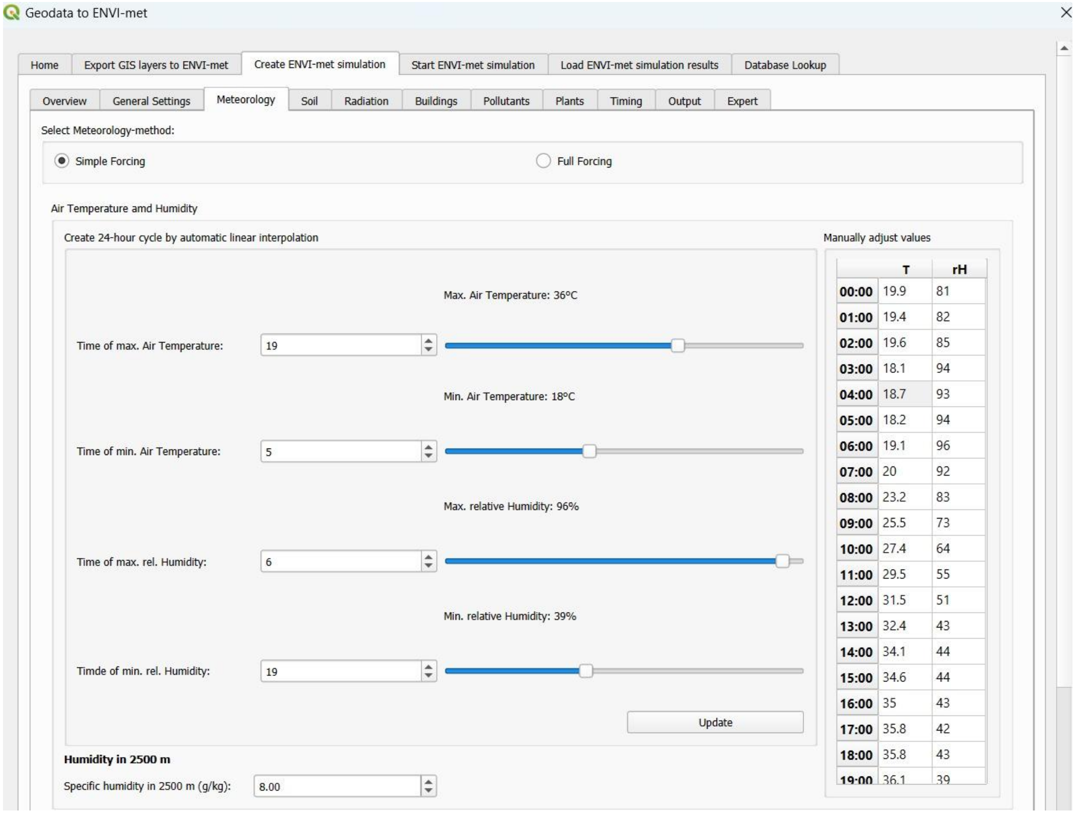


Figure 68: Meteorology settings QGIS to ENVI-met plugin, time values 00:00-19:00

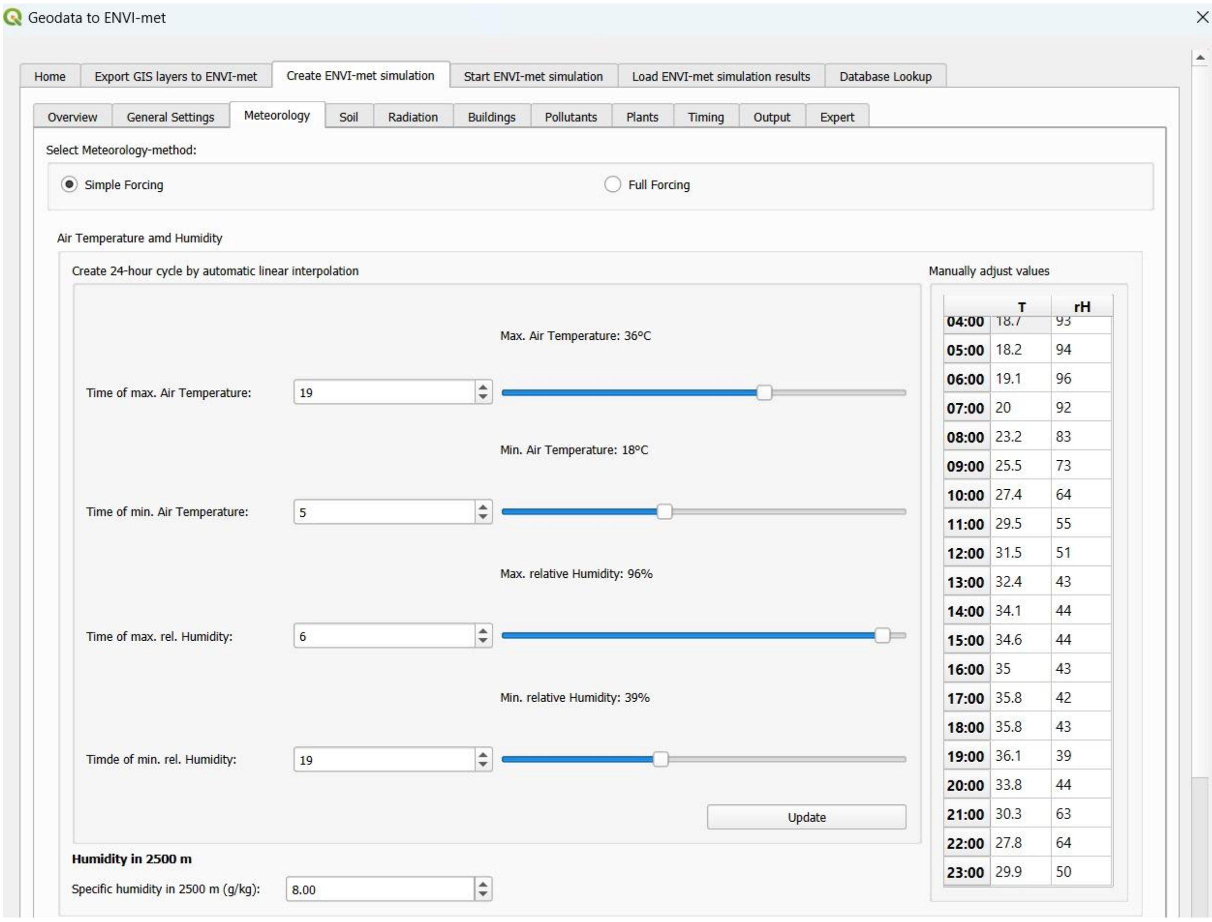


Figure 69: Meteorology settings QGIS to ENVI-met plugin, time values 04:00-23:00

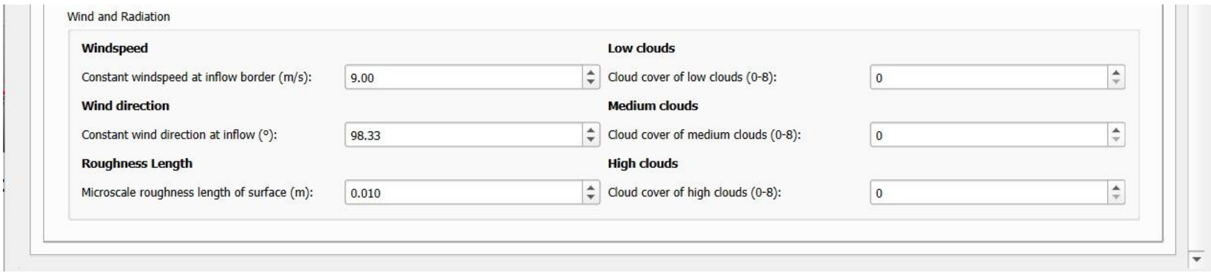


Figure 70: Meteorology settings of Wind and Radiation QGIS to ENVI-met plugin

ENVI-met

Potential Air Temperature Baseline

Potential Air Temperature map over 24 hours of the baseline scenario.

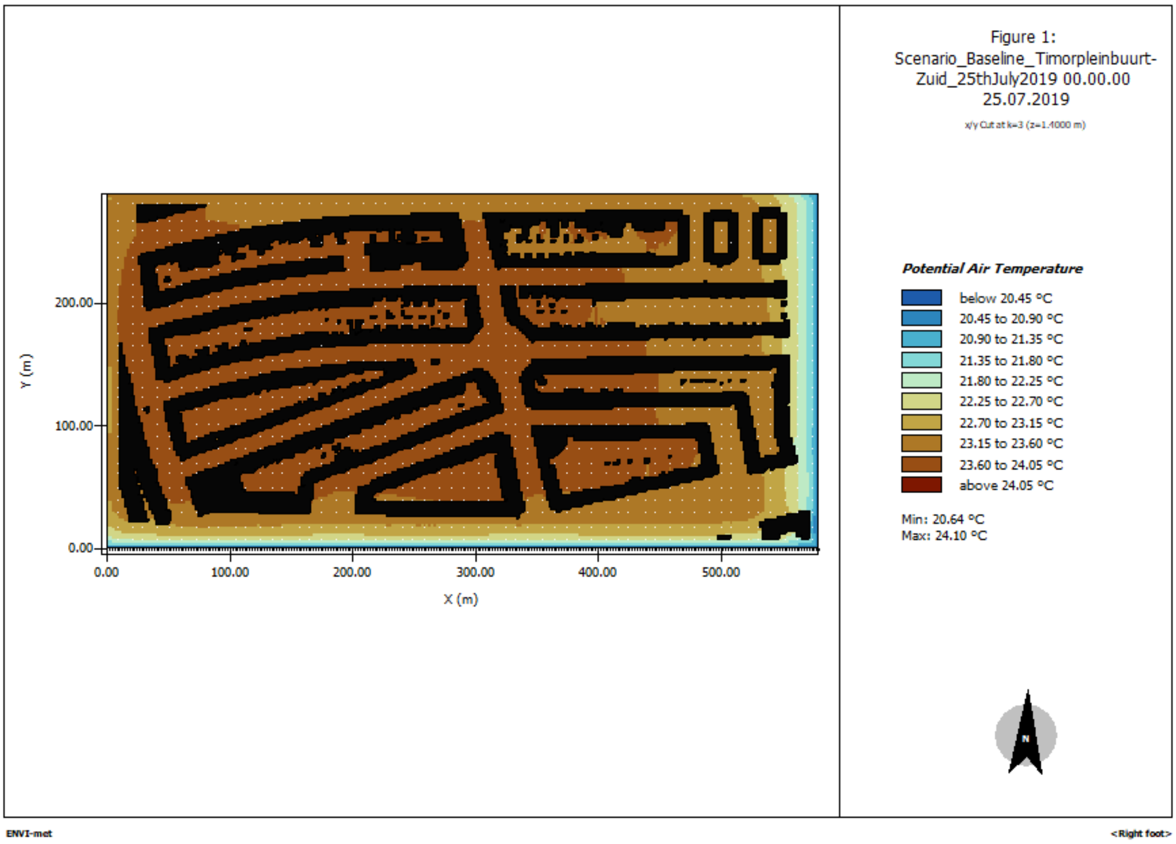


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 00.00.00
25.07.2019
x/y Cut at k=3 (z=1.4000 m)
Potential Air Temperature
below 20.45 °C
20.45 to 20.90 °C
20.90 to 21.35 °C
21.35 to 21.80 °C
21.80 to 22.25 °C
22.25 to 22.70 °C
22.70 to 23.15 °C
23.15 to 23.60 °C
23.60 to 24.05 °C
above 24.05 °C
Min: 20.64 °C
Max: 24.10 °C
Y (m)
200.00
100.00
0.00
0.00
100.00
200.00
300.00
400.00
500.00
X (m)
ENVI-met
<Right foot>

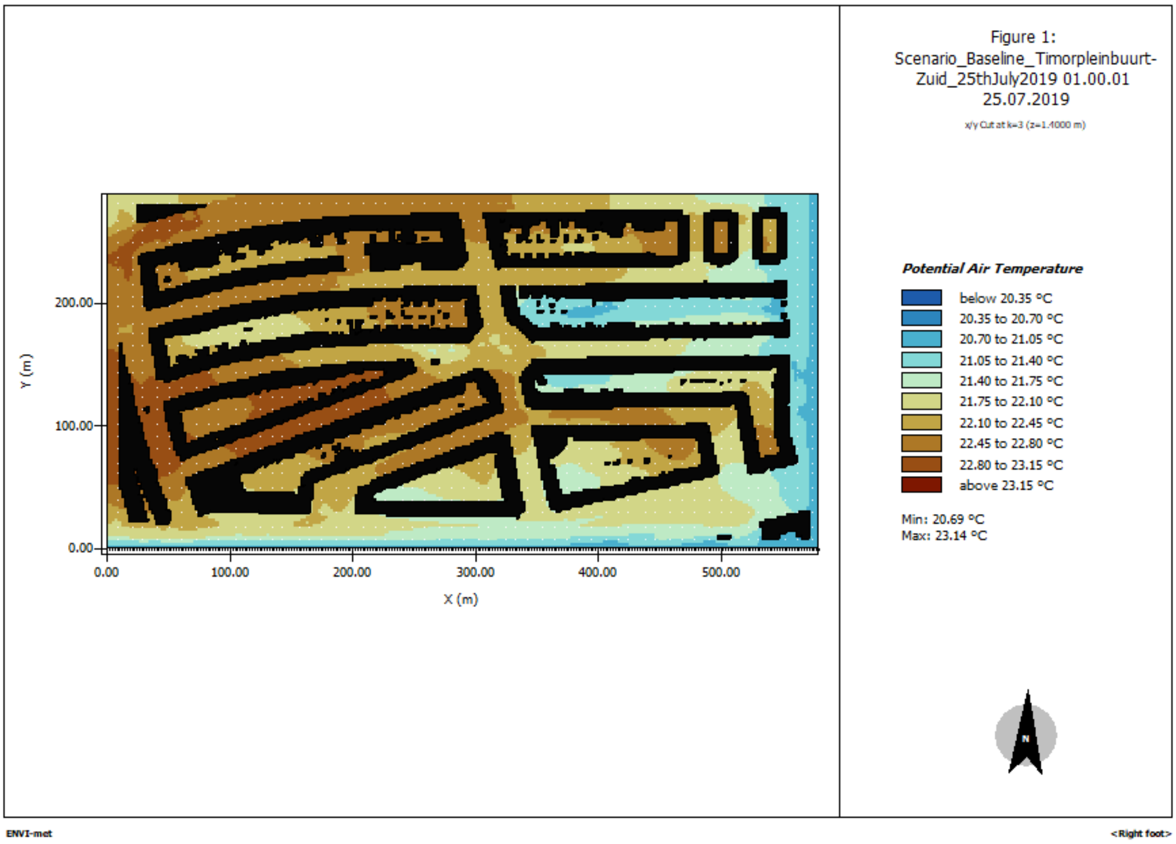


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 01.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)
Potential Air Temperature
below 20.35 °C
20.35 to 20.70 °C
20.70 to 21.05 °C
21.05 to 21.40 °C
21.40 to 21.75 °C
21.75 to 22.10 °C
22.10 to 22.45 °C
22.45 to 22.80 °C
22.80 to 23.15 °C
above 23.15 °C
Min: 20.69 °C
Max: 23.14 °C
Y (m)
200.00
100.00
0.00
0.00
100.00
200.00
300.00
400.00
500.00
X (m)
ENVI-met
<Right foot>

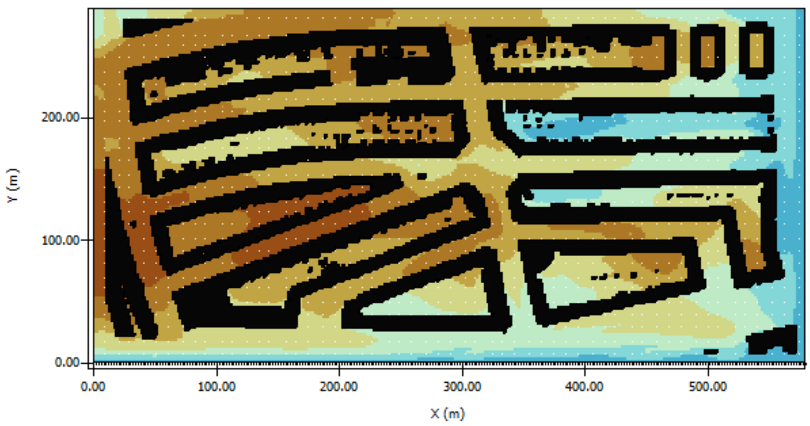


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 02.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

Potential Air Temperature

- below 20.30 °C
- 20.30 to 20.60 °C
- 20.60 to 20.90 °C
- 20.90 to 21.20 °C
- 21.20 to 21.50 °C
- 21.50 to 21.80 °C
- 21.80 to 22.10 °C
- 22.10 to 22.40 °C
- 22.40 to 22.70 °C
- above 22.70 °C

Min: 20.55 °C
Max: 22.67 °C

ENVI-met <Right foot>

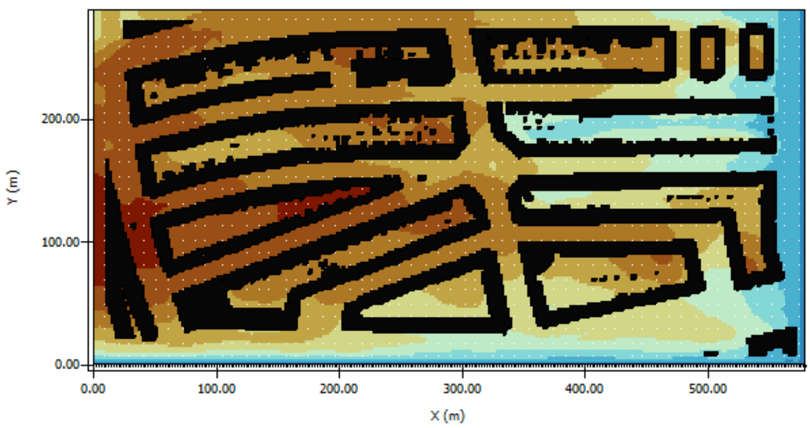


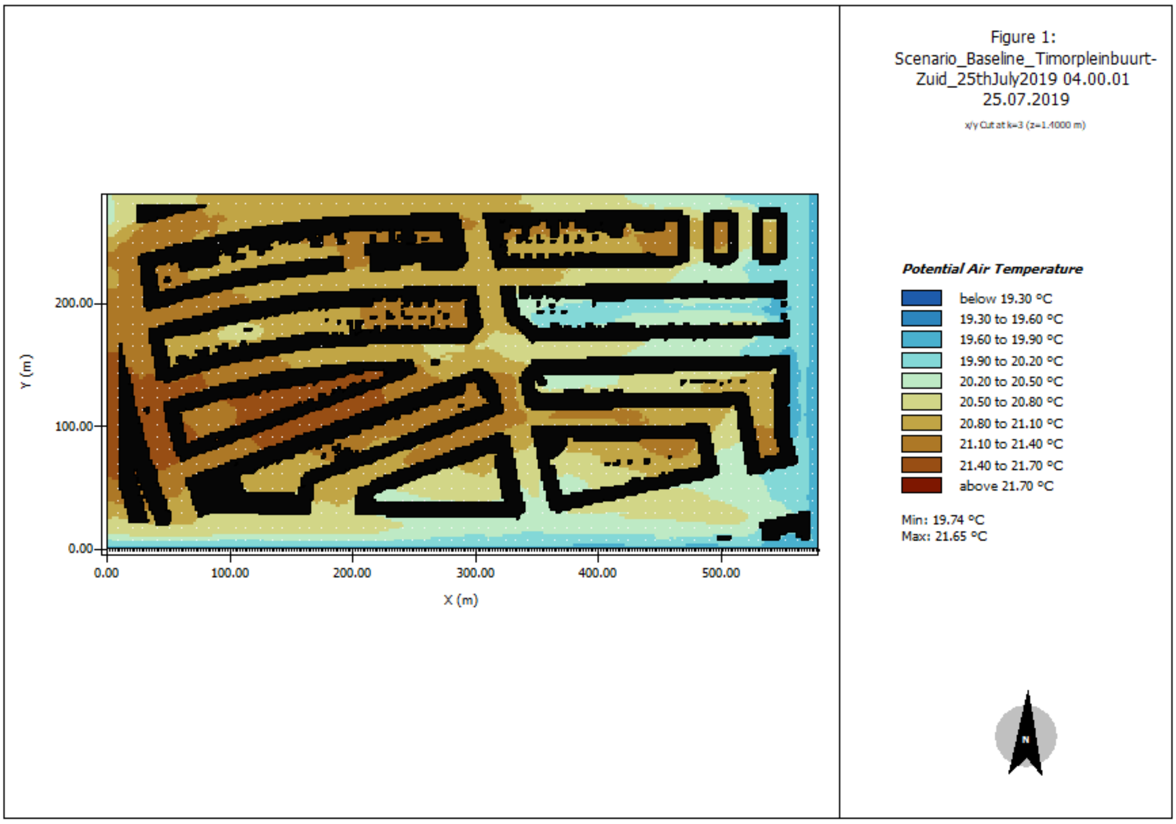
Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 03.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

Potential Air Temperature

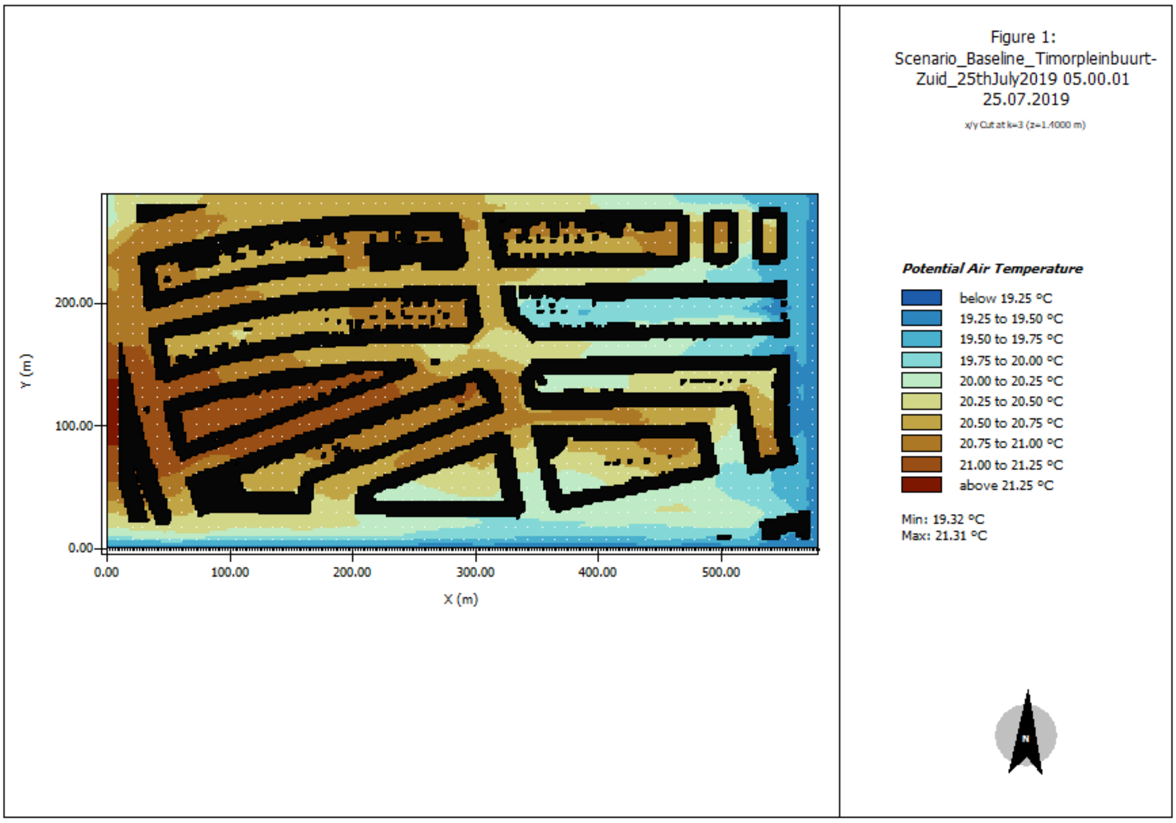
- below 19.30 °C
- 19.30 to 19.60 °C
- 19.60 to 19.90 °C
- 19.90 to 20.20 °C
- 20.20 to 20.50 °C
- 20.50 to 20.80 °C
- 20.80 to 21.10 °C
- 21.10 to 21.40 °C
- 21.40 to 21.70 °C
- above 21.70 °C

Min: 19.52 °C
Max: 21.90 °C

ENVI-met <Right foot>



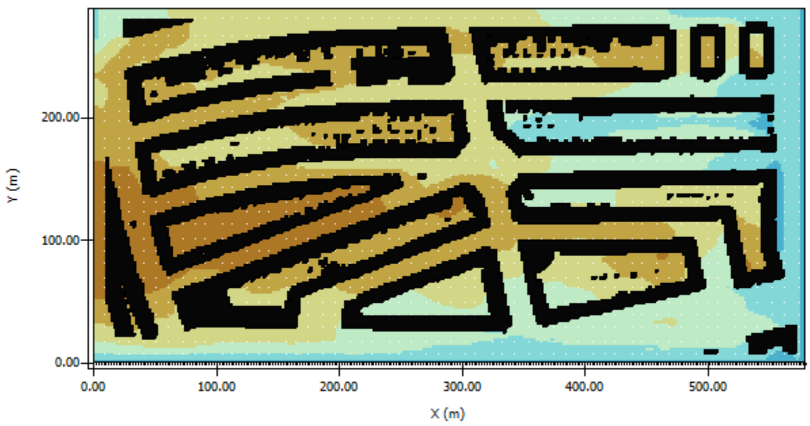
ENVI-met <Right foot>



ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 06.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



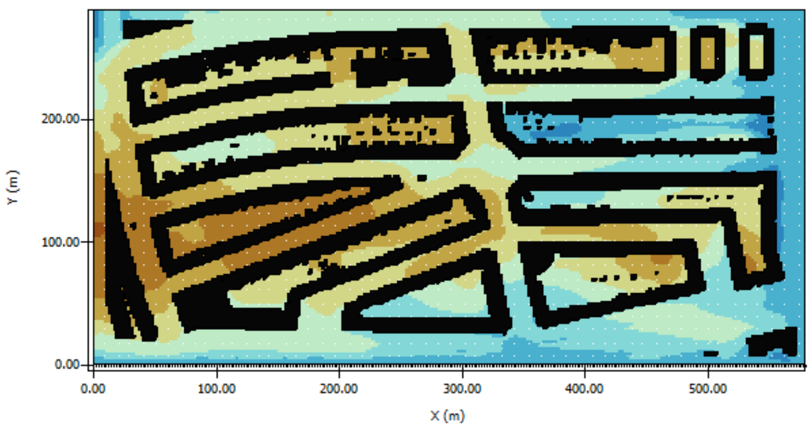
Potential Air Temperature

- below 19.30 °C
- 19.30 to 19.60 °C
- 19.60 to 19.90 °C
- 19.90 to 20.20 °C
- 20.20 to 20.50 °C
- 20.50 to 20.80 °C
- 20.80 to 21.10 °C
- 21.10 to 21.40 °C
- 21.40 to 21.70 °C
- above 21.70 °C

Min: 19.80 °C
Max: 21.37 °C

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 07.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



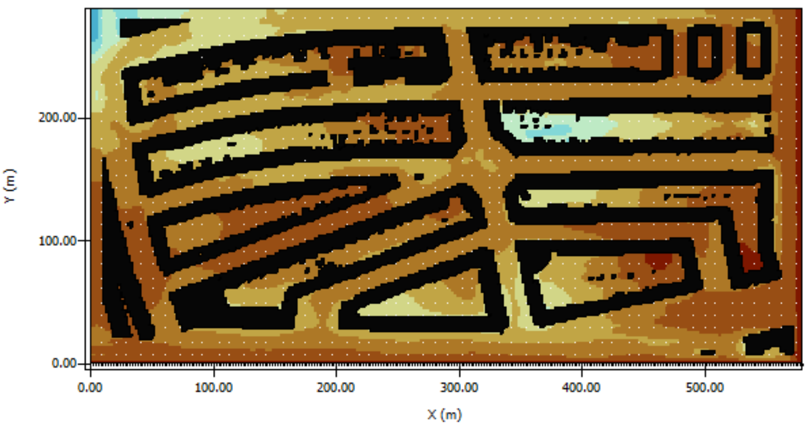
Potential Air Temperature

- below 20.20 °C
- 20.20 to 20.40 °C
- 20.40 to 20.60 °C
- 20.60 to 20.80 °C
- 20.80 to 21.00 °C
- 21.00 to 21.20 °C
- 21.20 to 21.40 °C
- 21.40 to 21.60 °C
- 21.60 to 21.80 °C
- above 21.80 °C

Min: 20.28 °C
Max: 21.60 °C

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 08.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



Potential Air Temperature

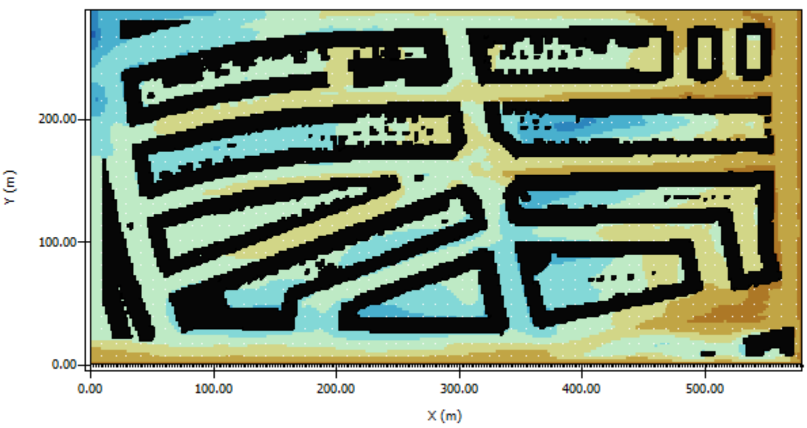
- below 21.20 °C
- 21.20 to 21.40 °C
- 21.40 to 21.60 °C
- 21.60 to 21.80 °C
- 21.80 to 22.00 °C
- 22.00 to 22.20 °C
- 22.20 to 22.40 °C
- 22.40 to 22.60 °C
- 22.60 to 22.80 °C
- above 22.80 °C

Min: 21.47 °C
Max: 22.89 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 09.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)

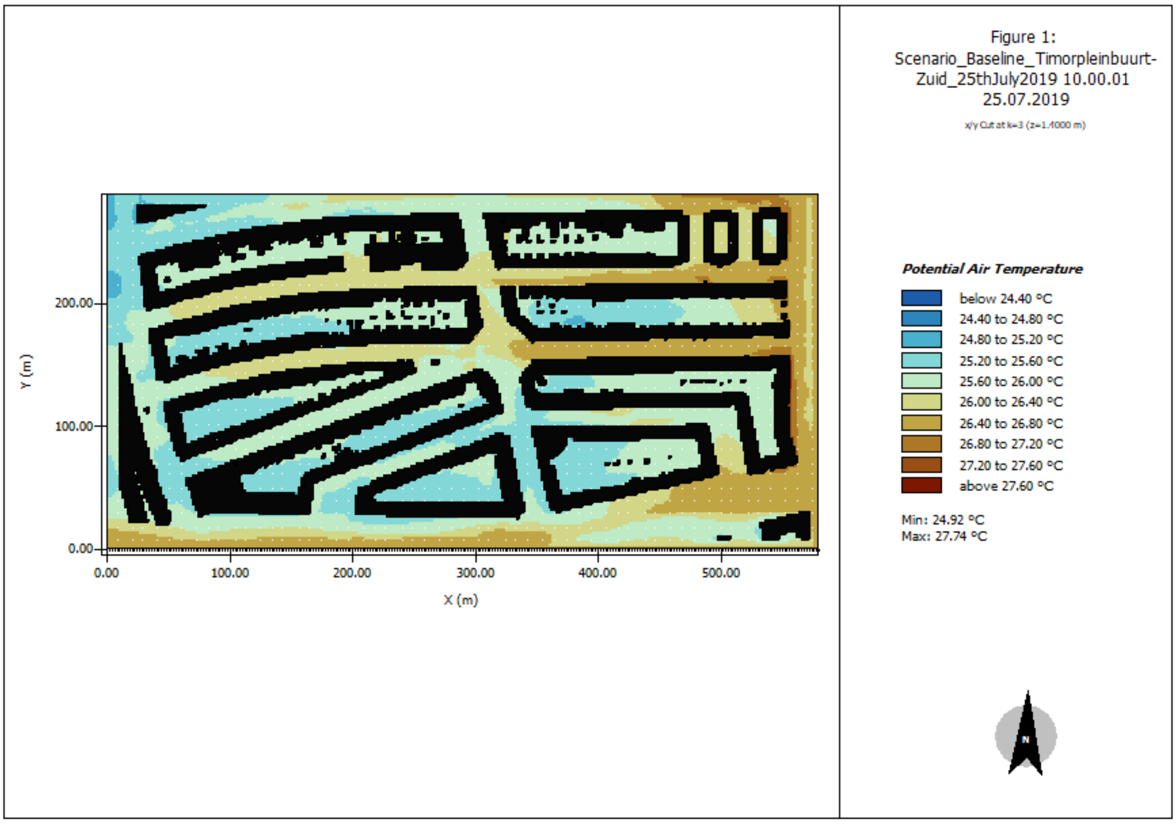


Potential Air Temperature

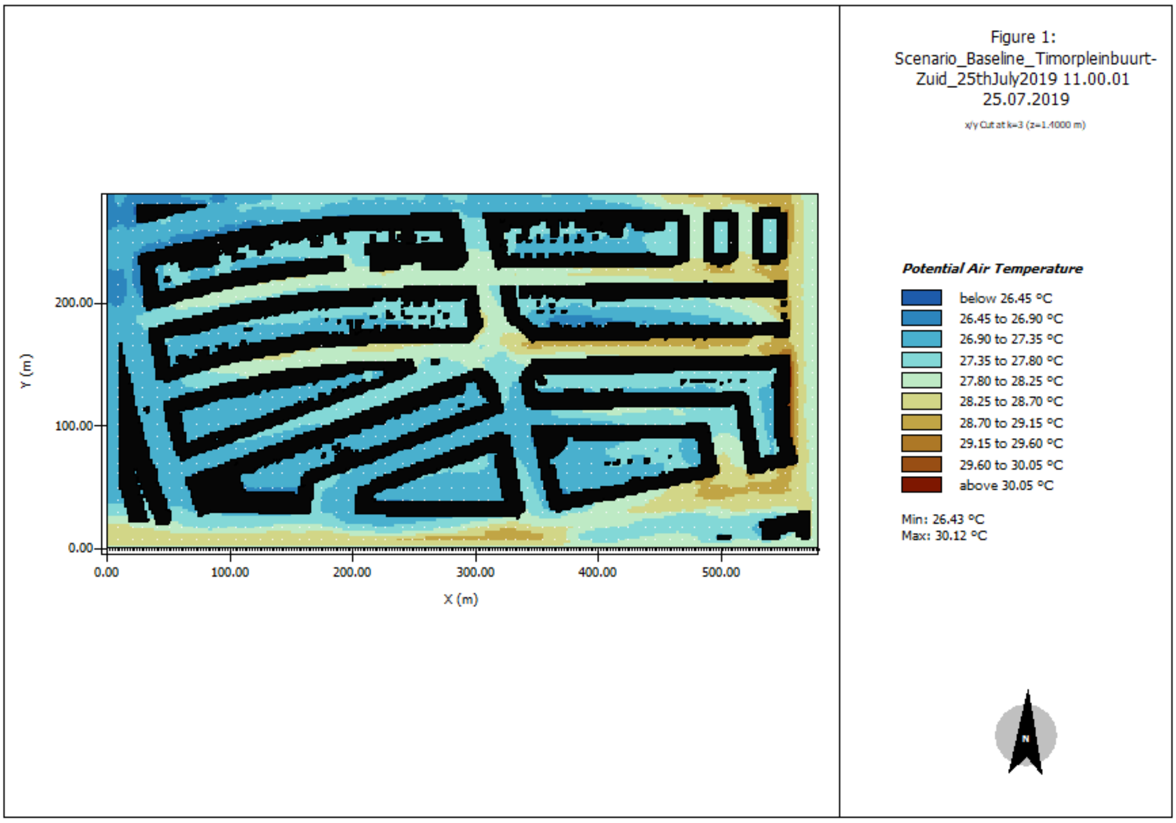
- below 23.25 °C
- 23.25 to 23.50 °C
- 23.50 to 23.75 °C
- 23.75 to 24.00 °C
- 24.00 to 24.25 °C
- 24.25 to 24.50 °C
- 24.50 to 24.75 °C
- 24.75 to 25.00 °C
- 25.00 to 25.25 °C
- above 25.25 °C

Min: 23.23 °C
Max: 25.23 °C

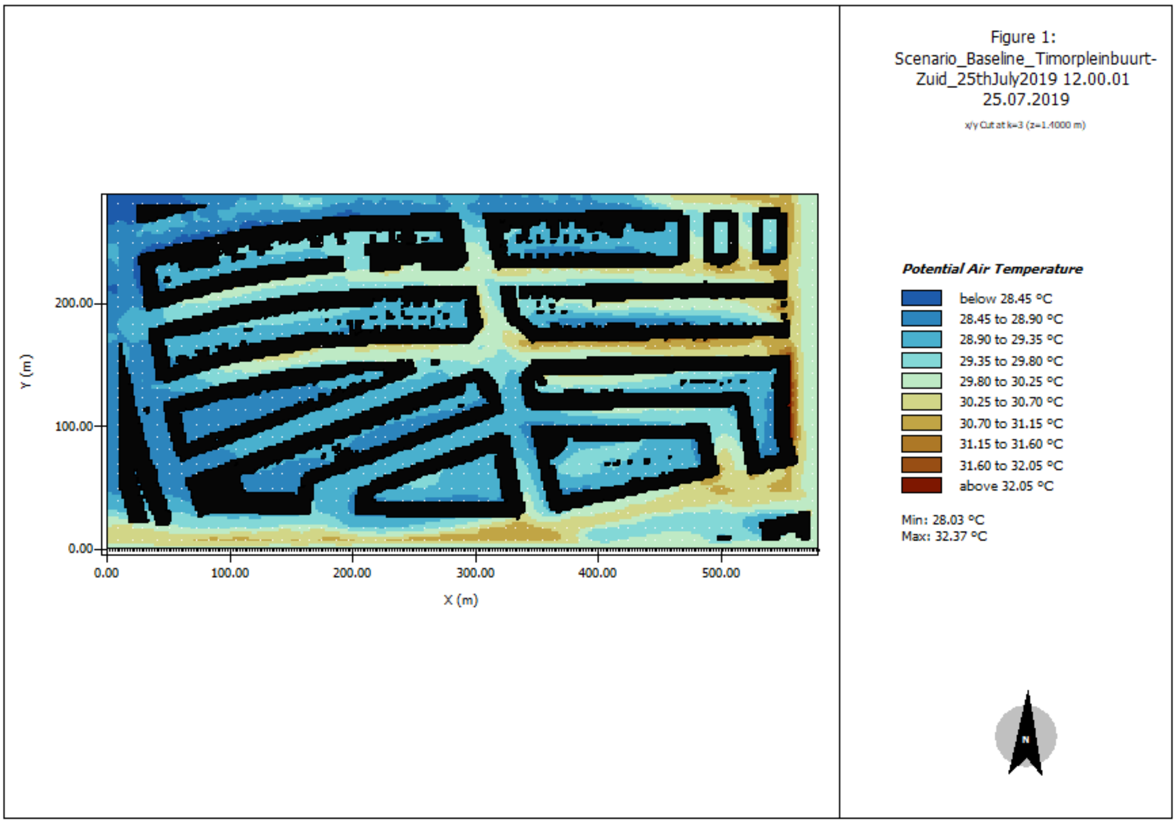
ENVI-met <Right foot>



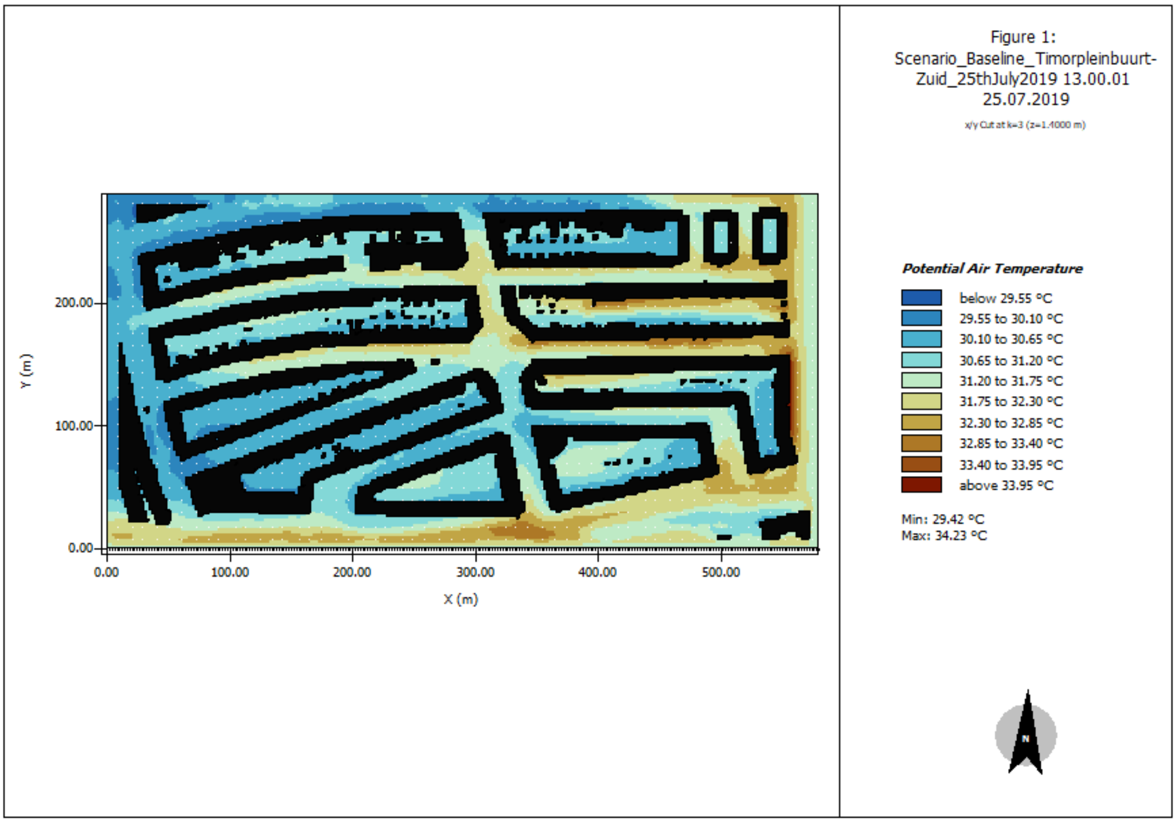
ENVI-met <Right foot>



ENVI-met <Right foot>

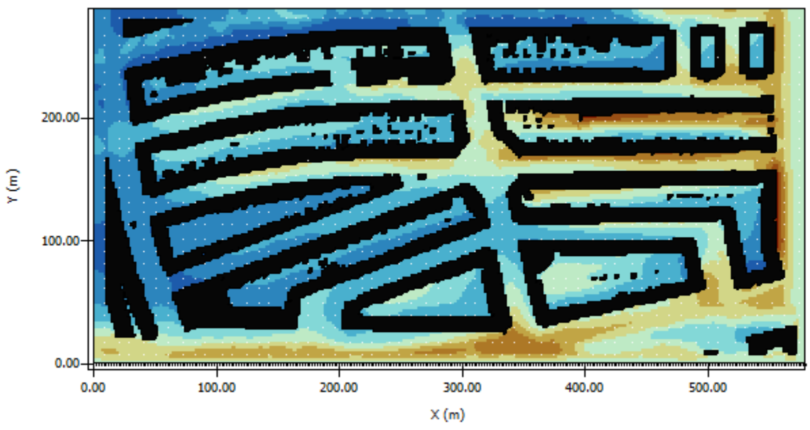


ENVI-met <Right foot>



ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 14.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



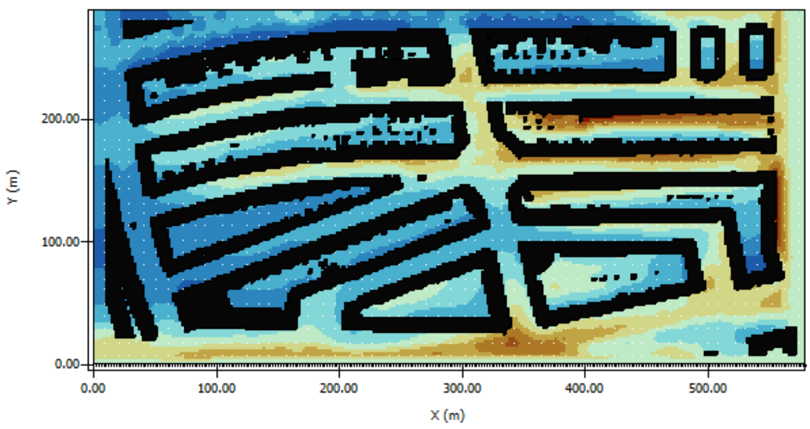
Potential Air Temperature

- below 31.50 °C
- 31.50 to 32.00 °C
- 32.00 to 32.50 °C
- 32.50 to 33.00 °C
- 33.00 to 33.50 °C
- 33.50 to 34.00 °C
- 34.00 to 34.50 °C
- 34.50 to 35.00 °C
- 35.00 to 35.50 °C
- above 35.50 °C

Min: 31.06 °C
Max: 35.92 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 15.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

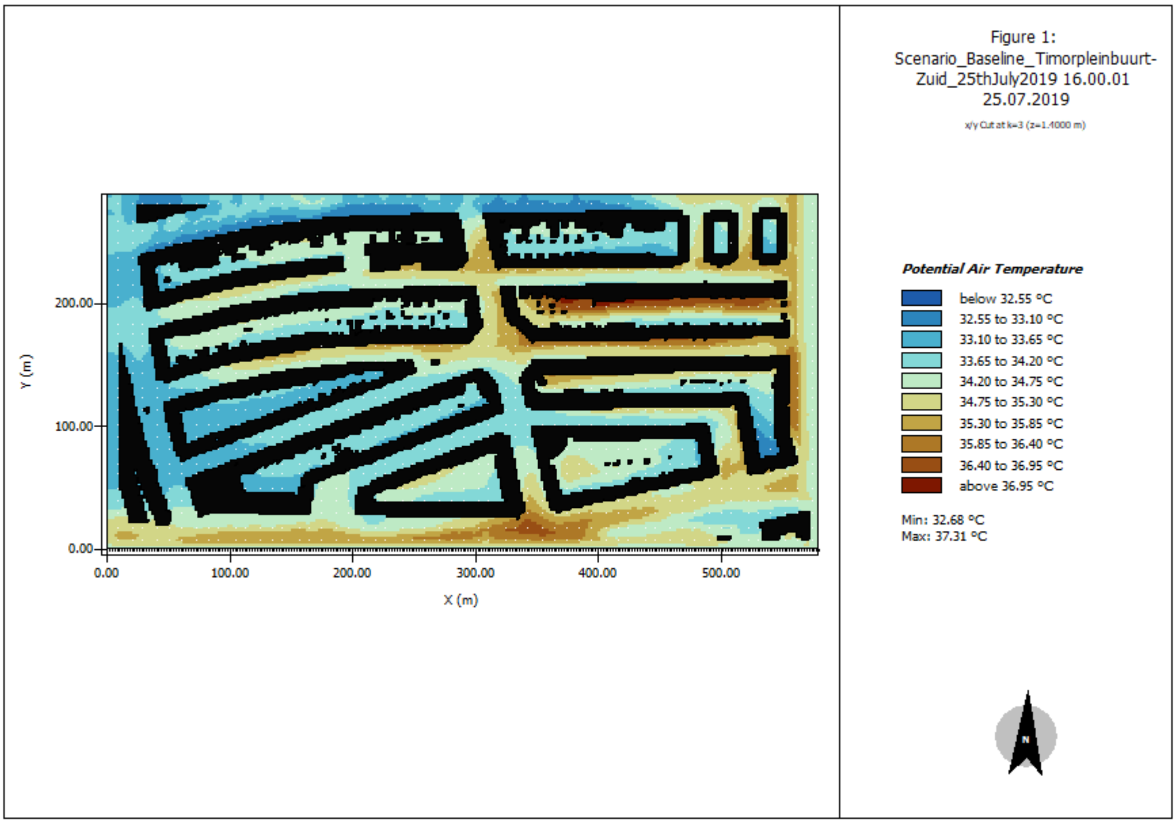


Potential Air Temperature

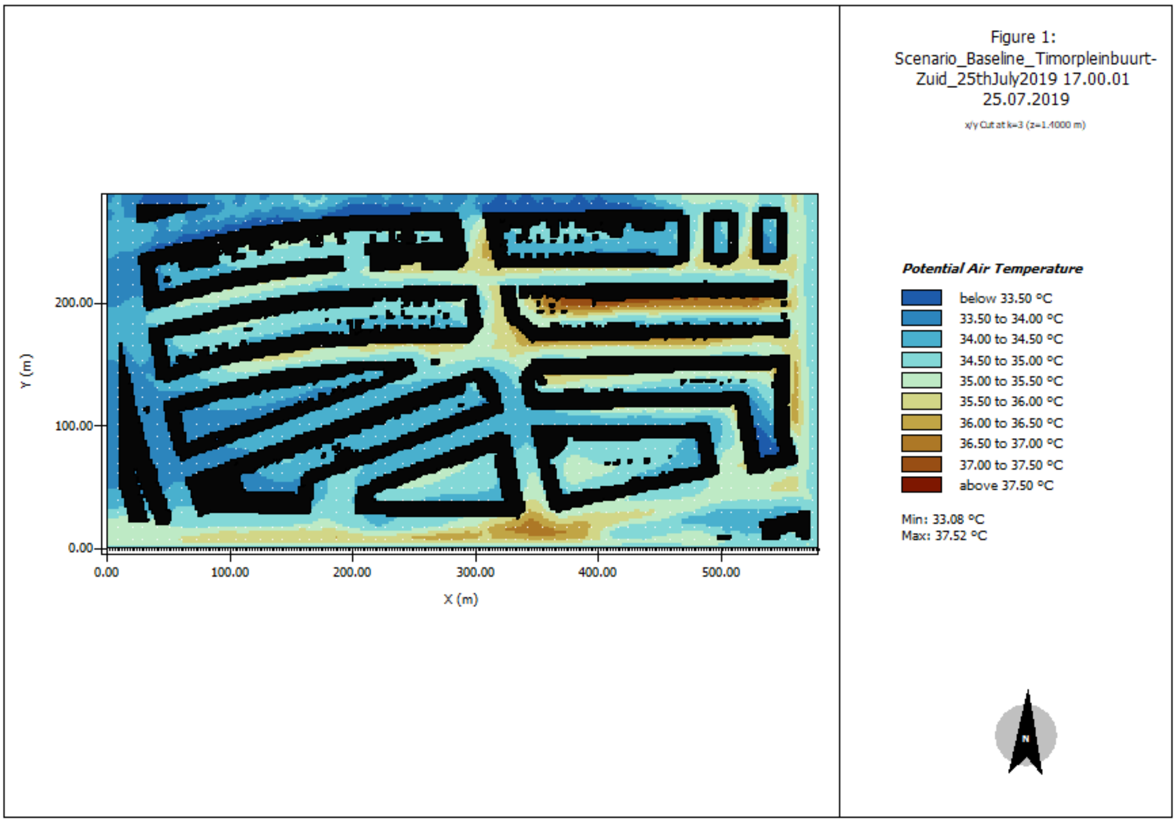
- below 32.50 °C
- 32.50 to 33.00 °C
- 33.00 to 33.50 °C
- 33.50 to 34.00 °C
- 34.00 to 34.50 °C
- 34.50 to 35.00 °C
- 35.00 to 35.50 °C
- 35.50 to 36.00 °C
- 36.00 to 36.50 °C
- above 36.50 °C

Min: 32.09 °C
Max: 36.78 °C

ENVI-met <Right foot>



ENVI-met <Right foot>



ENVI-met <Right foot>

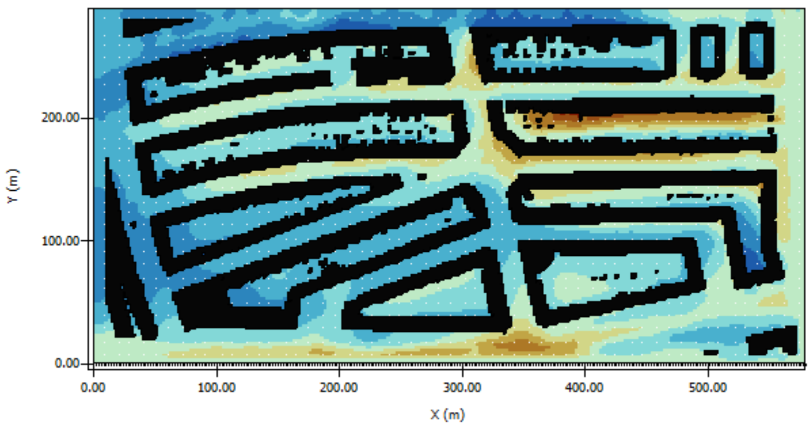


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 18.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

Potential Air Temperature

- below 33.45 °C
- 33.45 to 33.90 °C
- 33.90 to 34.35 °C
- 34.35 to 34.80 °C
- 34.80 to 35.25 °C
- 35.25 to 35.70 °C
- 35.70 to 36.15 °C
- 36.15 to 36.60 °C
- 36.60 to 37.05 °C
- above 37.05 °C

Min: 33.18 °C
Max: 37.24 °C

ENVI-met <Right foot>

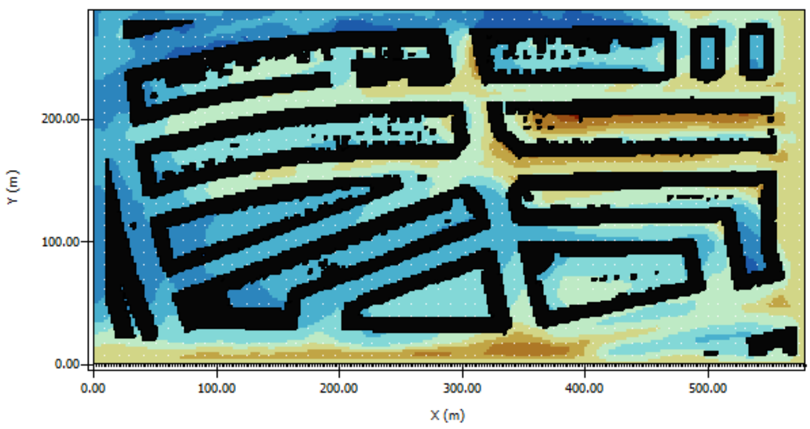


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 19.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

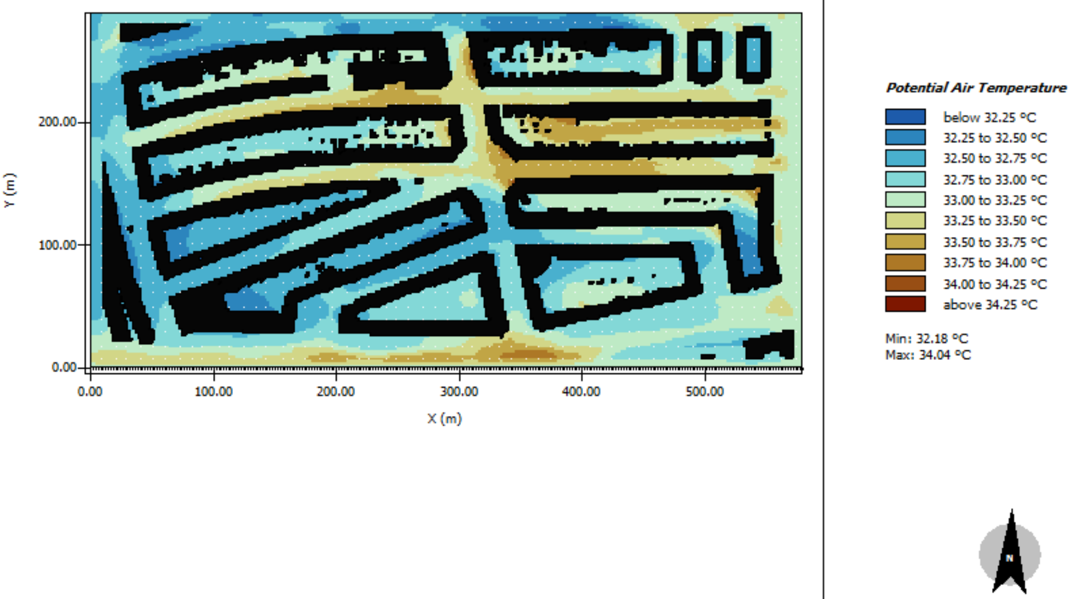
Potential Air Temperature

- below 33.35 °C
- 33.35 to 33.70 °C
- 33.70 to 34.05 °C
- 34.05 to 34.40 °C
- 34.40 to 34.75 °C
- 34.75 to 35.10 °C
- 35.10 to 35.45 °C
- 35.45 to 35.80 °C
- 35.80 to 36.15 °C
- above 36.15 °C

Min: 33.12 °C
Max: 36.48 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 20.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



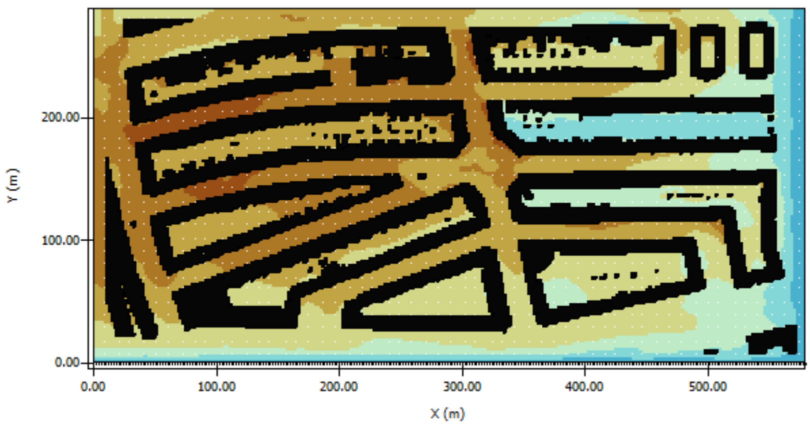
ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 21.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 22.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



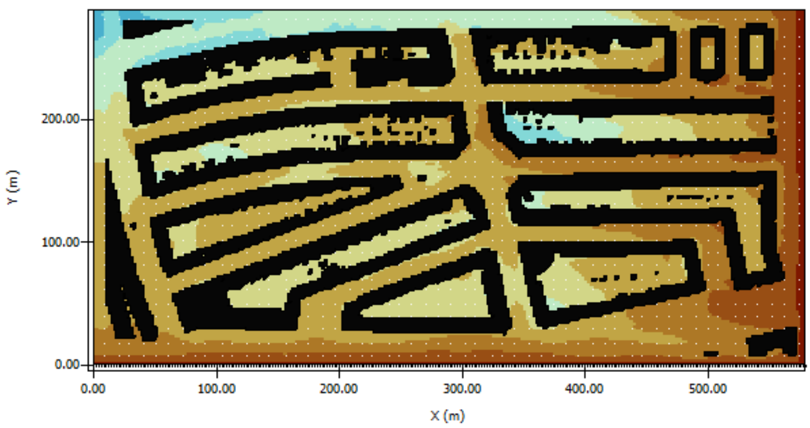
Potential Air Temperature

- below 28.15 °C
- 28.15 to 28.30 °C
- 28.30 to 28.45 °C
- 28.45 to 28.60 °C
- 28.60 to 28.75 °C
- 28.75 to 28.90 °C
- 28.90 to 29.05 °C
- 29.05 to 29.20 °C
- 29.20 to 29.35 °C
- above 29.35 °C

Min: 28.34 °C
Max: 29.28 °C

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 23.00.01
25.07.2019

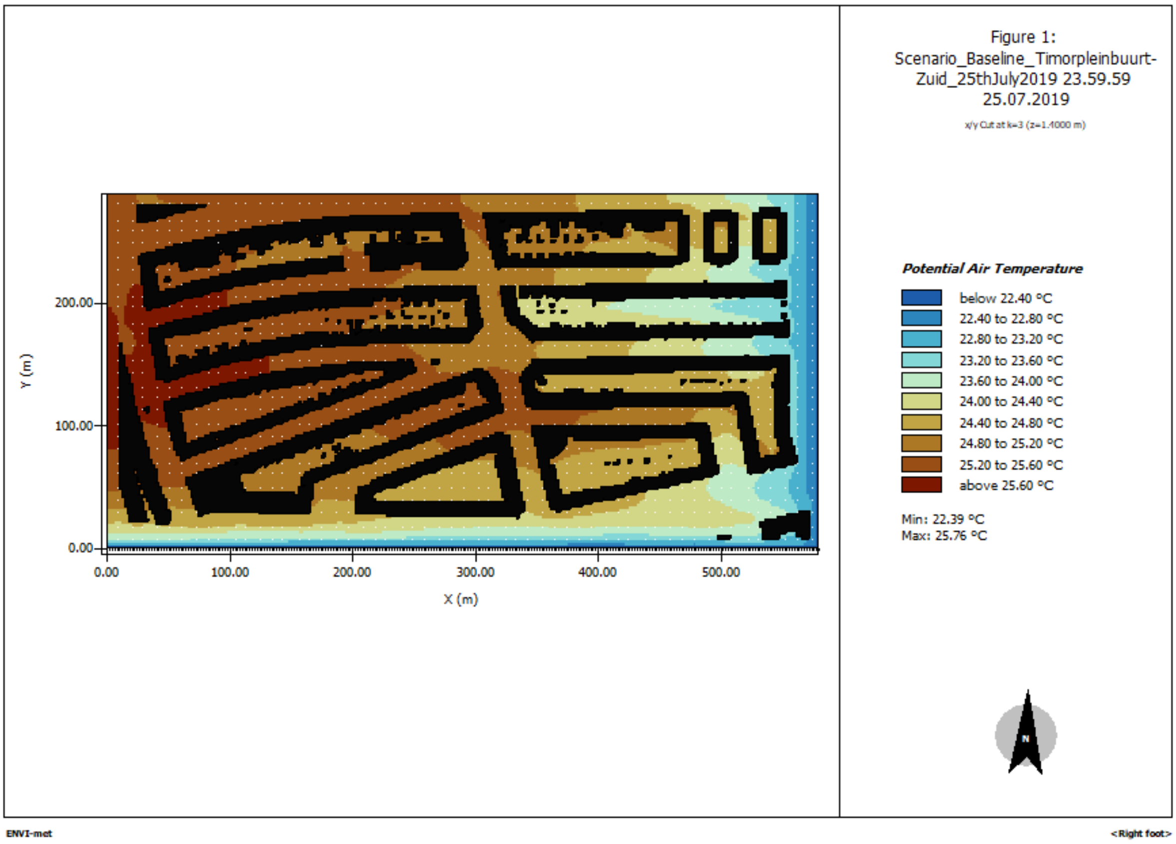
x/y Cut at k=3 (z=1.4000 m)



Potential Air Temperature

- below 28.15 °C
- 28.15 to 28.30 °C
- 28.30 to 28.45 °C
- 28.45 to 28.60 °C
- 28.60 to 28.75 °C
- 28.75 to 28.90 °C
- 28.90 to 29.05 °C
- 29.05 to 29.20 °C
- 29.20 to 29.35 °C
- above 29.35 °C

Min: 28.40 °C
Max: 29.41 °C

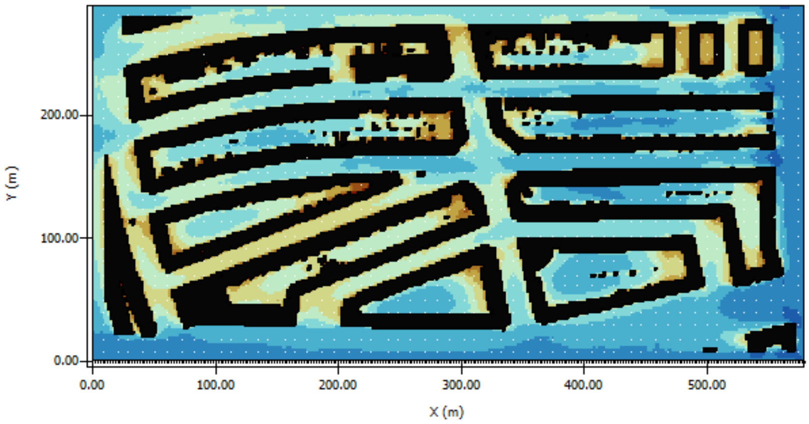


PET Baseline

PET map over 24 hours of the baseline scenario.

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 01.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



*PET**

- below 15.15 °C
- 15.15 to 16.30 °C
- 16.30 to 17.45 °C
- 17.45 to 18.60 °C
- 18.60 to 19.75 °C
- 19.75 to 20.90 °C
- 20.90 to 22.05 °C
- 22.05 to 23.20 °C
- 23.20 to 24.35 °C
- above 24.35 °C

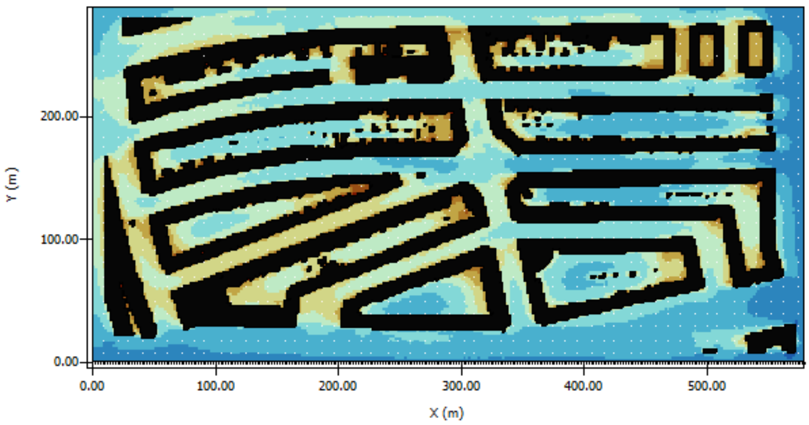
Min: 14.01 °C
Max: 25.39 °C

ENVI-met

<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 02.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



*PET**

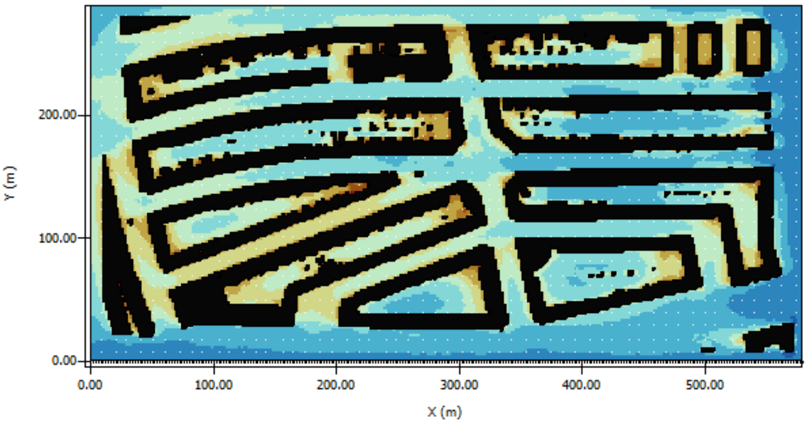
- below 14.25 °C
- 14.25 to 15.50 °C
- 15.50 to 16.75 °C
- 16.75 to 18.00 °C
- 18.00 to 19.25 °C
- 19.25 to 20.50 °C
- 20.50 to 21.75 °C
- 21.75 to 23.00 °C
- 23.00 to 24.25 °C
- above 24.25 °C

Min: 13.85 °C
Max: 25.19 °C

ENVI-met

<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 03.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



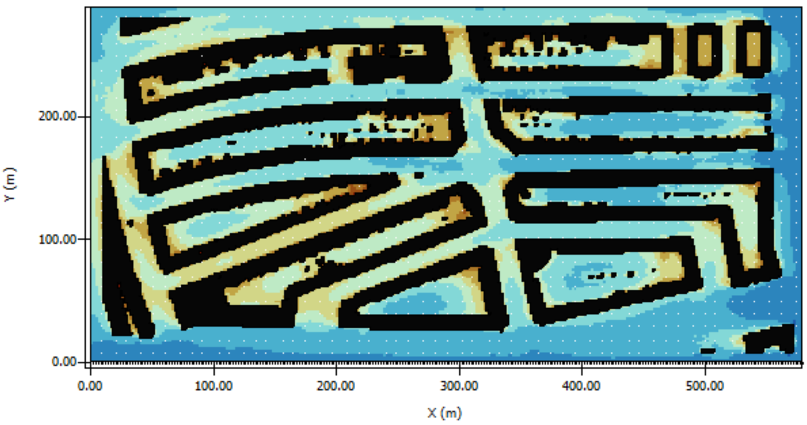
PET*

below 13.30 °C
13.30 to 14.60 °C
14.60 to 15.90 °C
15.90 to 17.20 °C
17.20 to 18.50 °C
18.50 to 19.80 °C
19.80 to 21.10 °C
21.10 to 22.40 °C
22.40 to 23.70 °C
above 23.70 °C

Min: 12.76 °C
Max: 24.78 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 04.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



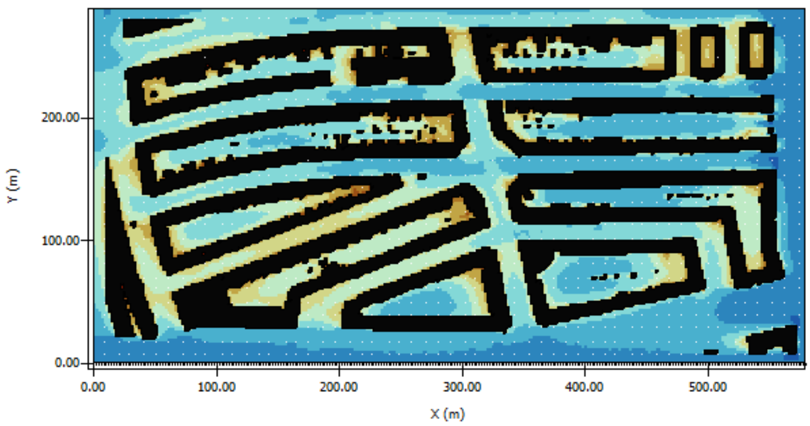
PET*

below 13.30 °C
13.30 to 14.60 °C
14.60 to 15.90 °C
15.90 to 17.20 °C
17.20 to 18.50 °C
18.50 to 19.80 °C
19.80 to 21.10 °C
21.10 to 22.40 °C
22.40 to 23.70 °C
above 23.70 °C

Min: 12.92 °C
Max: 24.64 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 05.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



*PET**

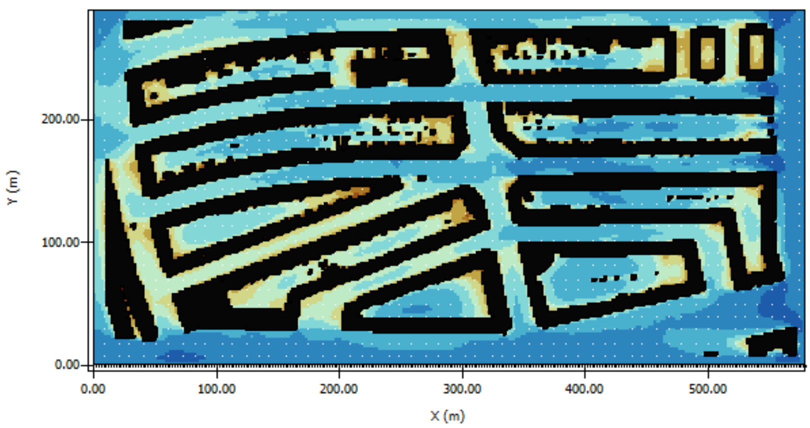
- below 13.30 °C
- 13.30 to 14.60 °C
- 14.60 to 15.90 °C
- 15.90 to 17.20 °C
- 17.20 to 18.50 °C
- 18.50 to 19.80 °C
- 19.80 to 21.10 °C
- 21.10 to 22.40 °C
- 22.40 to 23.70 °C
- above 23.70 °C

Min: 12.54 °C
Max: 24.44 °C

ENVI-met

<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 06.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



*PET**

- below 14.20 °C
- 14.20 to 15.40 °C
- 15.40 to 16.60 °C
- 16.60 to 17.80 °C
- 17.80 to 19.00 °C
- 19.00 to 20.20 °C
- 20.20 to 21.40 °C
- 21.40 to 22.60 °C
- 22.60 to 23.80 °C
- above 23.80 °C

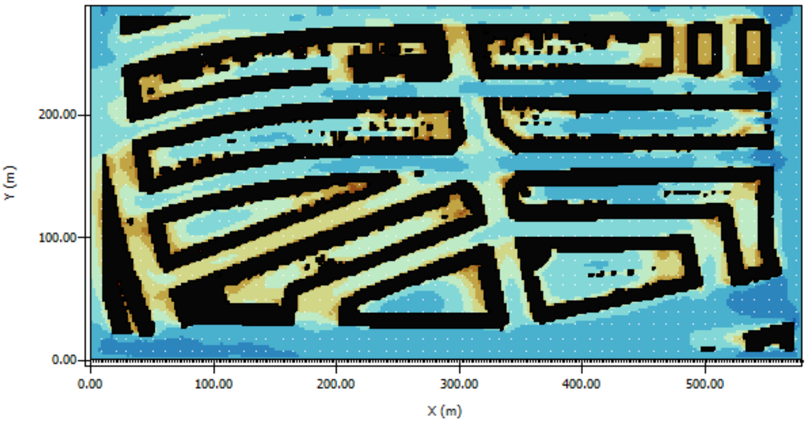
Min: 13.02 °C
Max: 24.51 °C

ENVI-met

<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 07.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



*PET**

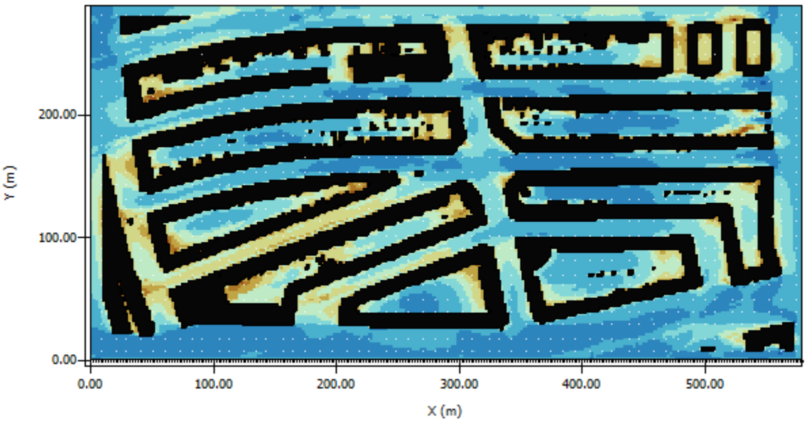
- below 14.20 °C
- 14.20 to 15.40 °C
- 15.40 to 16.60 °C
- 16.60 to 17.80 °C
- 17.80 to 19.00 °C
- 19.00 to 20.20 °C
- 20.20 to 21.40 °C
- 21.40 to 22.60 °C
- 22.60 to 23.80 °C
- above 23.80 °C

Min: 13.84 °C
Max: 24.68 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 08.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



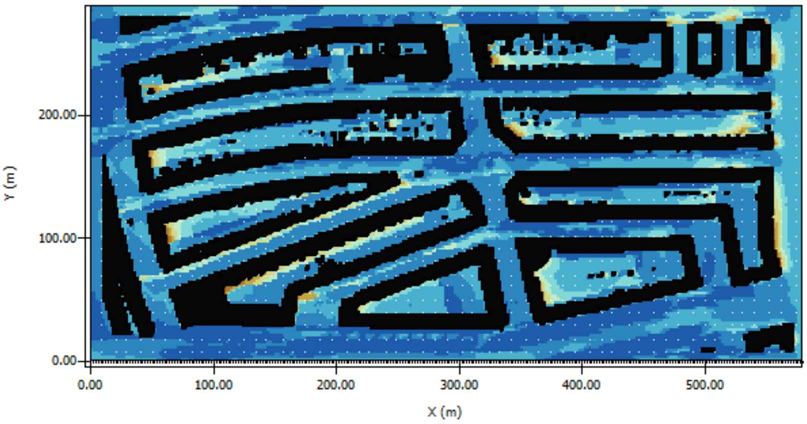
*PET**

- below 17.10 °C
- 17.10 to 18.20 °C
- 18.20 to 19.30 °C
- 19.30 to 20.40 °C
- 20.40 to 21.50 °C
- 21.50 to 22.60 °C
- 22.60 to 23.70 °C
- 23.70 to 24.80 °C
- 24.80 to 25.90 °C
- above 25.90 °C

Min: 16.86 °C
Max: 26.85 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 09.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

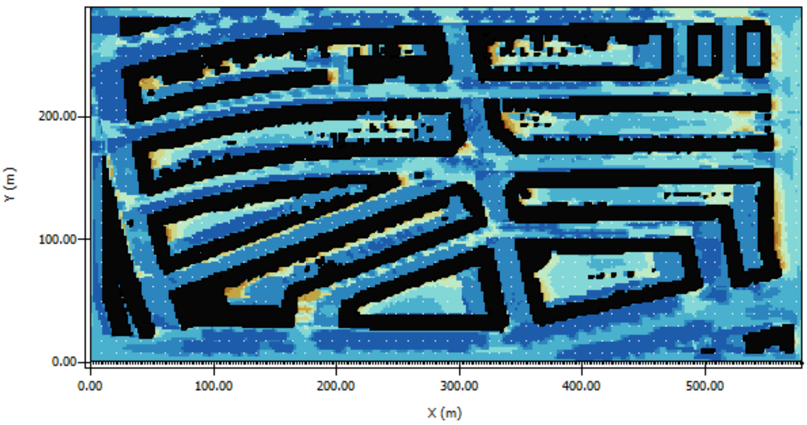


PET*

- below 21.80 °C
- 21.80 to 24.60 °C
- 24.60 to 27.40 °C
- 27.40 to 30.20 °C
- 30.20 to 33.00 °C
- 33.00 to 35.80 °C
- 35.80 to 38.60 °C
- 38.60 to 41.40 °C
- 41.40 to 44.20 °C
- above 44.20 °C

Min: 19.51 °C
Max: 46.70 °C

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 10.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

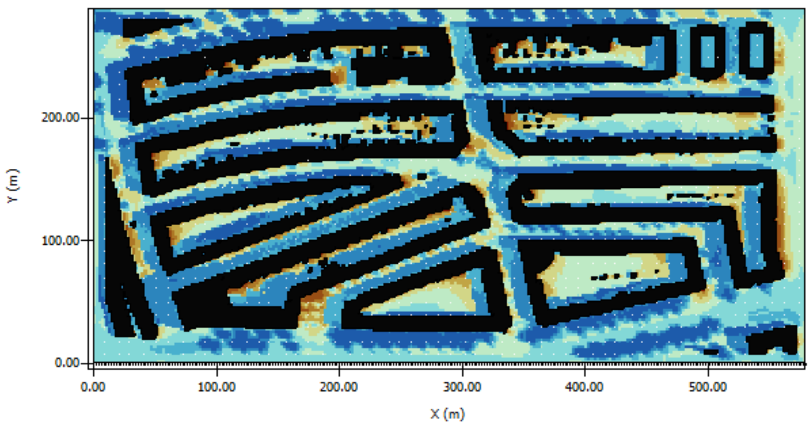


PET*

- below 24.70 °C
- 24.70 to 28.40 °C
- 28.40 to 32.10 °C
- 32.10 to 35.80 °C
- 35.80 to 39.50 °C
- 39.50 to 43.20 °C
- 43.20 to 46.90 °C
- 46.90 to 50.60 °C
- 50.60 to 54.30 °C
- above 54.30 °C

Min: 21.58 °C
Max: 57.94 °C

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 11.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



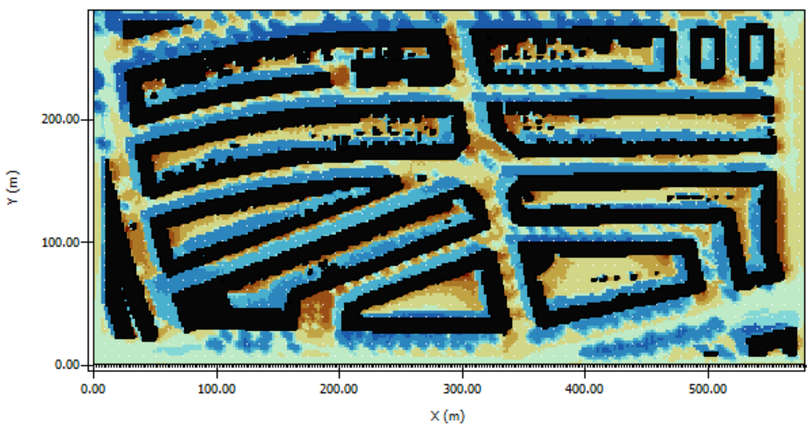
*PET**

- below 26.60 °C
- 26.60 to 30.20 °C
- 30.20 to 33.80 °C
- 33.80 to 37.40 °C
- 37.40 to 41.00 °C
- 41.00 to 44.60 °C
- 44.60 to 48.20 °C
- 48.20 to 51.80 °C
- 51.80 to 55.40 °C
- above 55.40 °C

Min: 23.21 °C
Max: 58.97 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 12.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



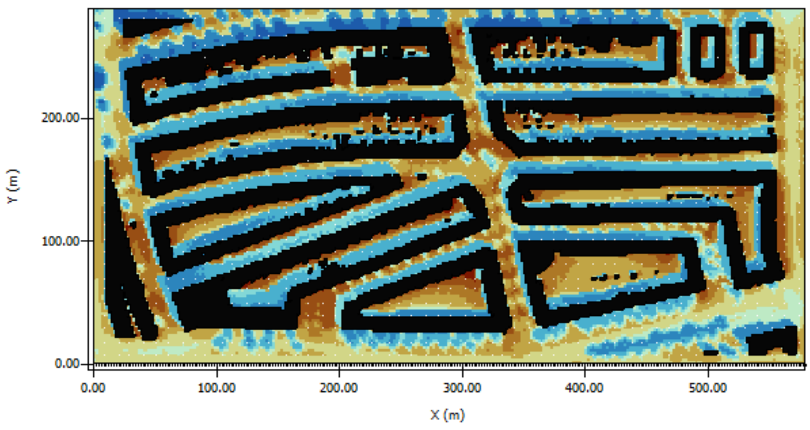
*PET**

- below 28.50 °C
- 28.50 to 32.00 °C
- 32.00 to 35.50 °C
- 35.50 to 39.00 °C
- 39.00 to 42.50 °C
- 42.50 to 46.00 °C
- 46.00 to 49.50 °C
- 49.50 to 53.00 °C
- 53.00 to 56.50 °C
- above 56.50 °C

Min: 25.27 °C
Max: 59.59 °C

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 13.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



*PET**

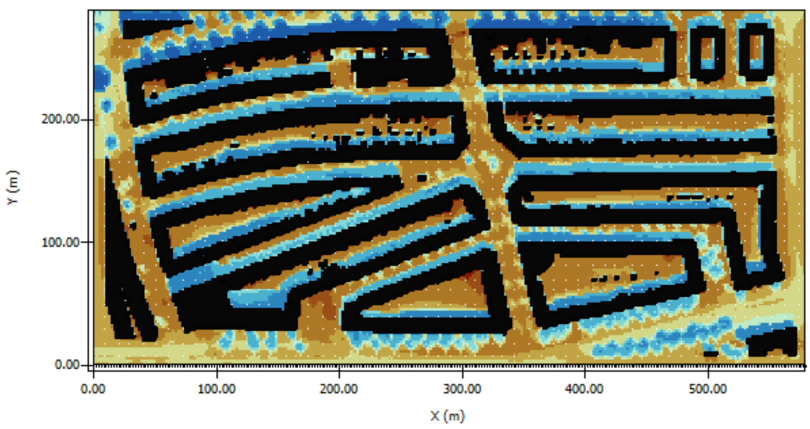
- below 30.30 °C
- 30.30 to 33.60 °C
- 33.60 to 36.90 °C
- 36.90 to 40.20 °C
- 40.20 to 43.50 °C
- 43.50 to 46.80 °C
- 46.80 to 50.10 °C
- 50.10 to 53.40 °C
- 53.40 to 56.70 °C
- above 56.70 °C

Min: 27.91 °C
Max: 59.86 °C

ENVI-met

<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 14.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



*PET**

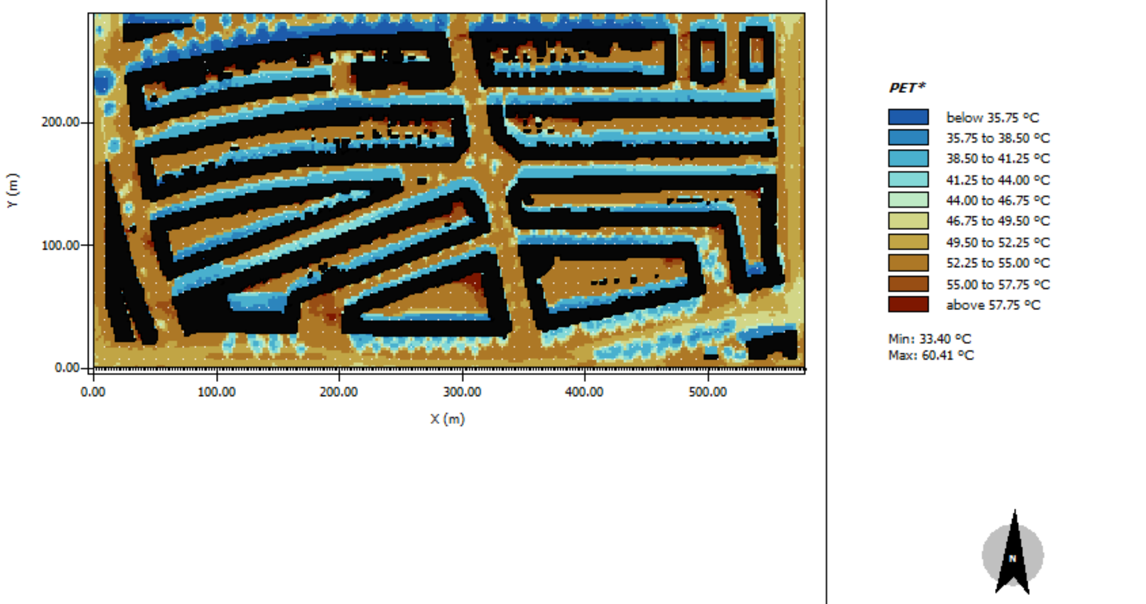
- below 34.00 °C
- 34.00 to 37.00 °C
- 37.00 to 40.00 °C
- 40.00 to 43.00 °C
- 43.00 to 46.00 °C
- 46.00 to 49.00 °C
- 49.00 to 52.00 °C
- 52.00 to 55.00 °C
- 55.00 to 58.00 °C
- above 58.00 °C

Min: 31.04 °C
Max: 60.15 °C

ENVI-met

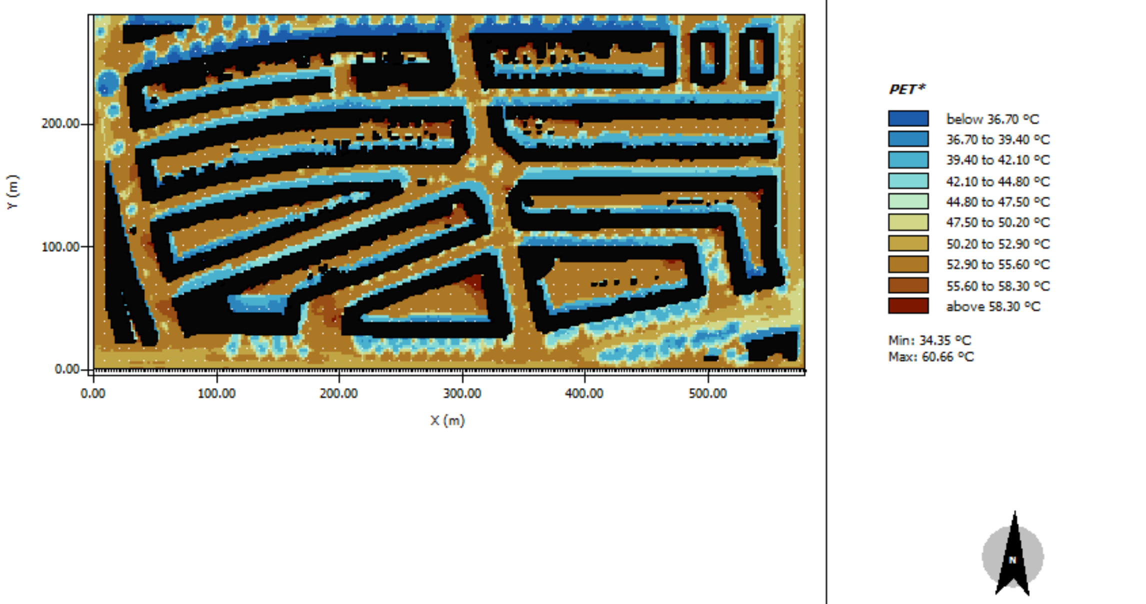
<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 15.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 16.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



ENVI-met <Right foot>

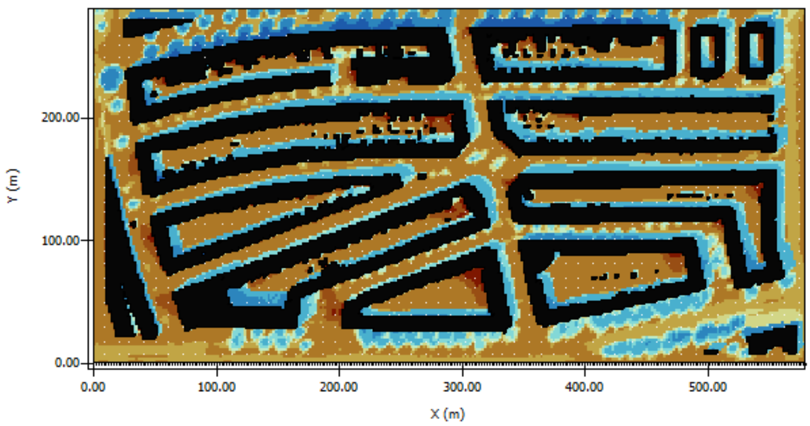


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 17.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)

PET*

below 36.70 °C
36.70 to 39.40 °C
39.40 to 42.10 °C
42.10 to 44.80 °C
44.80 to 47.50 °C
47.50 to 50.20 °C
50.20 to 52.90 °C
52.90 to 55.60 °C
55.60 to 58.30 °C
above 58.30 °C

Min: 34.97 °C
Max: 60.96 °C

ENVI-met

<Right foot>

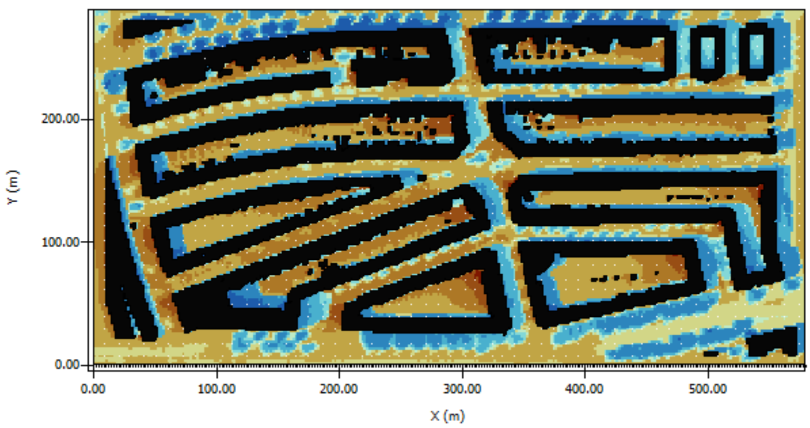


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 18.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)

PET*

below 37.70 °C
37.70 to 40.40 °C
40.40 to 43.10 °C
43.10 to 45.80 °C
45.80 to 48.50 °C
48.50 to 51.20 °C
51.20 to 53.90 °C
53.90 to 56.60 °C
56.60 to 59.30 °C
above 59.30 °C

Min: 35.03 °C
Max: 61.39 °C

ENVI-met

<Right foot>

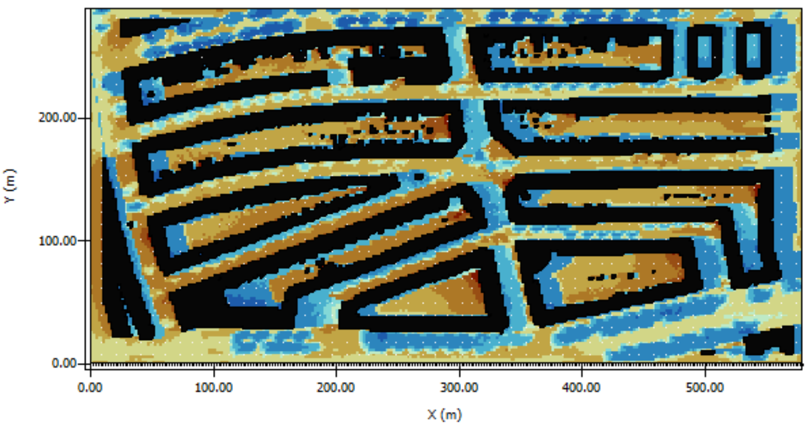


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 19.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

*PET**

- below 36.70 °C
- 36.70 to 39.40 °C
- 39.40 to 42.10 °C
- 42.10 to 44.80 °C
- 44.80 to 47.50 °C
- 47.50 to 50.20 °C
- 50.20 to 52.90 °C
- 52.90 to 55.60 °C
- 55.60 to 58.30 °C
- above 58.30 °C

Min: 34.69 °C
Max: 60.28 °C

ENVI-met <Right foot>

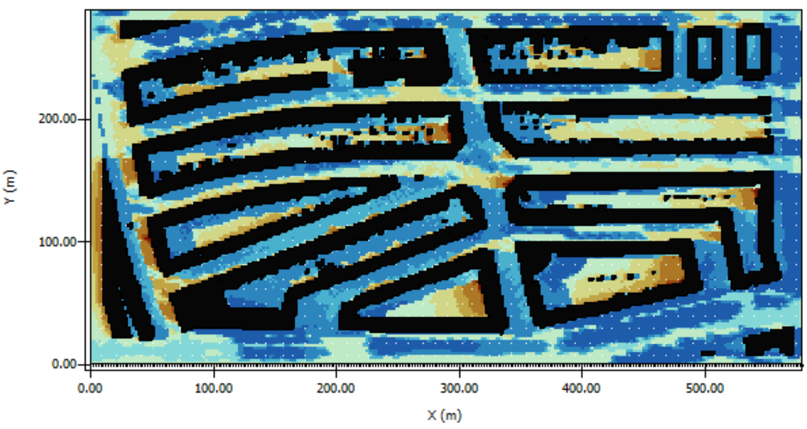


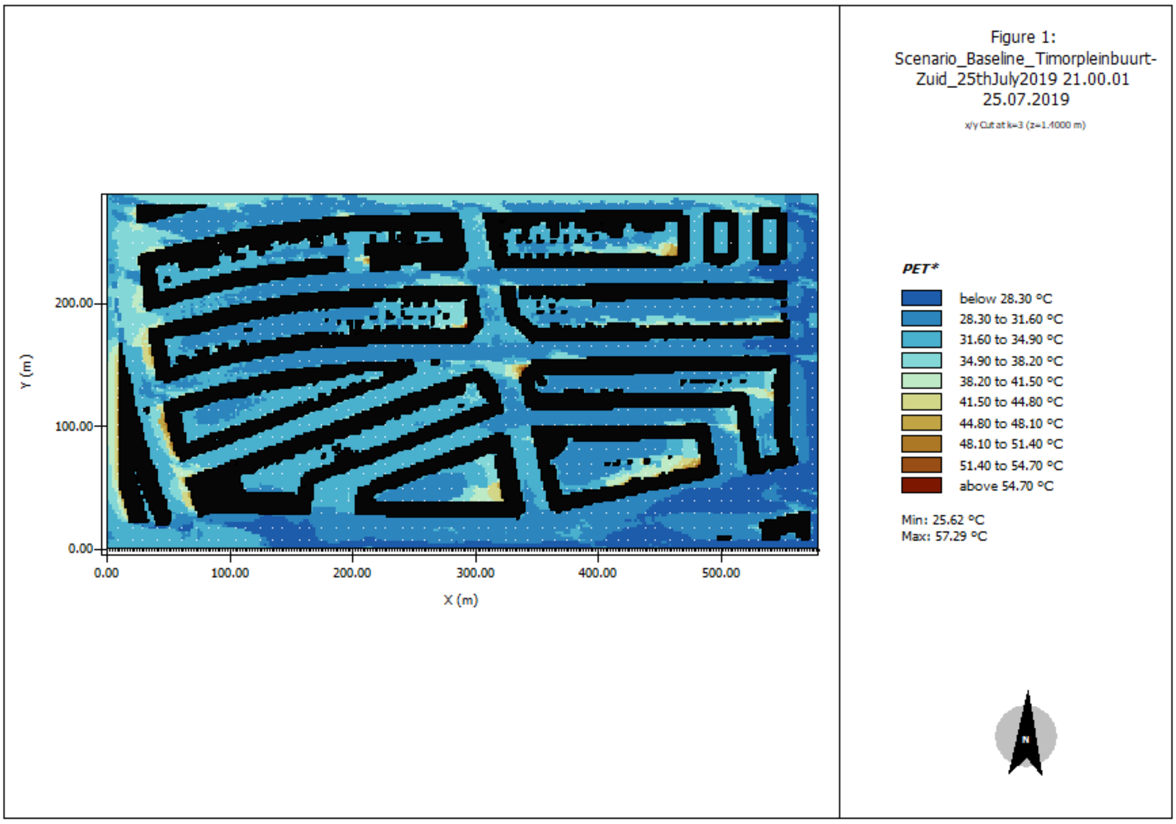
Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 20.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

*PET**

- below 34.80 °C
- 34.80 to 37.60 °C
- 37.60 to 40.40 °C
- 40.40 to 43.20 °C
- 43.20 to 46.00 °C
- 46.00 to 48.80 °C
- 48.80 to 51.60 °C
- 51.60 to 54.40 °C
- 54.40 to 57.20 °C
- above 57.20 °C

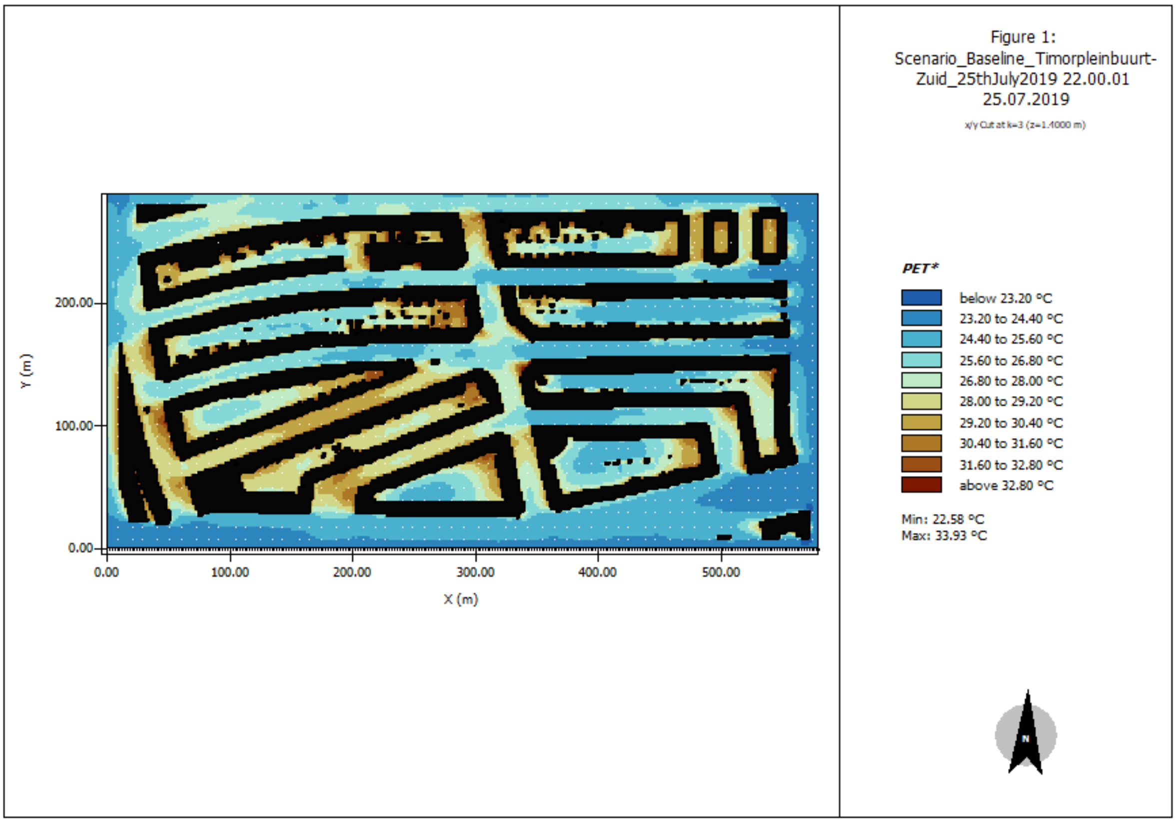
Min: 32.34 °C
Max: 59.18 °C

ENVI-met <Right foot>



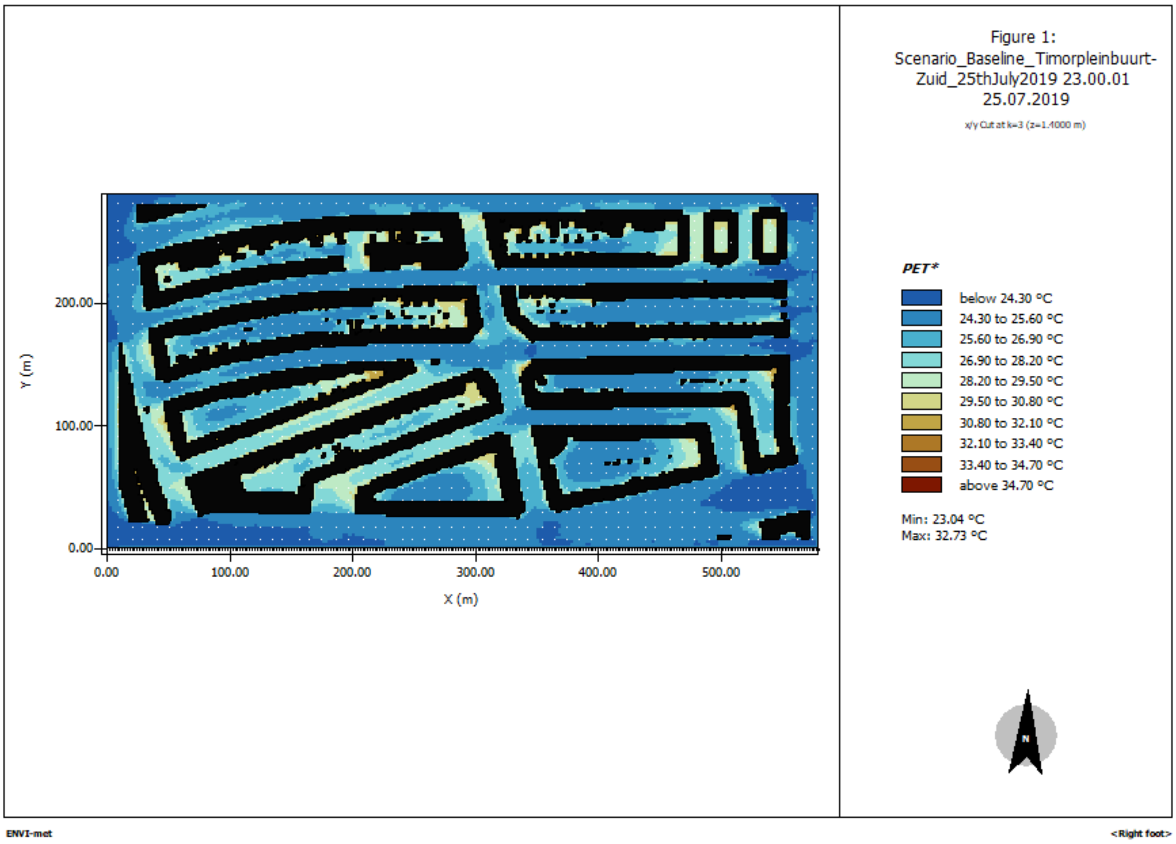
ENVI-met

<Right foot>



ENVI-met

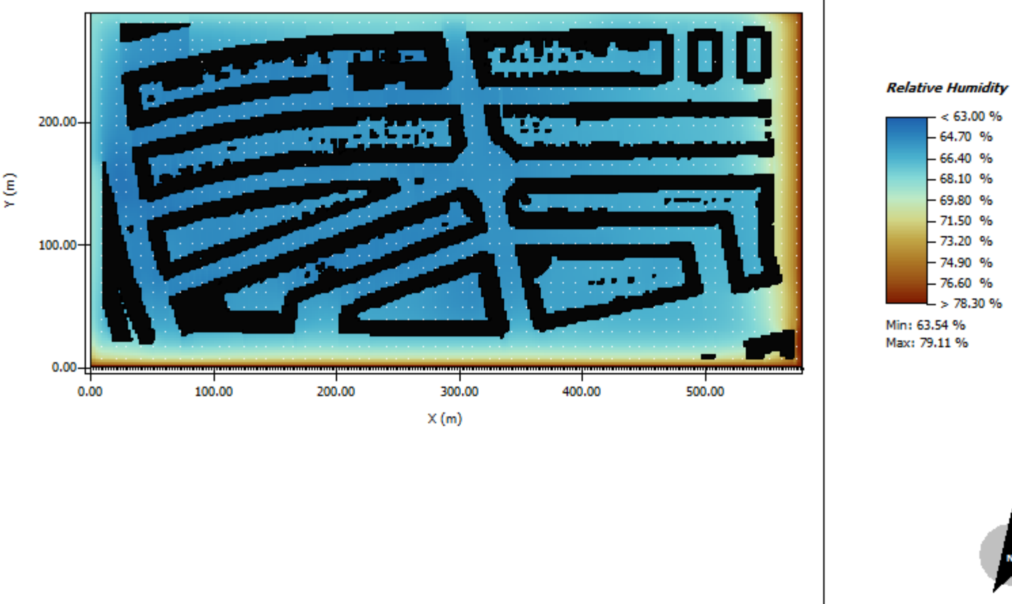
<Right foot>



Relative humidity Baseline

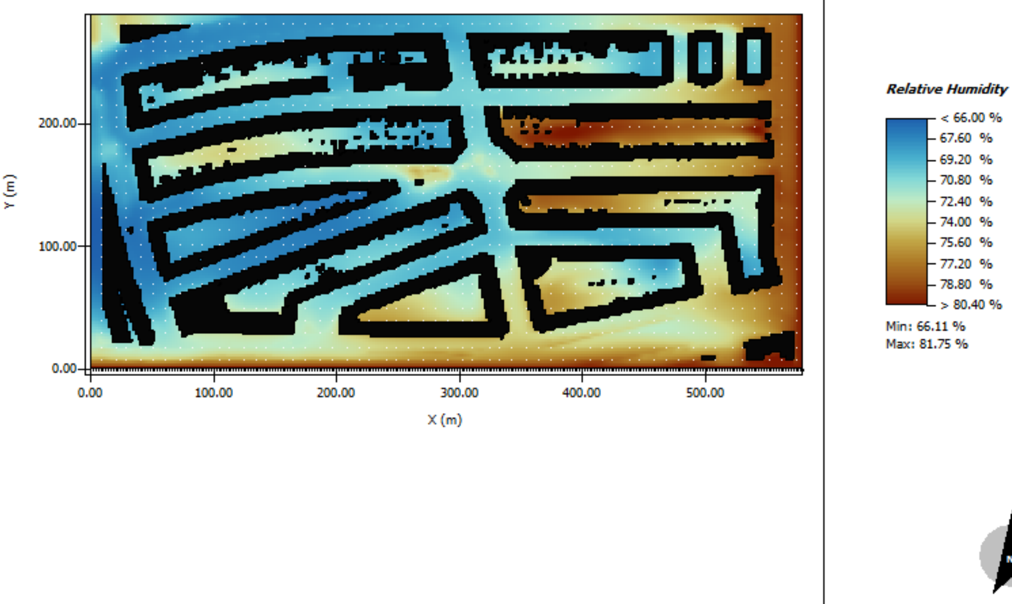
Relative humidity map over 24 hours of the baseline scenario.

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 00.00.00
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



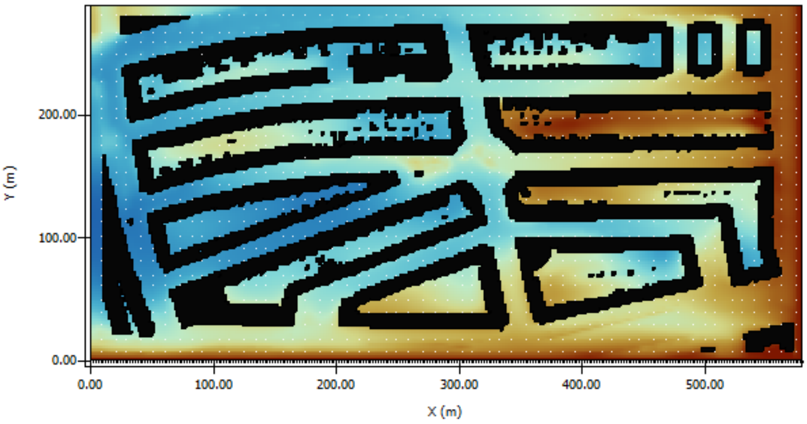
ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 01.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 02.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



Relative Humidity

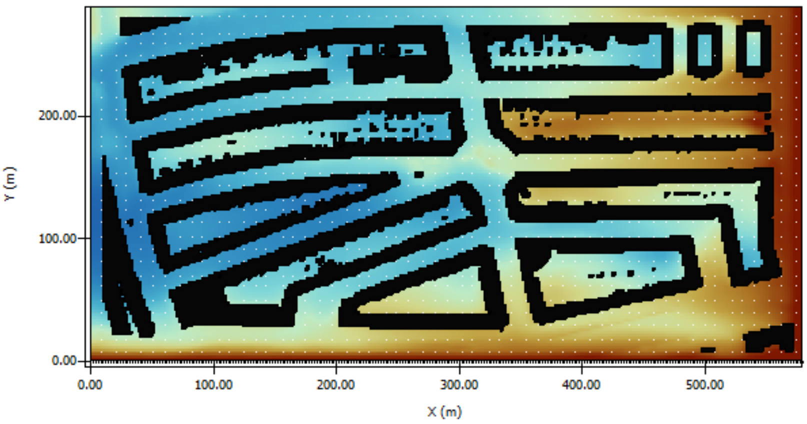
< 68.00 %
69.60 %
71.20 %
72.80 %
74.40 %
76.00 %
77.60 %
79.20 %
80.80 %
> 82.40 %

Min: 68.36 %
Max: 83.61 %

ENVI-met

<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 03.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



Relative Humidity

< 72.00 %
73.90 %
75.80 %
77.70 %
79.60 %
81.50 %
83.40 %
85.30 %
87.20 %
> 89.10 %

Min: 72.45 %
Max: 90.44 %

ENVI-met

<Right foot>

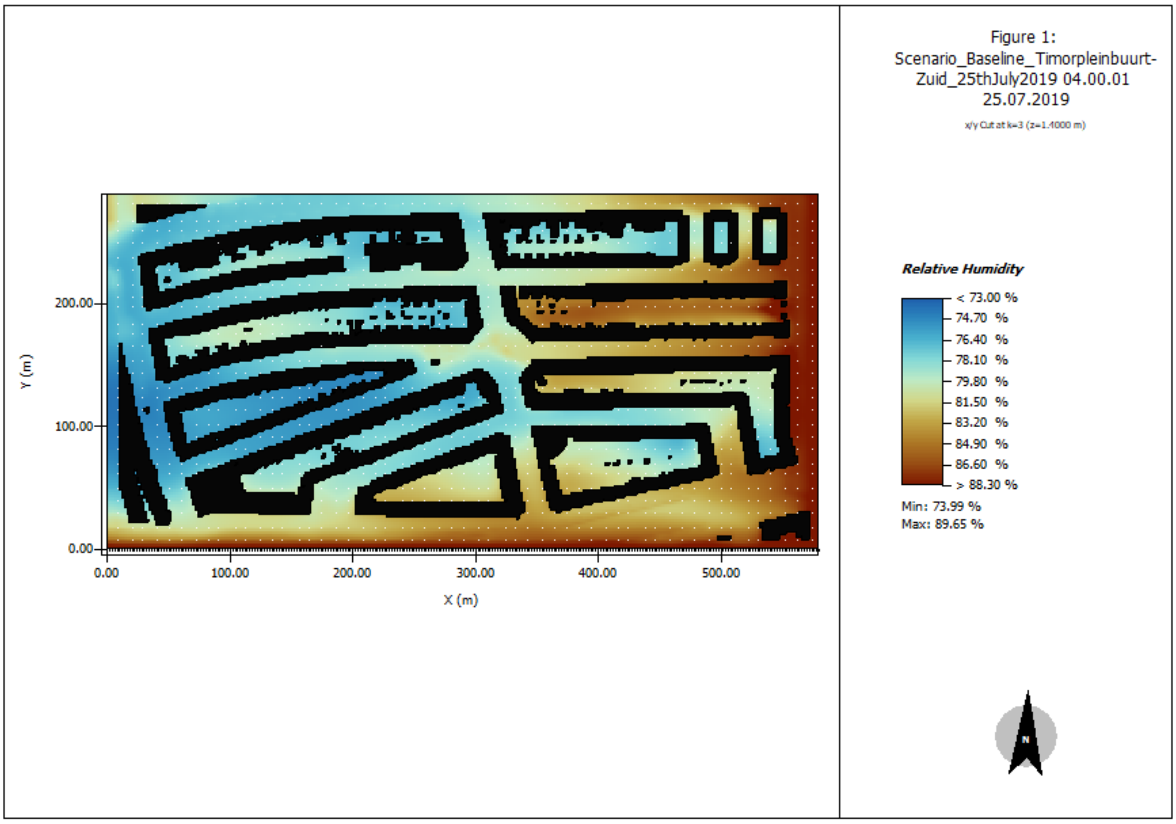


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 04.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)
Y (m)
200.00
100.00
0.00
100.00
200.00
300.00
400.00
500.00
X (m)
Relative Humidity
< 73.00 %
74.70 %
76.40 %
78.10 %
79.80 %
81.50 %
83.20 %
84.90 %
86.60 %
> 88.30 %
Min: 73.99 %
Max: 89.65 %

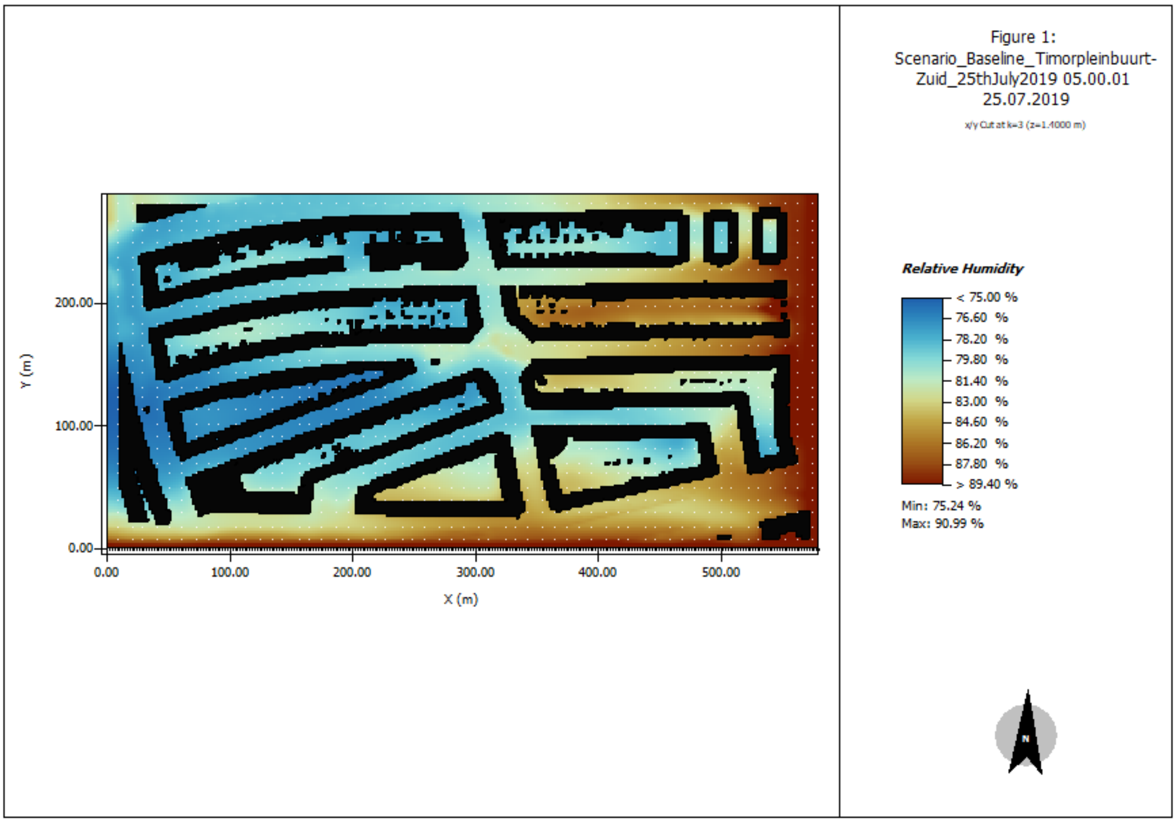
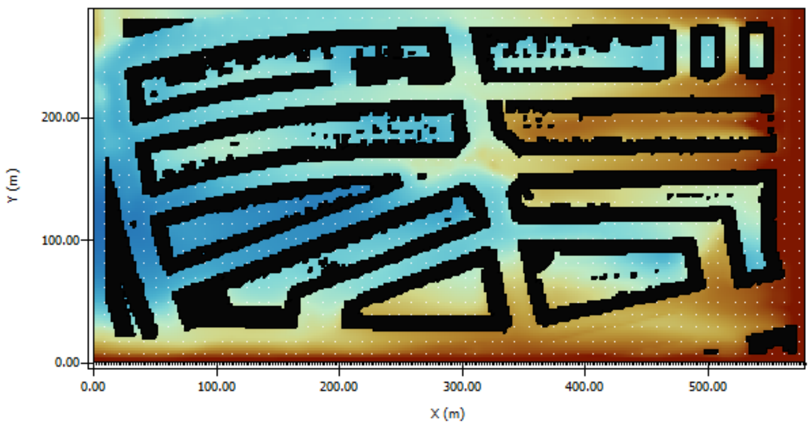


Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 05.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)
Y (m)
200.00
100.00
0.00
100.00
200.00
300.00
400.00
500.00
X (m)
Relative Humidity
< 75.00 %
76.60 %
78.20 %
79.80 %
81.40 %
83.00 %
84.60 %
86.20 %
87.80 %
> 89.40 %
Min: 75.24 %
Max: 90.99 %

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 06.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



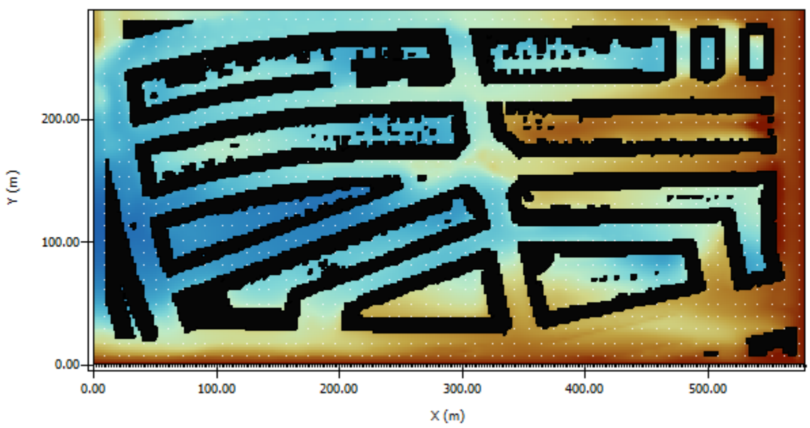
Relative Humidity

< 76.00 %
77.60 %
79.20 %
80.80 %
82.40 %
84.00 %
85.60 %
87.20 %
88.80 %
> 90.40 %

Min: 76.64 %
Max: 91.86 %

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 07.00.01
25.07.2019

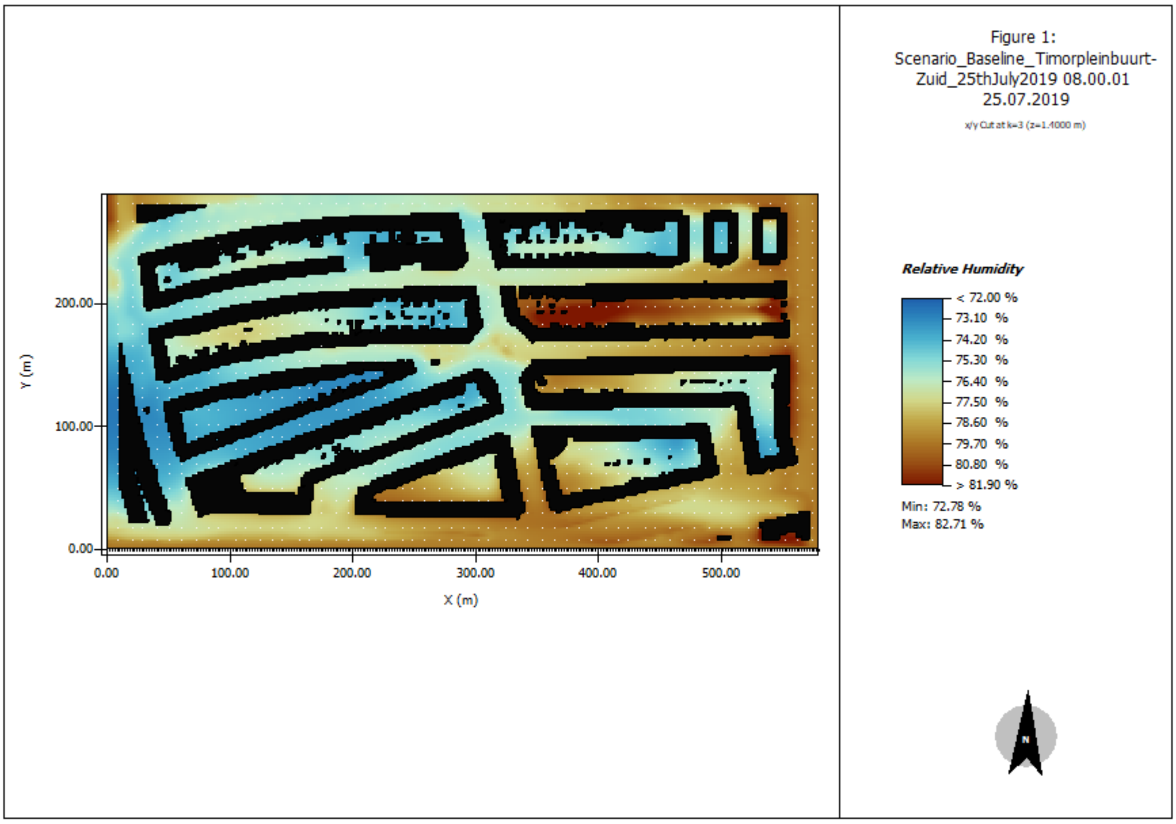
x/y Cut at k=3 (z=1.4000 m)



Relative Humidity

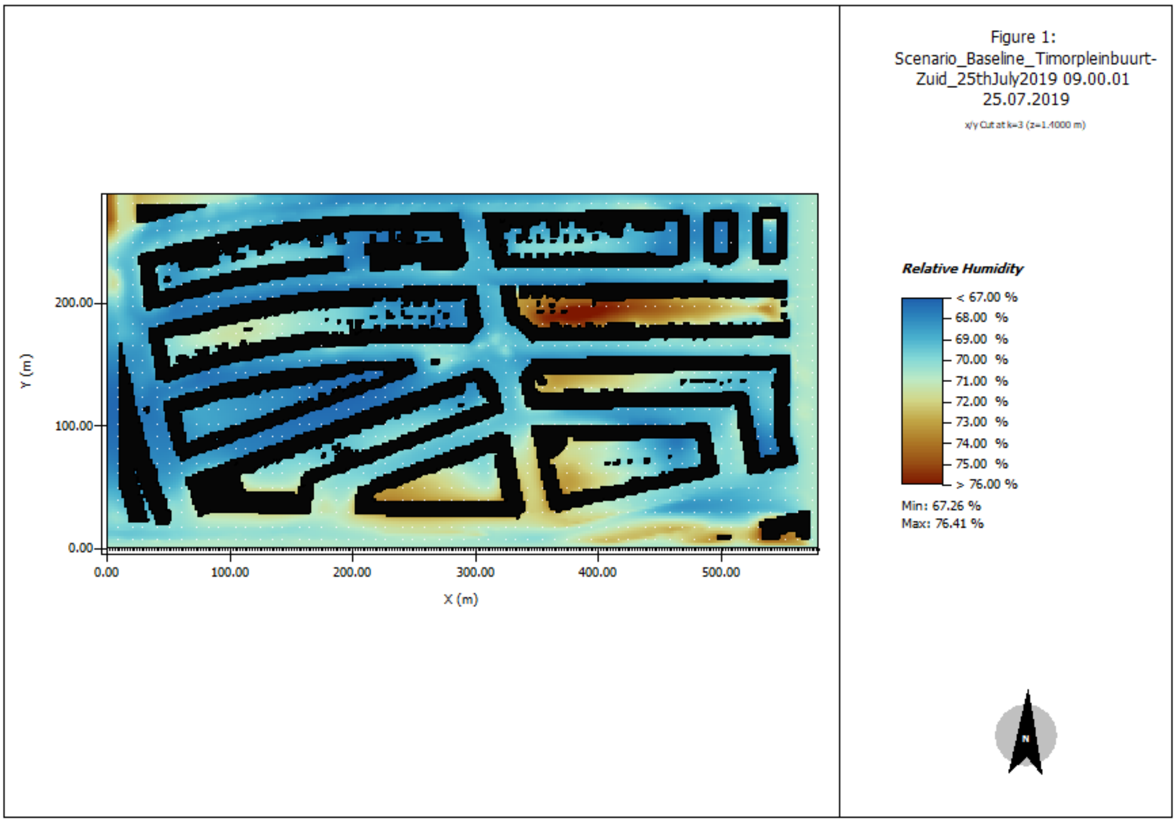
< 76.00 %
77.40 %
78.80 %
80.20 %
81.60 %
83.00 %
84.40 %
85.80 %
87.20 %
> 88.60 %

Min: 76.19 %
Max: 89.15 %



ENVI-met

<Right foot>

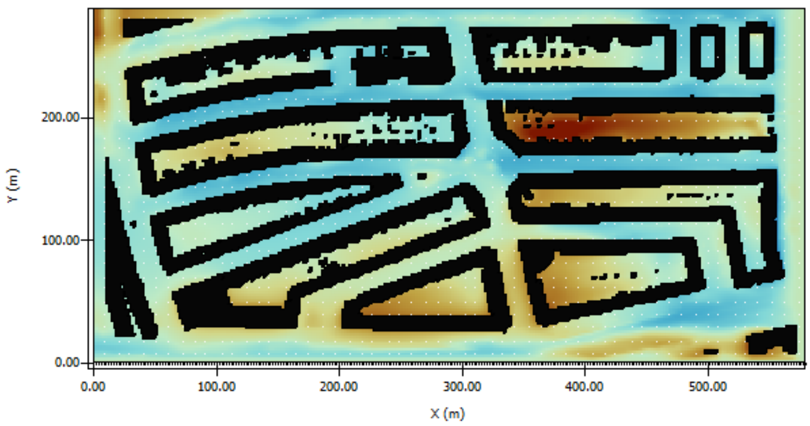


ENVI-met

<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 10.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)



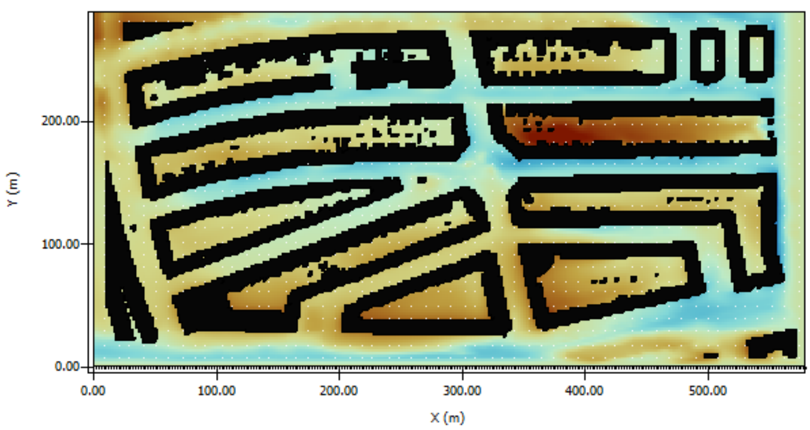
Relative Humidity

< 57.00 %
58.30 %
59.60 %
60.90 %
62.20 %
63.50 %
64.80 %
66.10 %
67.40 %
> 68.70 %

Min: 57.75 %
Max: 69.28 %

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 11.00.01
25.07.2019

x/y Cut at k=3 (z=1.4000 m)

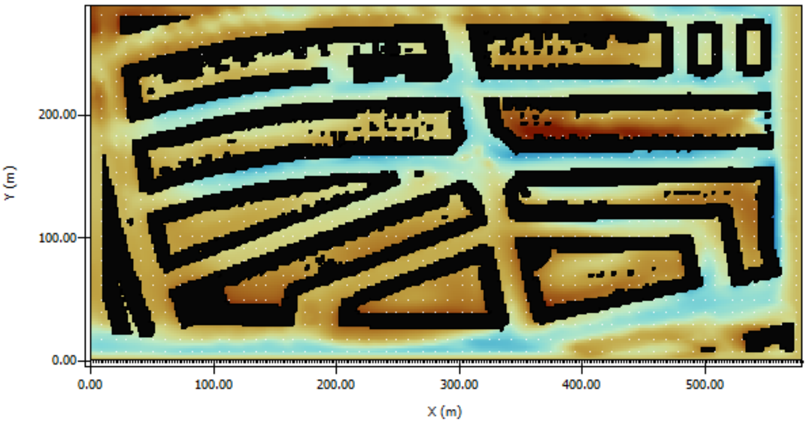


Relative Humidity

< 48.00 %
49.40 %
50.80 %
52.20 %
53.60 %
55.00 %
56.40 %
57.80 %
59.20 %
> 60.60 %

Min: 48.56 %
Max: 61.32 %

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 12.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



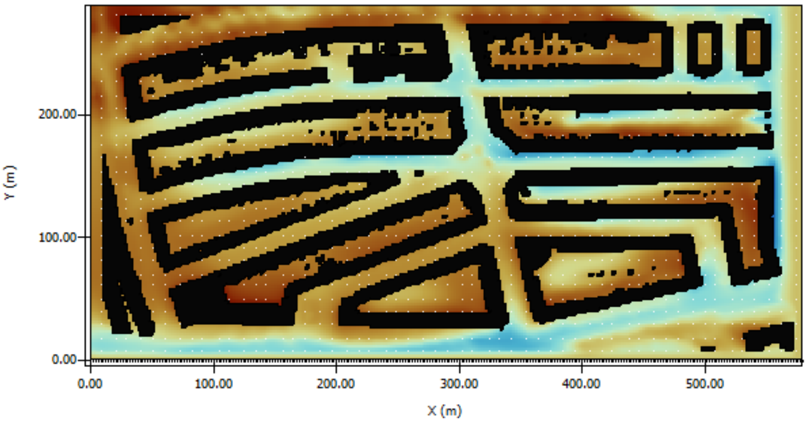
Relative Humidity

< 43.00 %
44.20 %
45.40 %
46.60 %
47.80 %
49.00 %
50.20 %
51.40 %
52.60 %
> 53.80 %

Min: 43.29 %
Max: 54.56 %

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 13.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



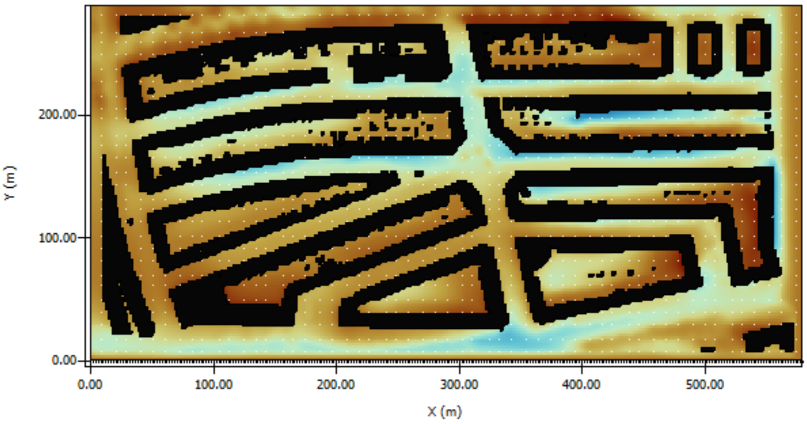
Relative Humidity

< 37.00 %
38.10 %
39.20 %
40.30 %
41.40 %
42.50 %
43.60 %
44.70 %
45.80 %
> 46.90 %

Min: 37.08 %
Max: 47.45 %

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 14.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



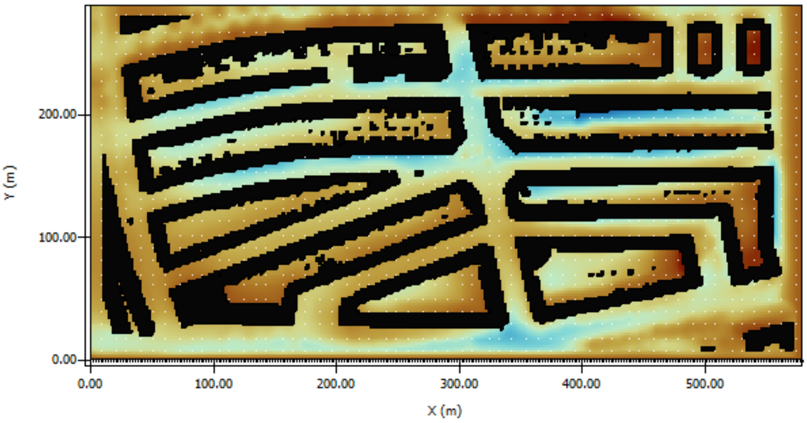
Relative Humidity

< 35.00 %
36.10 %
37.20 %
38.30 %
39.40 %
40.50 %
41.60 %
42.70 %
43.80 %
> 44.90 %

Min: 35.95 %
Max: 45.04 %

ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 15.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)

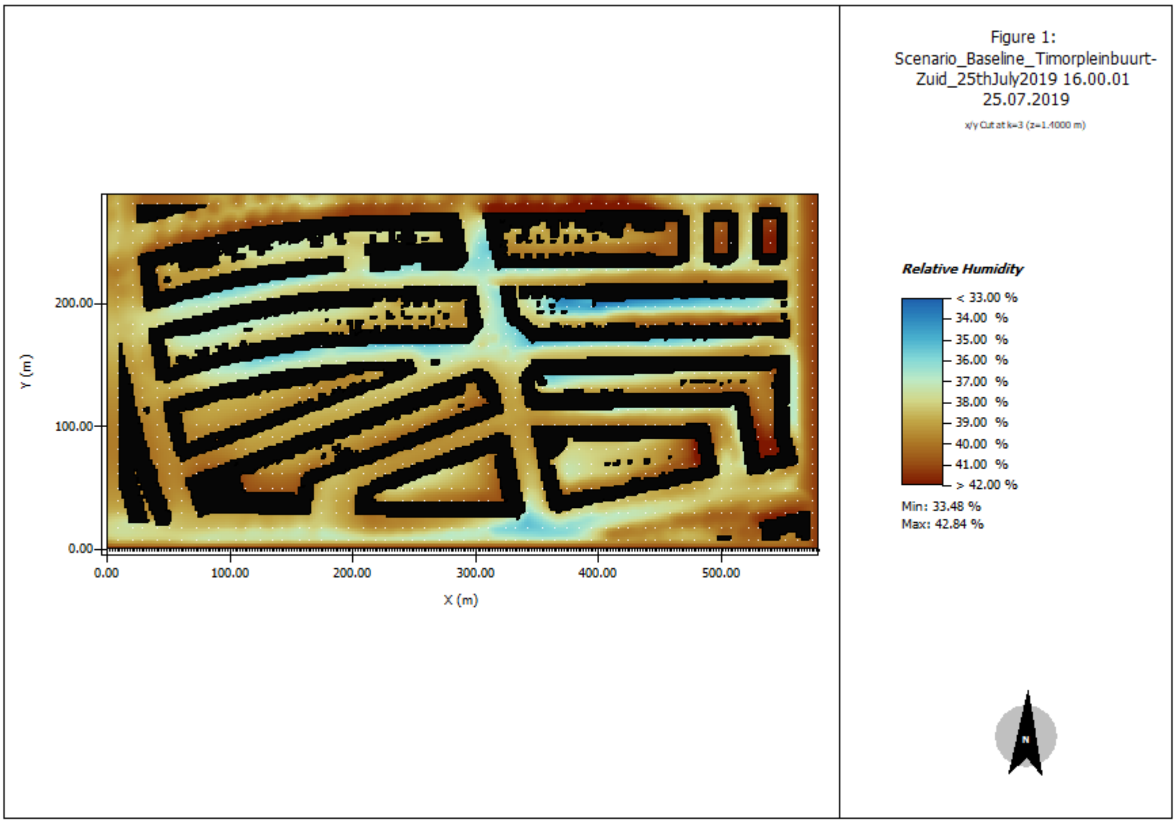


Relative Humidity

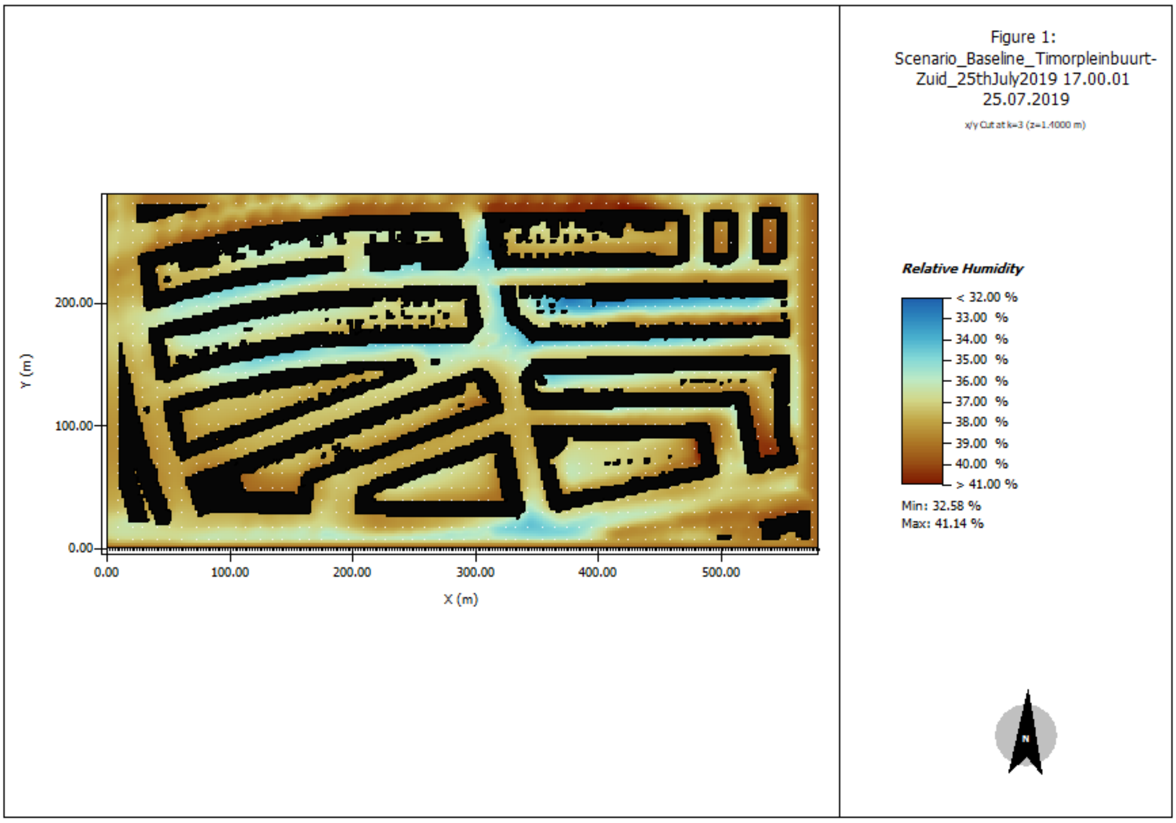
< 34.00 %
35.10 %
36.20 %
37.30 %
38.40 %
39.50 %
40.60 %
41.70 %
42.80 %
> 43.90 %

Min: 34.39 %
Max: 44.18 %

ENVI-met <Right foot>

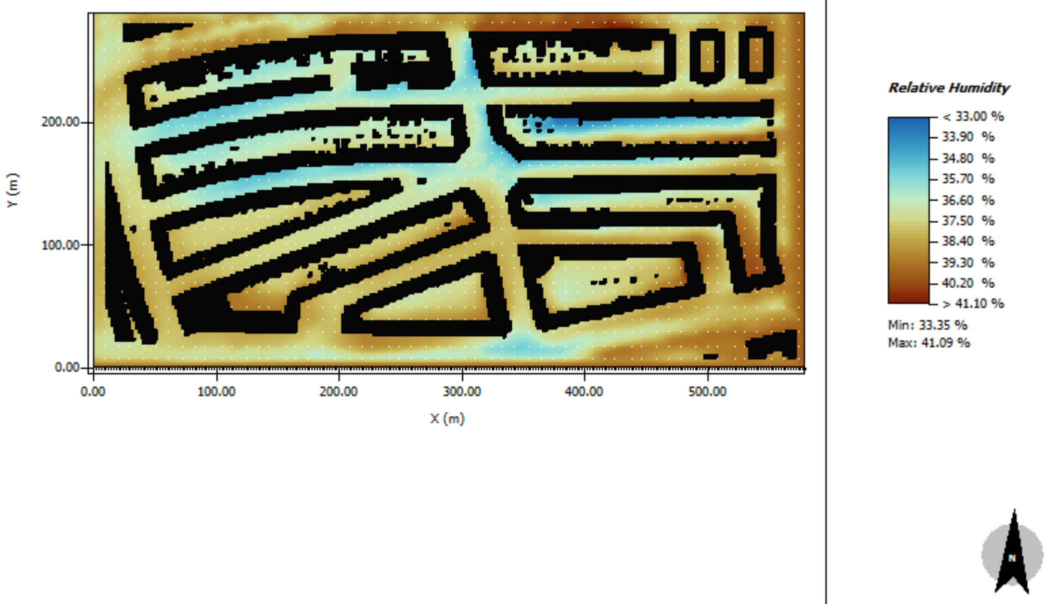


ENVI-met <Right foot>



ENVI-met <Right foot>

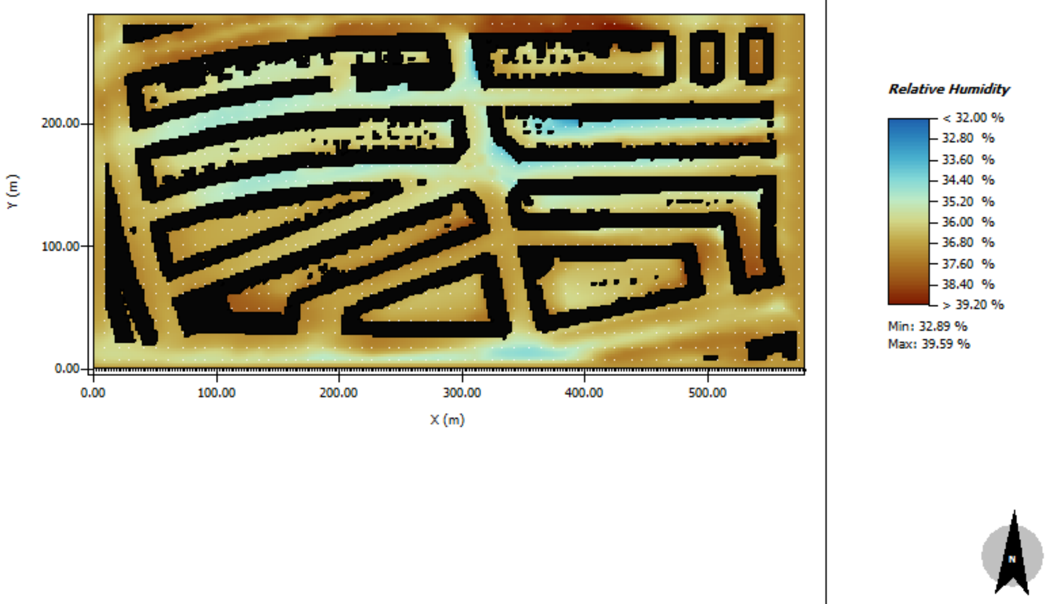
Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 18.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



ENVI-met

<Right foot>

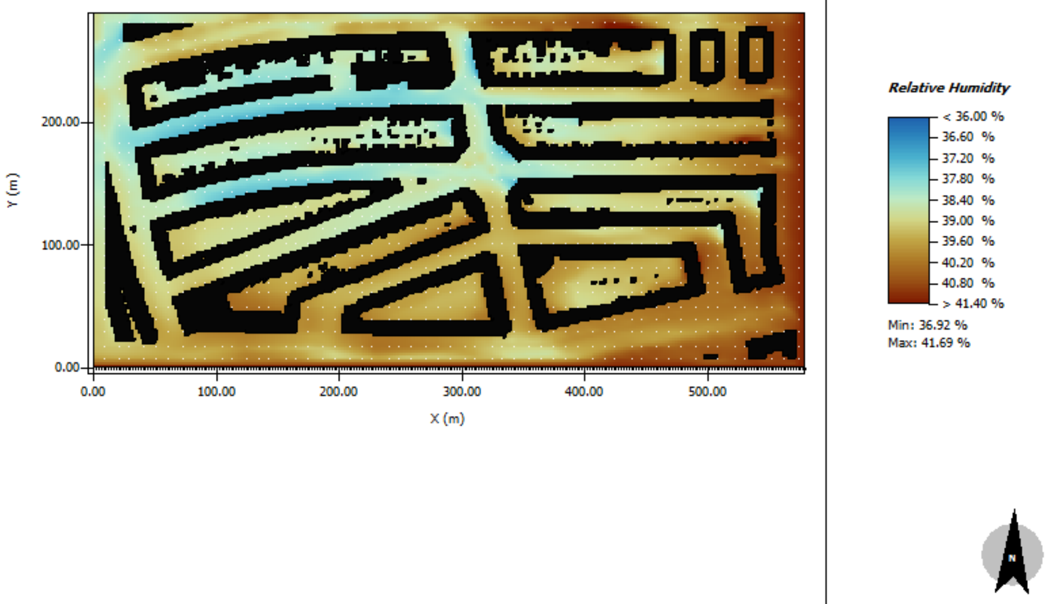
Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 19.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



ENVI-met

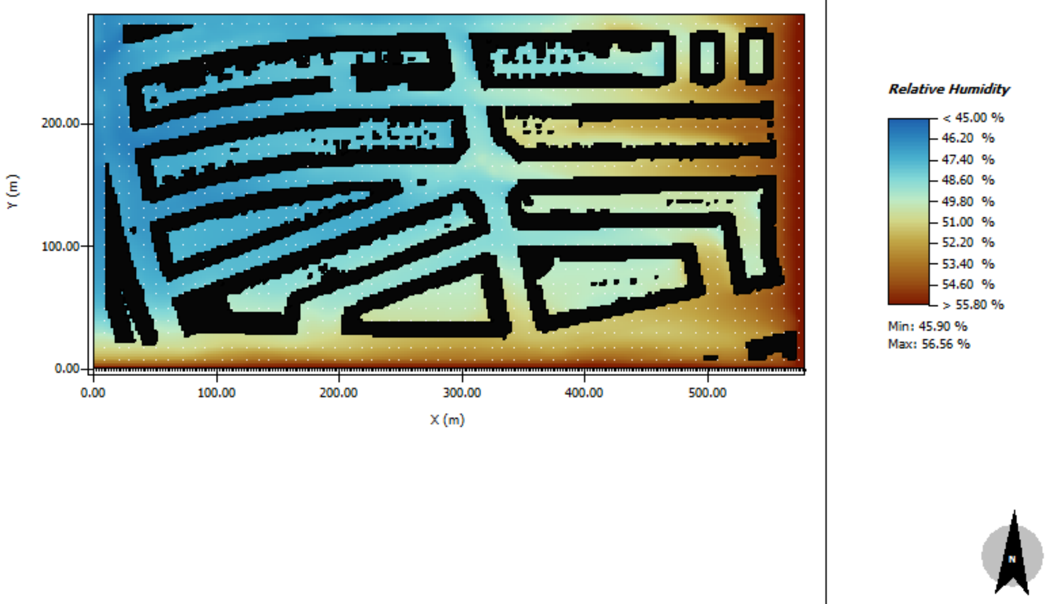
<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 20.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



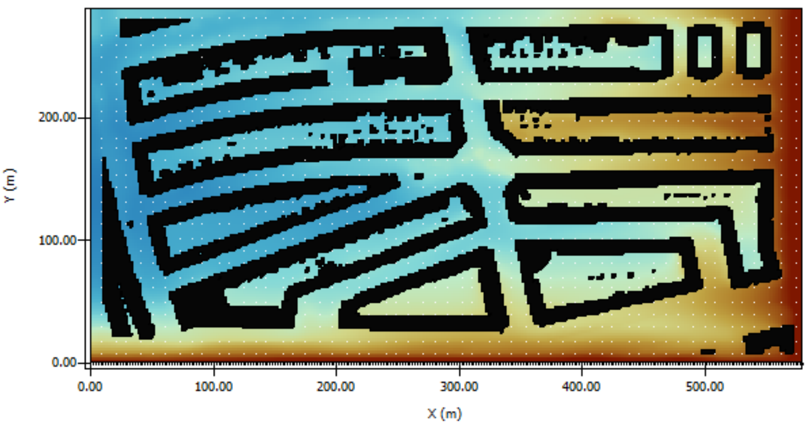
ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 21.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



ENVI-met <Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 22.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



Relative Humidity

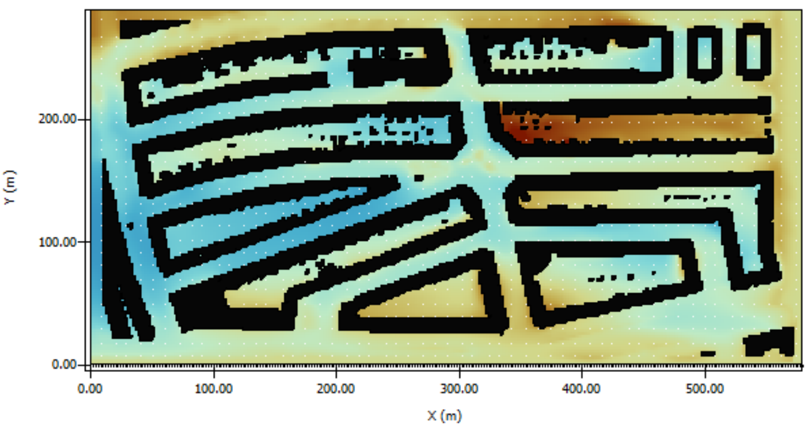
< 50.00 %
51.00 %
52.00 %
53.00 %
54.00 %
55.00 %
56.00 %
57.00 %
58.00 %
> 59.00 %

Min: 50.84 %
Max: 59.87 %

ENVI-met

<Right foot>

Figure 1:
Scenario_Baseline_Timorpleinbuurt-Zuid_25thJuly2019 23.00.01
25.07.2019
x/y Cut at k=3 (z=1.4000 m)



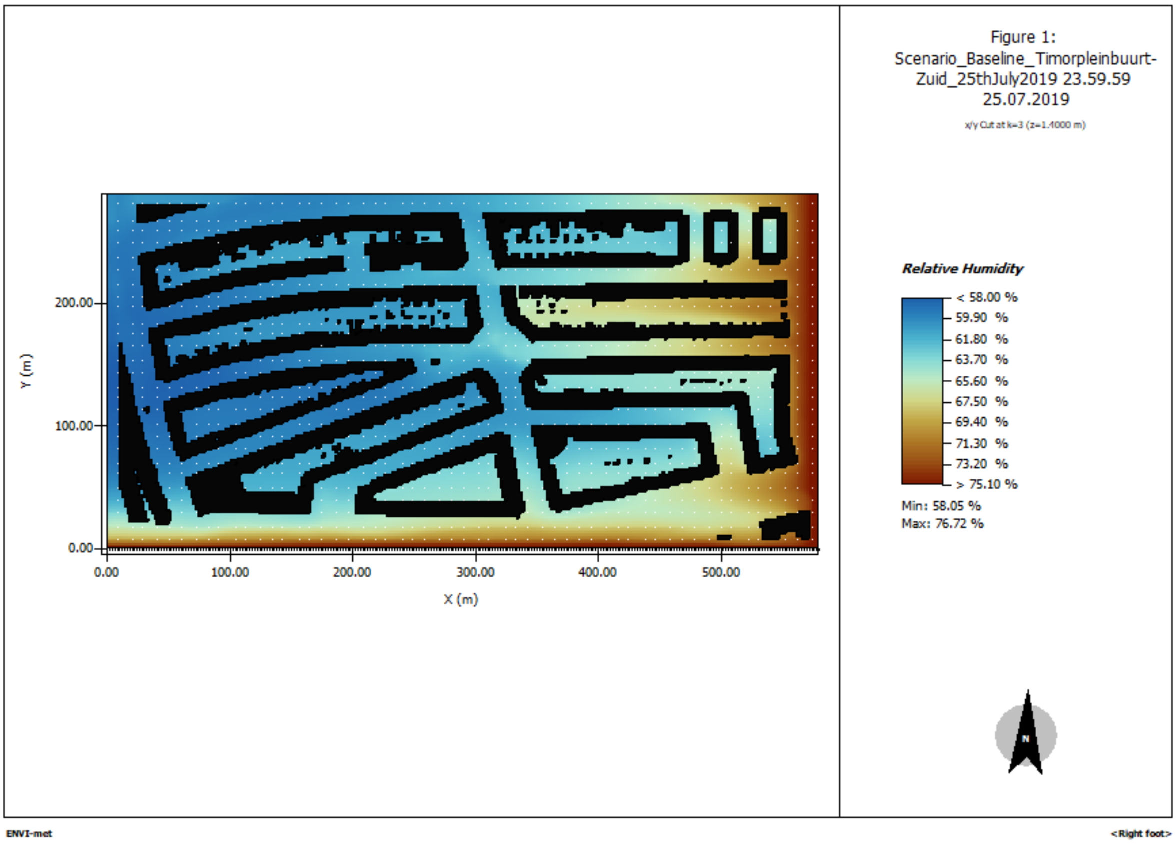
Relative Humidity

< 47.00 %
47.40 %
47.80 %
48.20 %
48.60 %
49.00 %
49.40 %
49.80 %
50.20 %
> 50.60 %

Min: 47.55 %
Max: 50.87 %

ENVI-met

<Right foot>



BIO-met Baseline setting

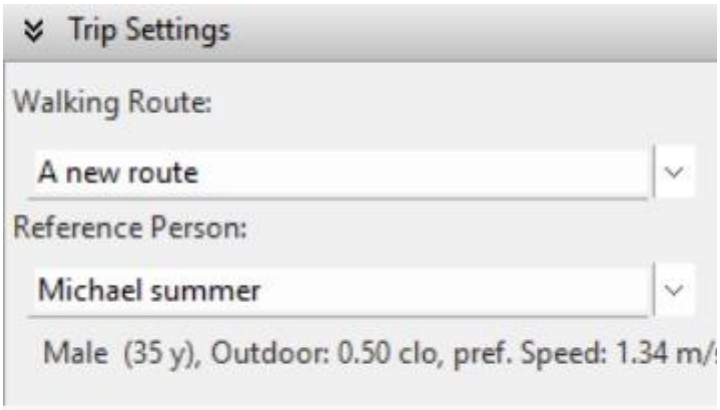


Figure 71: BIO-met baseline settings for Thermal Comfort Walk

Scenario Bioswale

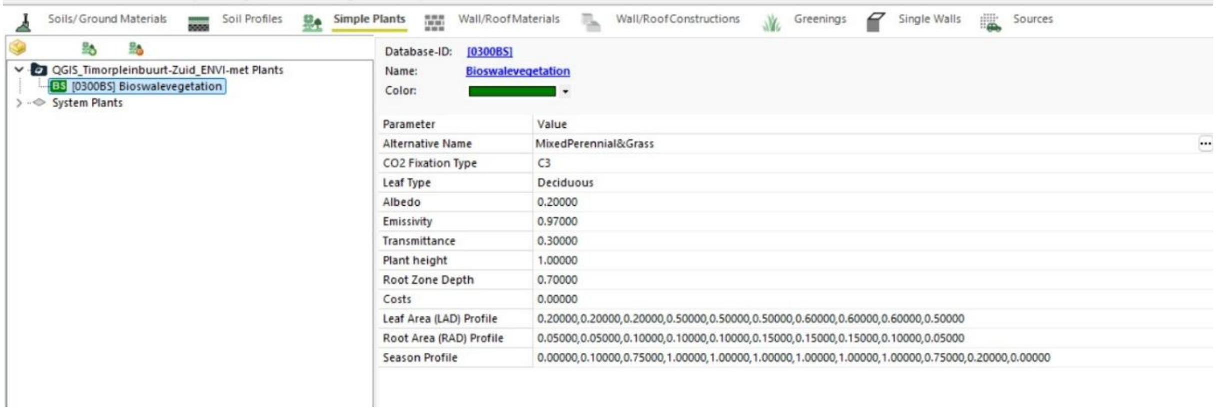


Figure 72: Custom Bioswale ENVI-met

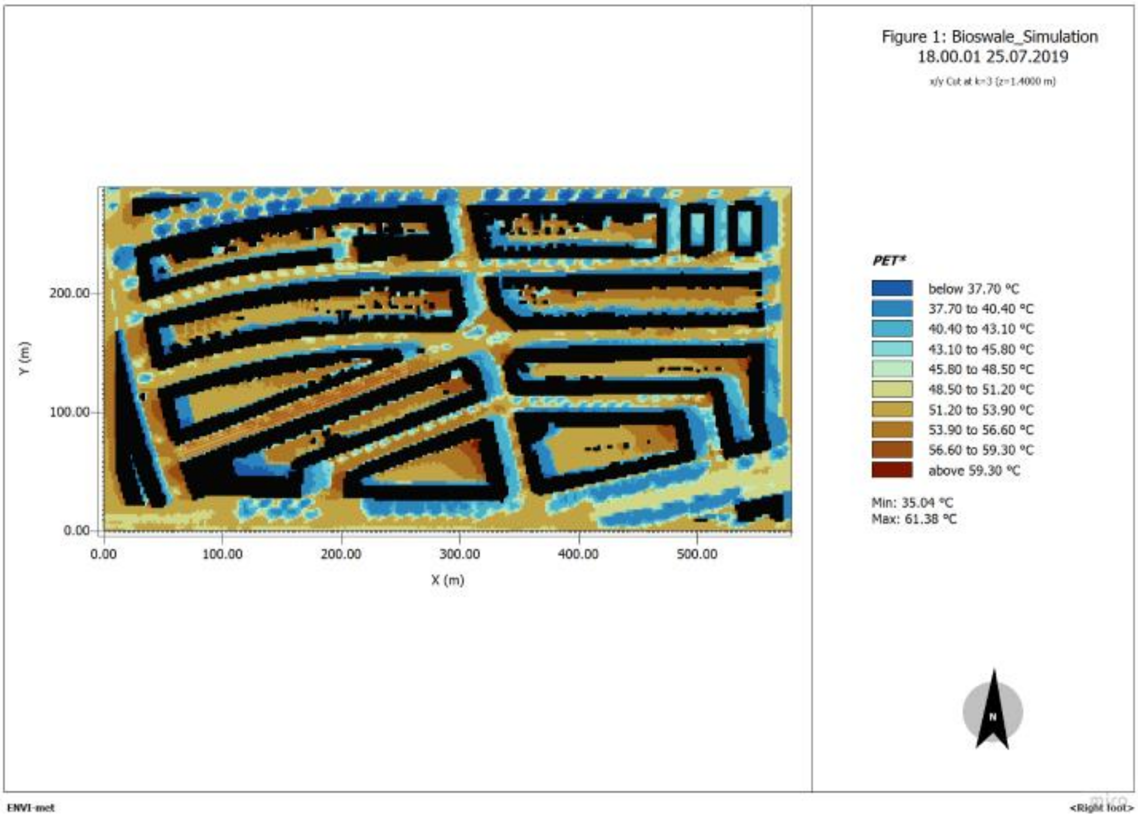


Figure 73: Location of the Bioswales PET effect in ENVI-met Leonardo map

Scenario Green Facade

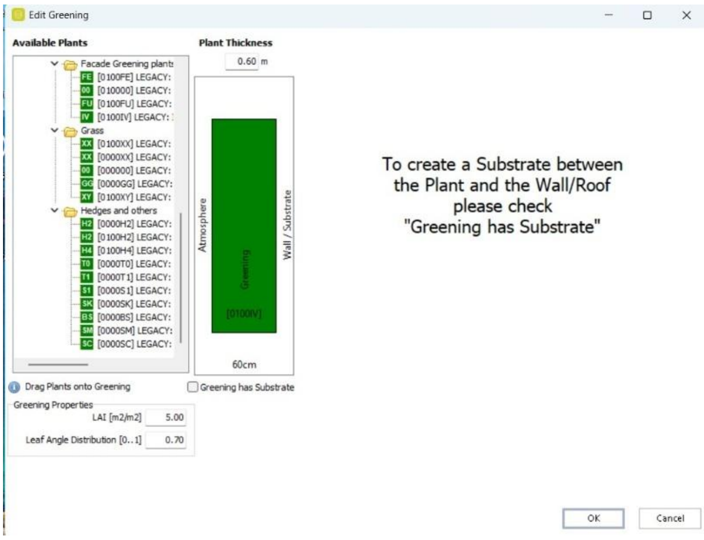


Figure 74: Custom green facade ENVI-met

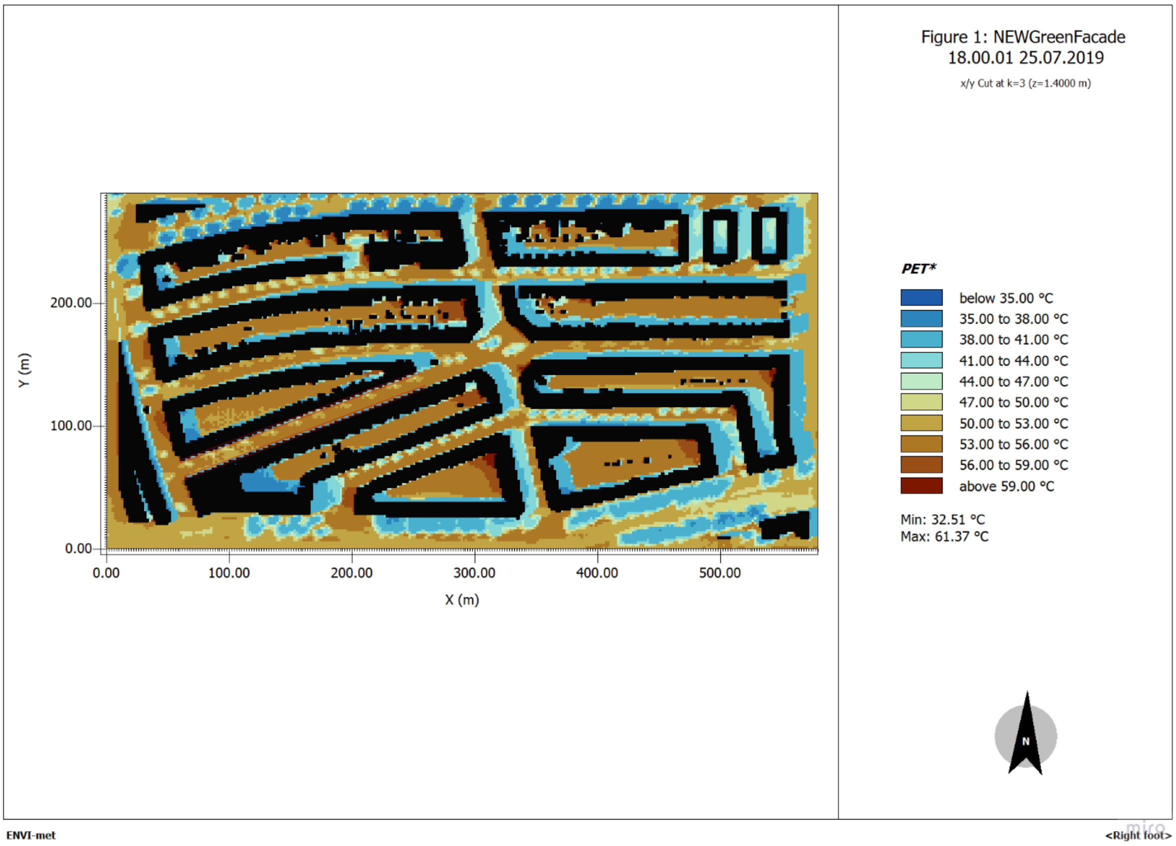


Figure 75: Location of the Green Facades' PET effect in ENVI-met Leonardo map

Scenario Vegetated Pergola

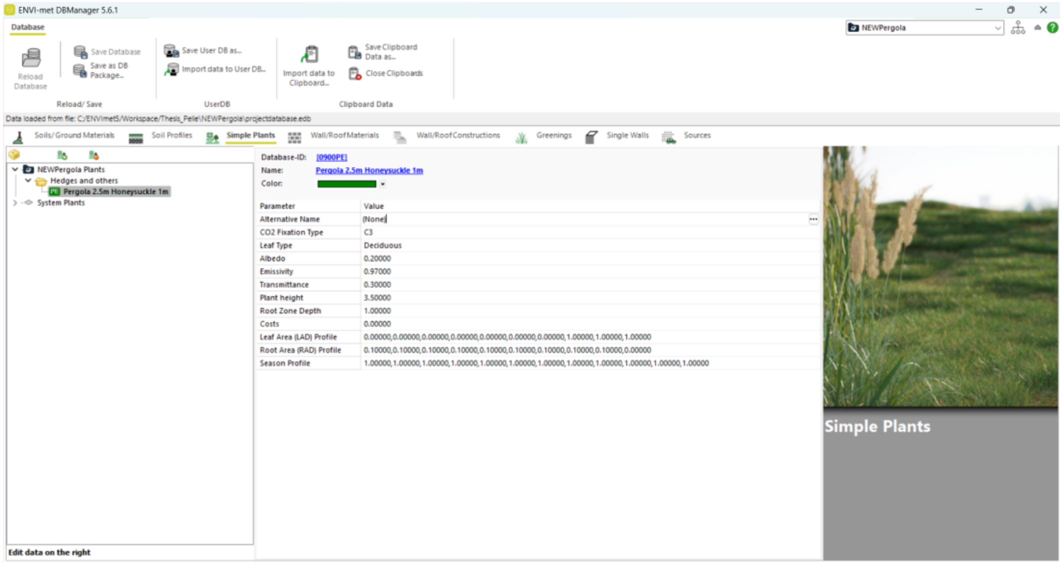


Figure 76: Custom Pergola ENVI-met

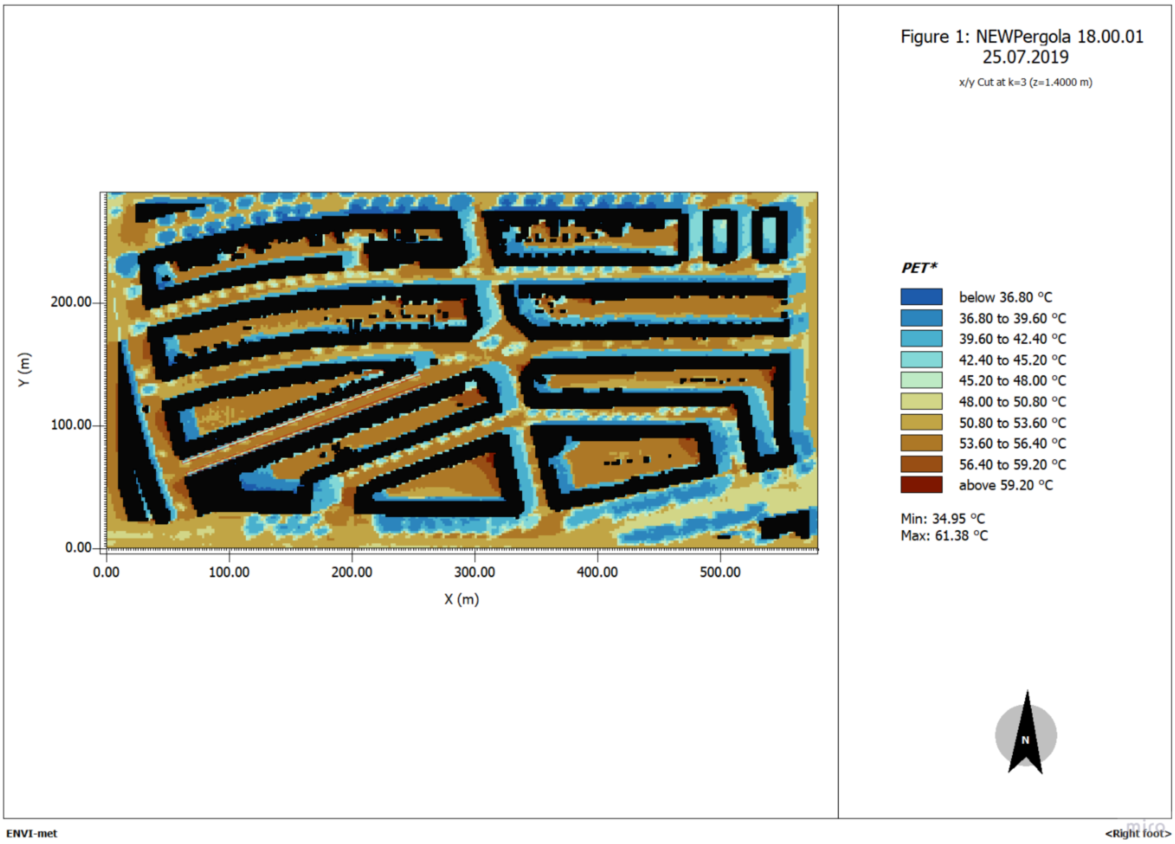


Figure 77: Location of the Vegetated Pergolas PET effect in ENVI-met Leonardo map

QGIS Bufferzone

Bioswale

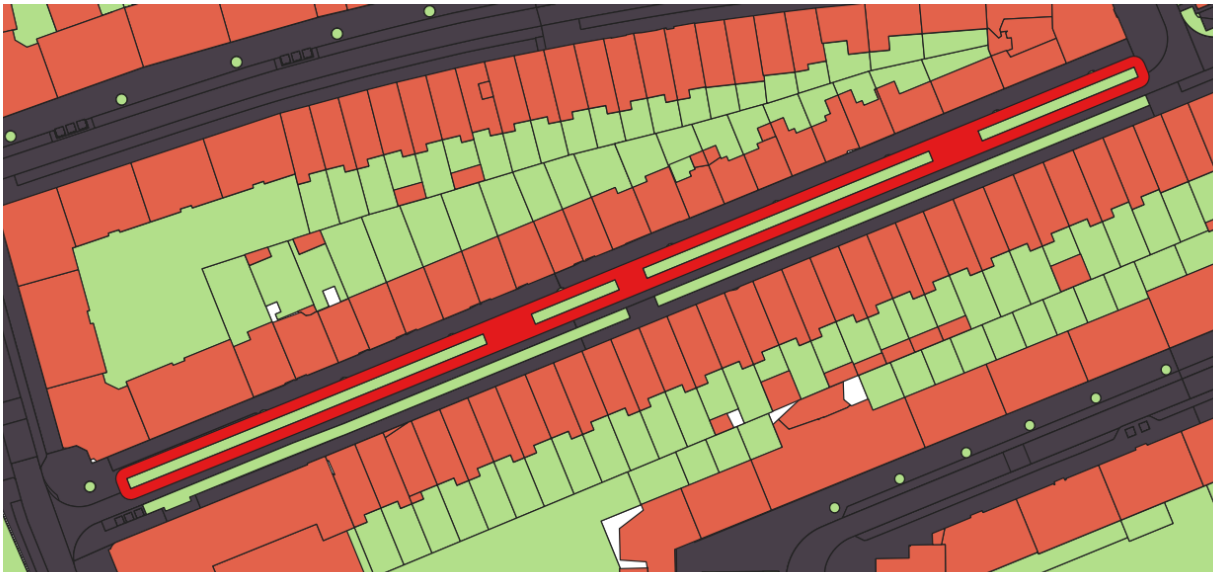


Figure 78: Upper row bufferzone Bioswale

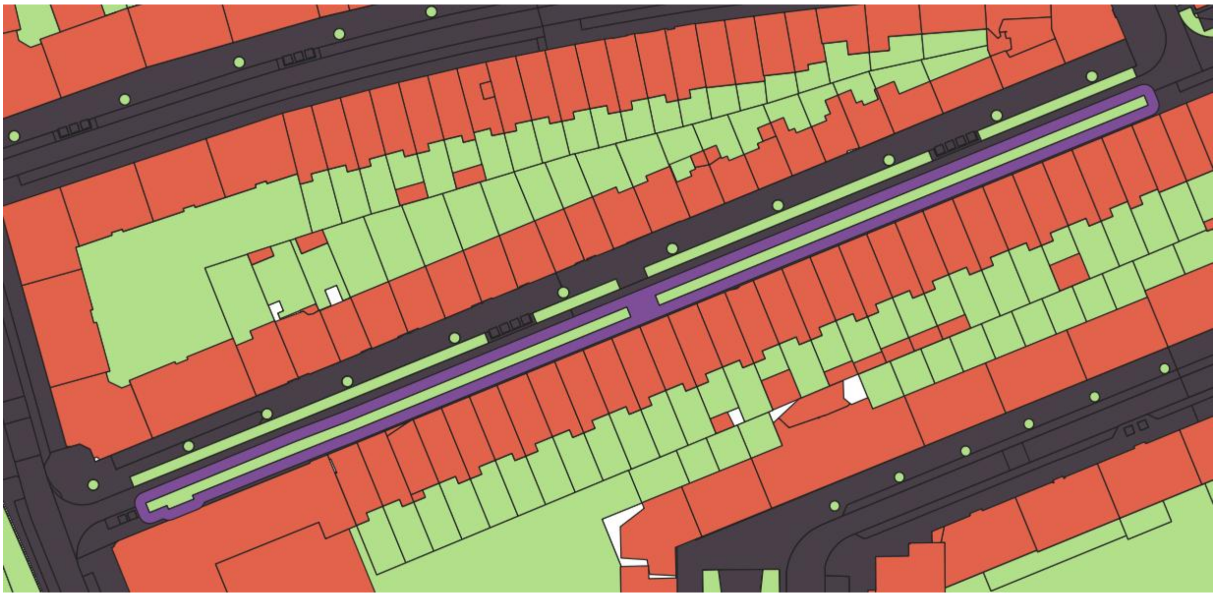


Figure 79: Lower row bufferzone Bioswale

Green façade

Figure 80: Upper row bufferzone Green façade

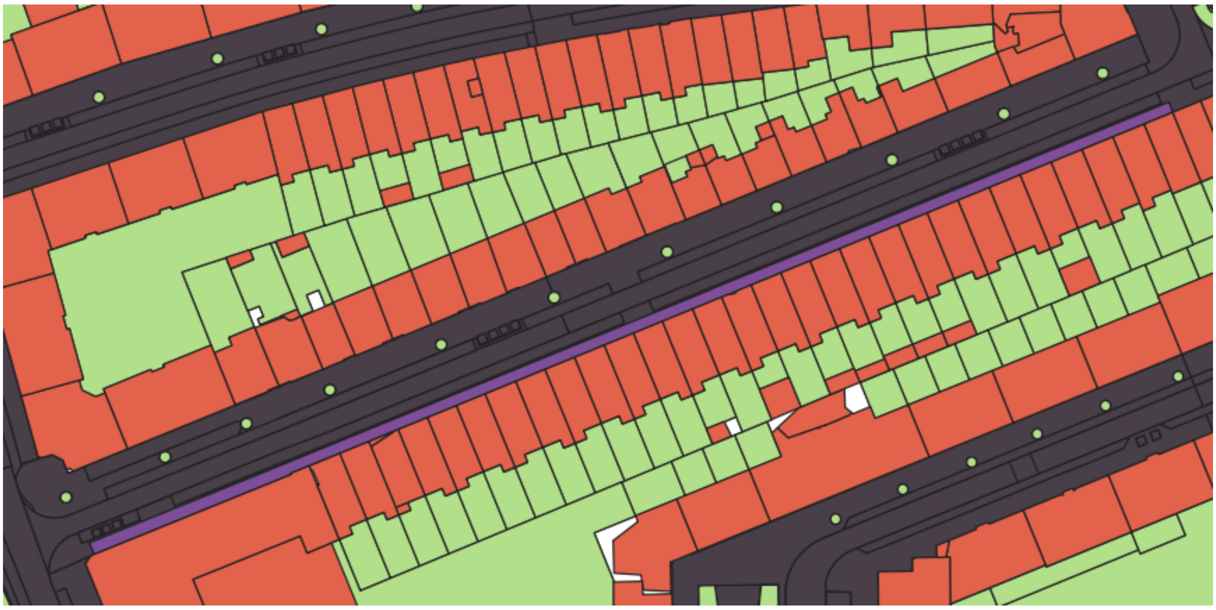


Figure 81: Lower row bufferzone Green façade

Vegetated pergola

Figure 82: Upper row bufferzone Vegetated Pergola

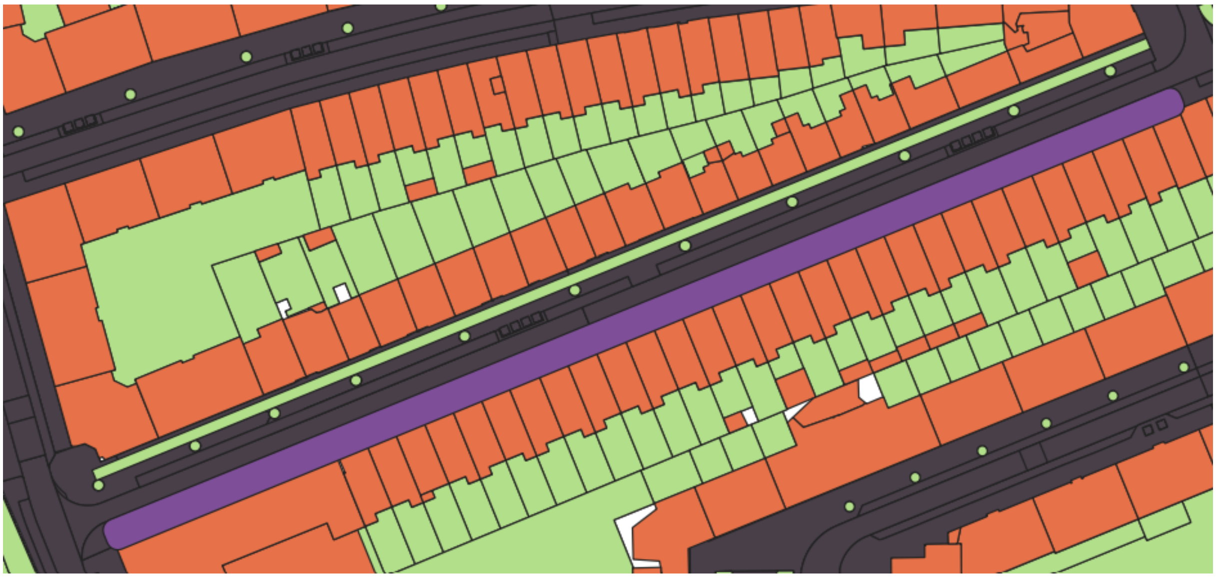


Figure 83: Lower row bufferzone Vegetated Pergola

Data

Gemeente Amsterdam

Gemeente Amsterdam. (n.d.) Bomen - in beheer van Gemeente Amsterdam. Maps.amsterdam.nl. https://maps.amsterdam.nl/bomen/

Dataset used→ Bomen (Trees)

PDOK

PDOK download viewer. (2025). Pdok.nl. https://app.pdok.nl/lv/bgt/download-viewer/

Dataset used→ Basisregistratie Grootschalige Topografie (BGT)

Weatherstation

Schiphol weather station

Dataset used→ Meteostat. (2019, July 25). Weather data for station 06240 [Dataset]. Meteostat. https://meteostat.net/en/station/06240?t=2025-08-14/2025-08-21

time	temp	dwpt	rhum	prcp	snow	wdir	wspd	wpgt	pres	tsun	coco
2019-07-25 00:00:00	19,9	16,5	81	0		350	7,2	11	1015,7		4
2019-07-25 01:00:00	19,4	16,2	82	0		360	3,6	7	1015,6		4
2019-07-25 02:00:00	19,6	17	85	0		0	0	7,4	1015,7		4
2019-07-25 03:00:00	18,1	17,1	94	0		50	3,6	4	1015,4		4
2019-07-25 04:00:00	18,7	17,5	93	0		50	3,6	4	1015,4		2
2019-07-25 05:00:00	18,2	17,2	94	0		0	0	9,3	1015,3		1
2019-07-25 06:00:00	19,1	18,4	96	0		50	3,6	4	1015,2		2
2019-07-25 07:00:00	20	18,7	92	0		60	3,6	7	1015,2		1
2019-07-25 08:00:00	23,2	20,1	83	0		110	3,6	11,1	1015,2		1
2019-07-25 09:00:00	25,5	20,1	72	0		90	7,2	7	1015,2		1
2019-07-25 10:00:00	27,4	20	64	0		100	10,8	11	1015		1
2019-07-25 11:00:00	29,5	19,5	55	0		100	7,2	16,7	1014,6		1
2019-07-25 12:00:00	31,5	20,4	52	0		90	10,8	18	1014,4		1
2019-07-25 13:00:00	32,4	18,2	43	0		80	10,8	18	1014,2		3
2019-07-25 14:00:00	34,1	20,1	44	0		80	14,4	25,9	1013,7		1
2019-07-25 15:00:00	34,6	20,5	44	0		90	18	25	1013,2		1
2019-07-25 16:00:00	35	20,5	43	0		70	18	22	1012,9		1
2019-07-25 17:00:00	35,8	20,9	42	0		70	14,4	24,1	1012,4		1
2019-07-25 18:00:00	35,8	21,2	43	0		80	14,4	22	1011,8		1
2019-07-25 19:00:00	36,1	19,9	39	0		120	10,8	18	1011,5		4
2019-07-25 20:00:00	33,8	19,8	44	0		110	10,8	20,4	1011,2		1
2019-07-25 21:00:00	30,3	22,5	63	0		80	10,8	11	1011,1		3
2019-07-25 22:00:00	27,8	20,4	64	0		80	14,4	25	1010,7		3
2019-07-25 23:00:00	29,9	18,3	50	0		90	14,4	20,4	1010,7		4

Table 28: Weather data of the Schiphol weather station (Meteostat, 2019).

Timorpleinbuurt-Zuid neighborhood

Dataset used→Weather station D2231 – Provided by my supervisor Dragan Milošević, retrieved from the AAMS (Amsterdam Atmospheric Monitoring Supersite) project. https://www.ams-institute.org/urban-challenges/resilient-cities/amsterdam-atmospheric-monitoring-supersite/

D2231	Ams19	52.36322 4.93824 Benkoelenstraat	SVF 0.335 LCZ 2

Figure 84: Weatherstation name, coordinates location

Data of weatherstation D2231:

datetime,"date","time","VP","RH","T","WS","WD"

2019-07-25 00:00:00,2019-07-24,"24",1.89014002083813,67,23.07,0.19,2.66

2019-07-25 01:00:00,2019-07-25,"01",1.89079257638378,69,22.59,0.16,20.34

2019-07-25 02:00:00,2019-07-25,"02",1.9244515680849,72,22.18,0.3,354.5

2019-07-25 03:00:00,2019-07-25,"03",1.99213687673452,76,21.86,0.28,354

2019-07-25 04:00:00,2019-07-25,"04",1.99872942741998,77,21.7,0.25,353.5

2019-07-25 05:00:00,2019-07-25,"05",2.03584553222049,78,21.79,0.28,353.83
2019-07-25 06:00:00,2019-07-25,"06",2.1578790075326,80,22.33,0.28,344.77
2019-07-25 07:00:00,2019-07-25,"07",2.1539350380283,77,22.93,0.36,353.48
2019-07-25 08:00:00,2019-07-25,"08",2.17805713566207,72,24.23,0.44,359.26
2019-07-25 09:00:00,2019-07-25,"09",2.21493838111843,67,25.72,0.37,14.98
2019-07-25 10:00:00,2019-07-25,"10",2.30321584133528,63,27.43,0.52,358.41
2019-07-25 11:00:00,2019-07-25,"11",2.50296017338571,63,28.86,0.61,356.43
2019-07-25 12:00:00,2019-07-25,"12",2.7977943890396,62,31.08,0.45,6.44
2019-07-25 13:00:00,2019-07-25,"13",2.97772344343354,62,32.18,0.63,355.2
2019-07-25 14:00:00,2019-07-25,"14",2.9815492672284,58,33.39,0.48,349.5
2019-07-25 15:00:00,2019-07-25,"15",2.87370227983007,52,34.69,0.6,346.31
2019-07-25 16:00:00,2019-07-25,"16",2.94090017241904,51,35.46,0.33,338.16
2019-07-25 17:00:00,2019-07-25,"17",2.92341845914041,52,35,0.33,346.24
2019-07-25 18:00:00,2019-07-25,"18",2.87904256896315,53,34.38,0.22,352.51
2019-07-25 19:00:00,2019-07-25,"19",2.90417600207116,54,34.2,0.16,2.34
2019-07-25 20:00:00,2019-07-25,"20",2.74305524444519,55,32.85,0.14,5.25
2019-07-25 21:00:00,2019-07-25,"21",2.67137769601598,58,31.44,0.12,8.99
2019-07-25 22:00:00,2019-07-25,"22",2.5787565446615,59,30.52,0.17,7.47
2019-07-25 23:00:00,2019-07-25,"23",2.3779536122356,55,30.33,0.18,7.97