Exploring Predictive Modelling with Green Infrastructure for Urban Resilience

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1 Introduction

As many cities today face escalating urban challenges such as climate change, fragmented ecological networks, as well as storm water management capacity, cities worldwide have increased pressure to become increasingly resilient. Urban resilience refers to a cities ability to absorb, adapt, and recover from environmental, social and economic deterrents while retaining functionality. Although efforts have been made to combat said urban challenges, significant gaps remain in the fight against the multi-dimensional nature of resilience, specifically using green infrastructure (GI).

GI in this case encompasses parks, linear street corridors, and urban forests have become pivotal strategies for enhancing urban resilience by delivering ecosystem services, such as Urban Heat Island (UHI) mitigation, storm water management, and biodiversity conservation. However, challenges persist in quantifying the multi-functional benefits of GI. This includes the identification of priority intervention areas, and integrating diverse indicators of resilience into urban planning frameworks.

Rotterdam, is a densely populated and climate-sensitive city. This may allow it to act as an ideal case study to examine how green infrastructure may intersect with urban resilience. Although the city has made significant progress in executing advanced planning strategies, Rotterdam continues to face persistent challenges, including rising temperatures, increased flood risk due to its geographical location, and disparities in green space accessibility in different neighborhoods. This makes Rotterdam a reasonable case study for studying the advantages or disadvantages of GI in urban resilience.

This thesis aims to develop a predictive modelling framework that leverages spatial data, geographical information systems (GIS), machine learning techniques, and network analysis to evaluate and optimise green infrastructure to enhance urban resilience. By the use of integrating environments, social, biodiversity, as well as morphological indicators, the study aims to identify high resilience areas, assess the effectiveness of existing green infrastructure and possibly propose strategies that may aid in urban resilience of cities.

Through this research, it will be attempted to show how using data driven analysis to execute GI related intervention strategies can be utilised to create sustainable, equitable and resilient urban environments. The findings aim to output urban resilience scores and classify urban areas into different levels of resilience. This allows for the project to contribute to a better understanding of the relationship between urban environments and green infrastructure.

2 Related work

This section presents an overview of the relevant literature studied, giving an overall view of key findings and methodologies from previous work that inform and support the foundation of this thesis. The reviewed work addresses the roles and impacts of green infrastructure in urban resilience, modelling approaches for evaluating GI, and the challenges specific to Rotterdam in implementing sustainable GI solutions.

2.1 GI role in Urban resilience

Green infrastructure has a large potential in contribution to the improvements of urban resilience, addressing many environmental challenges. Works done by Staddon et al. (2018)

place emphasis on the environmental importance of GI in the case of mitigating UHI intensity, storm water management, and biodiversity protection. Similarly, as demonstrated by (Pamukcu-Albers et al., 2021) GI may function to aid in climate adaptation processes and enhance capacity in withstanding and recovery of environmental related stresses.

Additionally, (Salih and Báthoryné Nagy, 2024) specifically focuses on the role of GI in heat mitigation strategies and highlight how 'ecological corridors' can contribute in maintaining biodiversity and thermal comfort. These studies collectively highlight how GIs can be multifunctional where environmental and morphological benefits can be jointly observed to build long term urban resilience.

With regards to Rotterdam, (van der Berg, 2023) and (Brears and Brears, 2018) feature innovative strategies to integrate GI into the urban landscape of the city. For example, the blue-green infrastructure approach, which incorporates water and vegetative based solutions. This has recently been seen more globally in turn, as a form of sustainable urban planning. However, gaps remain in spatial equity and connectivity of green spaces across neighborhoods, reinforcing the need for continued research in this field.

2.2 Modelling Approaches

Modern modelling approaches have been applied in many recent research to evaluate and optimise GI for urban resilience. Machine learning techniques such as Random Forest (RF), Support Vector Machines (SVM) as well as Gradient Boosting Machines (GBM) are some that have been widely employed due to their ability to handle large datasets and identify complex relationships between environmental, and morphological indicators. This is demonstrated by (Kutty et al., 2022) where machine learning was used to predict urban resilience outcomes based on multi-dimensional datasets.

In Addition, using machine learning jointly with GIS-based spatial analysis techniques have also been used to map and assess GI distribution and accessibility. (Wanghe et al., 2020) showcase how GIS tools can be used to prioritise ecological corridors by analysing spatial connectivity and least cost paths. Similarly, (Gkontzis et al., 2024) integrate GIS with digital twins to simulate highly accurate spatial impacts of green infrastructure implementations.

Network analysis, shown by (Amado, 2022) can further provide deeper comprehension into the connectivity and spatial relationships within urban areas. These combined methodologies demonstrate the value of integrating machine learning, GIS, and network analysis to evaluate and optimise urban resilience strategies effectively.

2.3 Challenges in Rotterdam

Rotterdam serves as an ideal case study for investigating the role of GI in Urban resilience, as its unique environmental, and geographical challenges. As described by (Tillie and van der Heijden, 2016) the city faces persistent challenges related to spatial disparities in green space accessibility and fragmented ecological corridors. While Rotterdam has made significant progress in combating climate change with climate adaptation strategies such as the "Rotterdam Climate Adaptation Strategy" and the "Resilient Rotterdam Programme", some barriers remain in achieving equitable distribution of GI across all neighbourhoods. (Wiebenga, 2024) examines the urban morphology changes of integrating GI into densely built urban environments, highlighting the importance of considering building typologies and street layouts in planning interventions. Additionally, Studies like (Sarabi et al., 2022) emphasise the need for evidence

based decision making frameworks to bridge the gap between planning policies and practical implementation.

Furthermore, (Xue et al., 2024) identifies knowledge gaps in long term monitoring and life cycle management of GIs, raising questions about sustained impact of urban resilience. These overall findings show that the need for a predictive modelling approach to prioritise GI investments in Rotterdam may be effective.

3 Research Objectives

3.1 Objectives

The main objective of this research is to explore different machine learning techniques in the context of green infrastructure and their effect on urban resilience. The main research question of the thesis is:

"How can predictive modelling techniques be used to evaluate the effectiveness of green infrastructure in improving urban resilience across different dimensions of the built environment"

To fully examine this research question, the project will be broken down into smaller sub questions, where each will be attempted to be explored in detail.

- What aspects of green infrastructure (GI) can be assessed in a multifunctional way to evaluate their contributions to urban resilience across multiple dimensions?

- How can environmental, biodiversity, and morphological indicators be combined to comprehensively assess and enhance urban resilience?

- How can predictive modelling techniques, such as machine learning, be used to evaluate and optimise green infrastructure for improving urban resilience?

- How can the multi-benefits of green infrastructure, such as environmental, social, and morphological impacts, be effectively incorporated into urban planning frameworks?

- How can the proposed framework be applied to assess and prioritise green infrastructure interventions in Rotterdam?

3.2 Scope

The scope of this thesis will be divided into sections where tasks will be split into a list of priorities, following the MoSCow List.

- Must:
  - Explore at least three machine learning techniques.
  - Explore at least three types of green infrastructure.
  - Utilise at least three key urban resilience indicators.

- Should:
  - Identify key resilience hotspots across Rotterdam based on predictive model outputs.

- Classify areas of Rotterdam into categories based on resilience performance (e.g high, mid low).

- Could:
  - Explore scenario modelling to simulate future urban resilience outcomes based on GI changes.
  - Assess social or economic benefits of green infrastructure investments.
  - Provide potential policy recommendations based on model evidence from spatial analysis

- Won't:
  - Develop a real-time predictive system.
  - Focus on privately available GI data.

4 Methodology

This section gives an overall view of the general method applied in the project. It gives insight into the integration of the study region, data collection, data cleaning, different modelling approaches as well as the key indicators and metrics to assess the state of urban resilience in Rotterdam. The purpose of this section is to provide a systematic understanding of the interaction between green infrastructure and urban resilience in Rotterdam by integrating spatial analysis and predictive modelling.

4.1 Data Collection

The data used in this project is primarily spatial data that have been obtained from a variety of reliable public databases, municipal datasets as well as remote sensing platforms such as the Basisregistratie Grootschalige Topografie (BGT), the Nationaal Wegen Bestand (NWB), and the Klimate Effect Atlas. The overall data covers environmental, morphological and network related information. This collection of data forms the foundation that the project will use in developing resilience indicators and predictive models.

The following subsections will explain each dataset in detail, discussing the source of each dataset, its significance, the subsequent preprocessing steps applied, and the relevance of the dataset with the study. Finally, this paper will describe how these datasets can be integrated into a common analytical framework, showcasing how each dataset can help improve our understanding of the relationship between green infrastructure and urban resilience.

Key focus areas will include:

- **Climate data**: Urban Heat Island (UHI) maps, Flood Risk Maps, NVDI Imagery

- **Biodiversity data**: Percentage Green/Grey cover, Tree Species Distribution

- **Morphological Data**: Road networks, Road Centre Lines, Pedestrian Networks, Building Footprints

Climate Data

The climate data used in this study serves as a starting foundation for creating environmental indicators to evaluate urban resilience. These datasets capture spatial variations in Urban Heat islands (UHI), flood risk, and vegetation density (NDVI) across Rotterdam. These factors are crucial in recognising how green infrastructure can be addressed to reduce the environmental vulnerabilities and to improve urban resilience.

Firstly, UHI maps as well as Flood risk maps were found on the Klimate Effect Atlas. The Klimate Effect Atlas is an online Dashboard where the public is able to view different types of climate maps. The data used to create these maps are sourced from a collection of partner universities, governmental departments, and companies that are commissioned by the Ministry of Infrastructure and Water Management. However, the data used to create these maps were further gathered from different sources. The raw UHI raster map was created by Rijksinstutuut voor Volksgenzondheid en Milieu (RIVM) at 10m resolution and sourced from the Nationaal Geo Register. The UHI raster map downloaded covered of the entirety of the Netherlands, requiring preprocessing to isolate the greater Rotterdam area. This task was executed using QGIS, where a polygon of Rotterdam obtained from the Publieke Dienstverlening Op de Kaart (PDOK) was overlaid. Following this, the 'Clip Raster by Mask Layer' tool in QGIS was used to clip the raster to match the boundary of Rotterdam. The UHI maps are relevant to this study as these maps highlight the areas that experience elevated temperatures due to urban heat island effects, allowing for identification of zones where green infrastructure additions can have significant cooling impacts.

Similarly, the flood risk map was also found on the Klimate Effect Atlas. However, the base source for the flood risk maps were the Landelijk Informatiesysteem Water en Overstromingen (LIWO) and were available at 5m resolution. The flood risk maps had multiple options available where it was able to select the depth of flood risk namely 0cm, 20cm, 50cm and 200cm. The process of cleaning this data where we only want the extent of Rotterdam was done in the same method as the UHI map. The raster map was imported into QGIS, where the 'Clip Raster by Mask Layer' tool was used. Using flood risk maps in this study reveals areas prone to waterlogging and flood hazards, enabling the study to pinpoint locations where stormwater management solutions through green infrastructure can be implemented.

In addition, NDVI raster maps were obtained from Copernicus Land Monitoring Service. This dataset consisted of a global raster map at 300m resolution. The raster map was cropped to the extent of Rotterdam using the same methodology as the UHI maps and flood risk maps. NDVI maps in the case of this project allows for the measure of health, density, and spatial distribution of vegetation. It is derived from satellite imagery by analysing the difference between near-infrared (NIR) and red light reflectance with healthy vegetation reflecting more NIR light and absorbing more red light.

Biodiversity Data

Biodiversity data in this project will be used in the context of analysing species typologies and distribution along different parts of Rotterdam. These datasets were also found on the Klimate Effect Atlas. The Klimate Effect Atlas hosts multiple large datasets in regards to environmental statistics. One of which contains a large set of data containing percentage of green and grey areas within the Netherlands at neighbourhood level. Green areas are described as areas that contain trees, as well as low level greenery such as grass and shrubs. Grey areas are described as stones, pavement, bare ground and sand drifts (descriptions form KEA). This dataset was

downloaded as a CSV file directly from Klimate Effect Atlas. However, the data sourced by the Klimate Effect Atlas was created by partner company Cobra Groeninzicht.

Morphological Data

The morphological data used to conduct this study provides a data driven basis for a better understanding of the spatial features and general physical qualities of Rotterdam's Urban landscapes. The datasets used provide insights into the built environment, including road networks, road centre lines, pedestrian networks, building footprints. These datasets allow for the assessment of how green infrastructure can be implemented in urban areas to enhance resilience, accessibility to green spaces and ecological functionality. The morphological data for this study was primarily sourced from the PDOK, which then uses raw data from two other main sources, the BGT, and the NWB.

The datasets from the BGT were downloaded using a QGIS plugin. The QGIS plugin **BGT Loader** simplifies data acquisition by allowing users to easily select and download specific layers of BGT data. Using the **BGT Loader**, the datasets accessed are, building polygon data, road data, and vegetation data. Through the use of this plugin, no further cleanup was necessary as the boundary of Rotterdam was considered before the download process. Using the BGT dataset allows us to identify urban typologies that are most suitable for GI interventions as well as assessing the spatial integration of green spaces with the built environment.

Contrastingly, the NWB dataset did not offer a dedicated plugin for simplified downloads, this required manual extraction via the PDOK web viewer. This process involved a careful selection of relevant road network data focusing on features that can have a significant contribution to network analysis in green infrastructure assessment. The specific data that was needed from the NWB consisted of road centre line data. The data downloaded manually was then later imported into QGIS before being clipped to the Rotterdam boundary polygon previously used for other datasets. This step was done to ensure consistency and alignment across all datasets to prevent any discrepancies in results. This road centre line data would later be the baseline data needed for network analysis. The network analysis can be used to evaluate accessibility metrics for green infrastructure, identify nodes and corridors for ecological connectivity, as well as perform spatial overlays with other datasets to highlight areas for green infrastructure implementation.

4.2 Indicators and metrics

Indicators and metrics in this paper aid in connections between raw data and the insights gathered. This enables the evaluation of urban resilience through a structured, quantitative approach. Indicators are derived from the climate, biodiversity, and morphological datasets previously described. These indicators will later be used as features in predictive modelling and inputs for network analysis to assess urban resilience across different areas in Rotterdam.

Similar to data collection, the indicators can be split into specific categories. Firstly, with environmental indicators, this includes UHI intensity, flood risk scores and NDVI values. Using these indicators together can aid in evaluating environmental vulnerabilities and identify zones where green infrastructure can have the greatest impact, such as cooling and flood risk management strategies.

Following environmental indicators are biodiversity indicators, these are directly related to green space coverage as well as overall species distribution. Here, the measure of tree species

richness per neighbourhood and percentage of green/grey cover will highlight the ratio between vegetated and impervious surfaces and potentially pin point areas that may need direct green infrastructure attention.

Finally, morphological indicators focus on the spatial structure and physical layout of the urban environment. These include the building to width ratio, which evaluates the relationship between building dimensions and available green space, the sidewalk to road proportion, which identifies areas for linear street tree implementation, road typologies which assess the suitability of different road types for different green infrastructure implementation and accessibility to green space, which determine urban areas within 300m of green spaces.

Together, these 3 categories of indicators are crucial in evaluating climate vulnerabilities, ensuring equitable access to green spaces, supporting urban resilience and green space connectivity for users. These will serve as input features for predictive modelling and spatial analysis in the next step of this project.

4.3 Modelling Approaches

Modelling Approaches used in this study aim to combine spatial analysis, network analysis and machine learning techniques to evaluate and optimise green infrastructure for urban resilience in Rotterdam. Using the integrated methodology allows for a comprehensive assessment of environmental, biodiversity and morphological indicators, further joining spatial data insights with predictive analysis to guide data driven urban planning.

Firstly, GIS spatial analysis will be used as the basis for mapping and assessing the distribution, accessibility and spatial characteristics of GI across Rotterdam. This step involves spatial mapping and overlays to visualise green space coverage, UHI intensity, and flood prone zones. Zonal statistics are applied and aggregated over raster datasets, such as NDVI and UHI maps, at the neighbourhood level, while spatial joins link vector datasets, including road networks and building footprints, to administrative boundaries. The resulting datasets provide key spatial indicators that act as inputs for both network analysis and machine learning models. GIS tools, such as QGIS and python libraries like geopandas and rasterio are used in this section.

Continuously, network analysis will be performed to evaluate the spatial connectivity and accessibility of green infrastrcuture networks. This analysis focuses on metrics such as accessibility scores and connectivity indices. Techniques such as least-cost path analysis will be applied to optimise pedestrian movement between green spaces and green space connectivity. The results of the network analysis will generate indicators that are incorporated as features in machine learning in the next step, ensuring spatial connectivity is quantitatively represented in predictive modelling.

Following network analysis, machine learning modelling is employed to predict and evaluate the resilience outcomes across Rotterdam's neighbourhoods. Predictive modelling developed using techniques such as Random Forest (RF), Gradient Boosting Machines (GBMs), and support Vector Machines (SVM). These models will be tasked with either predicting continuous resilience scores (which is regression analysis) or classifying neighbourhoods into resilience categories (classification analysis). The performance of these models will be evaluated using metrics such as R^2 scores or RMSE for regression tasks, and accuracy, precision, and F1 scores for classification tasks. Furthermore, feature importance analysis using tools like SHAP (shapley Additive Explanations) to identify which indicators have the most significant impact on

resilience outcomes. These will be implemented using python libraries scikit-learn, xgboost, and shap.

The results from the machine learning models are then interpreted and analysed to identify key resilience patterns across Rotterdam's neighbourhoods. Outputs from these models, such as predicted resilience scores and classification categories are cross referenced with network and spatial analysis findings to ensure consistency and highlight critical trends. This step ensures that results are not only statistically robust but also spatially relevant, enabling planners to understand where green infrastructure investments can have a larger impact.

Lastly, the findings are visualised and map to communicate key insights effectively to urban planners, policy makers and stakeholders. Outputs include resilience heatmaps, which display spatial variations in resilience scores, accessibility maps to highlight undeserved areas, and connectivity maps showing the strengths and weaknesses of green infrastructure networks.

In summary, the modelling approach will begin with GIS spatial analysis to prepare datasets and generate indicators, followed by network analysis to derive spatial connectivity metrics. These results are then incorporated into machine learning models as features to predict and classify resilience outcomes. The final interpretation and visualisation stage transforms the data output into actionable insights, supporting data driven strategies to enhance urban resilience with green infrastructure in Rotterdam. These visualisations may include choropleth maps, cluster maps, or confusion matrices that classify neighbourhoods into different resilience levels as well as residual maps, scatter plots or trend line graphs that show the difference between predicted and actual resilience scores or show trends in more or less resilient neighbourhoods.

5 Preliminary Results

In this section, some preliminary results are highlighted. These come from the data collected in the methodology section. Firstly, figure 1 gives an overview of the total green areas across Rotterdam. This provides an initial understanding into the overall vegetation coverage and spatial distribution of basic green infrastructure in Rotterdam.

Figures 2 and 3 highlight the tree cover percentage, and low level greenery. This offers a deeper look into areas with high-density tree cover and low level greenery which are important when looking at biodiversity, cooling effects and how it may correlate to UHI as well as other resilience indicators in the following parts of this project.

Initial observations show that some neighborhoods may exhibit lower green coverage than others, which may align with the impression that there may be specific vulnerable areas in Rotterdam. This information provides a base to understand if there are priority zones for green infrastructure implementation. Further analysis will explore how these resuls can relate to other key indicators such as flood risk, accessibility and morphological factors to ensure a multi dimensional assessment of this case study.
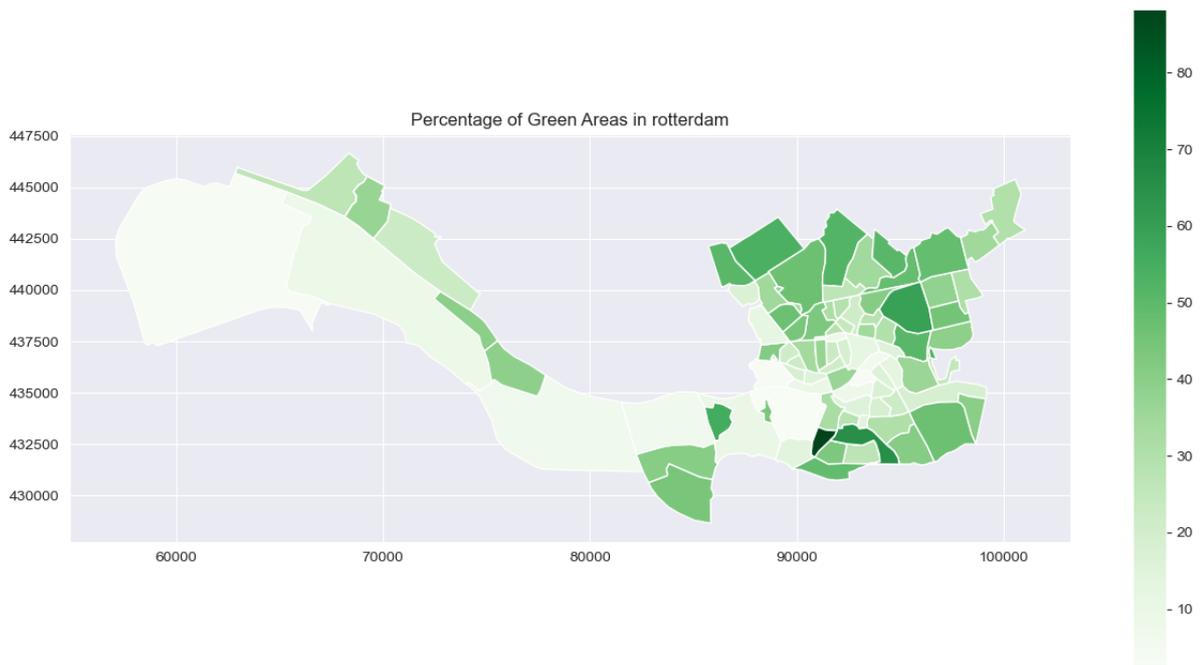
Figure 1: Percentage of Green areas in Rotterdam

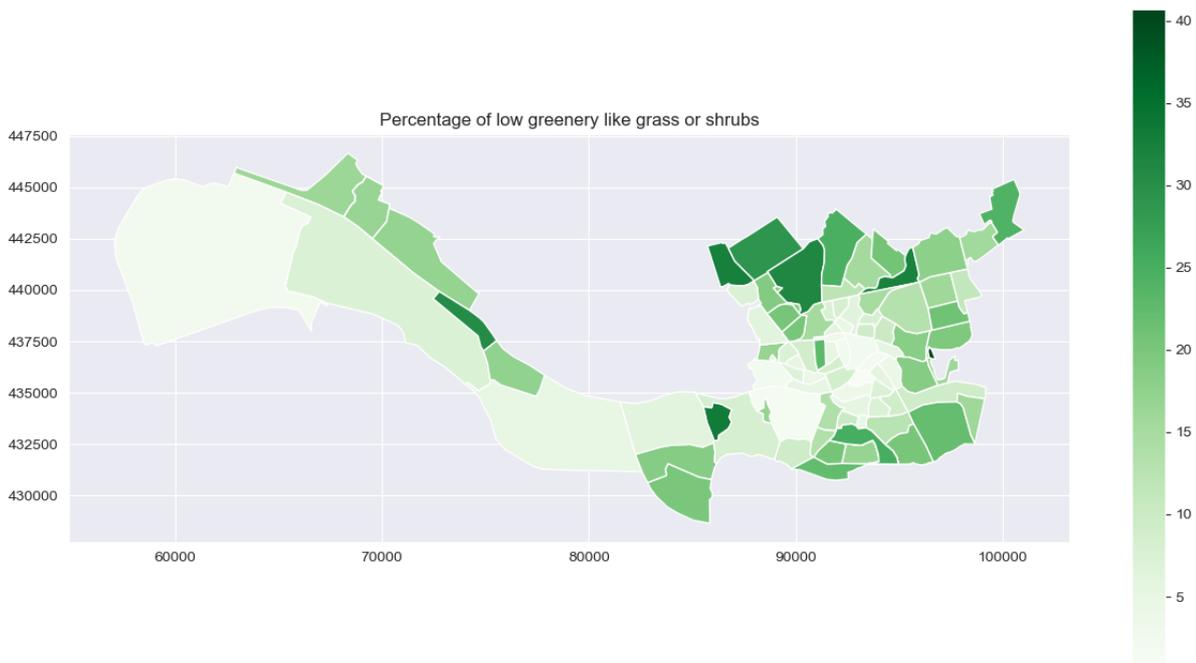Figure 2: Percentage of Tree Cover in Rotterdam

Figure 3: Percentage of low greenery

Following the initial analysis, Principal Component Analysis (PCA) was done on a merged dataset. Using PCA, it was able to reduce the dimensionality of the dataset and look at different neighbourhoods in Rotterdam, taking into account more features at the same time. Firstly, figure 4 shows the loadings for Principal Component one. A conclusion we can draw from this is that, in the neighbourhoods with a high PC1 score, it will have low green area percentages, low paved area percentages but high amounts of water. This pattern may highlight some characteristics of wavefront or water-dominated areas which may be prone to flooding, but may induce cooling effects. Looking at the neighbourhoods while taking into account multiple features simultaneously is valuable as it may reveal correlations that may not be as obvious in singular variable analyses.

Additionally, using PCA for initial understanding provides an initial framework for comparing neighbourhoods across multidimensional indicators, such as environmental, biodiversity and morphological indicators. This approach may aid identifying clusters of neighbourhoods that may share similar traits which will in turn give a better understanding of why these areas might be more or less resilient. Looking at different principal components may aid in giving insights to the relative importance of individual features that shape a specific neighbourhood. For example, the influence of low green areas in PC 1 may highlight the need for further exploration into the role green infrastructure within the landscape of neighbourhoods in Rotterdam.

Figure 5 and 6 give us an overview of the principal component scores sorted by Neighbourhood throughout Rotterdam. Using the bar chart gives us a direct comparison of which Neighbourhoods have higher and lower PC1 scores, and using the map gives us a visual representation where it may be easier to find clusters that require more immediate attention.

Figure 4: Principal Component Analysis 1 Loadings
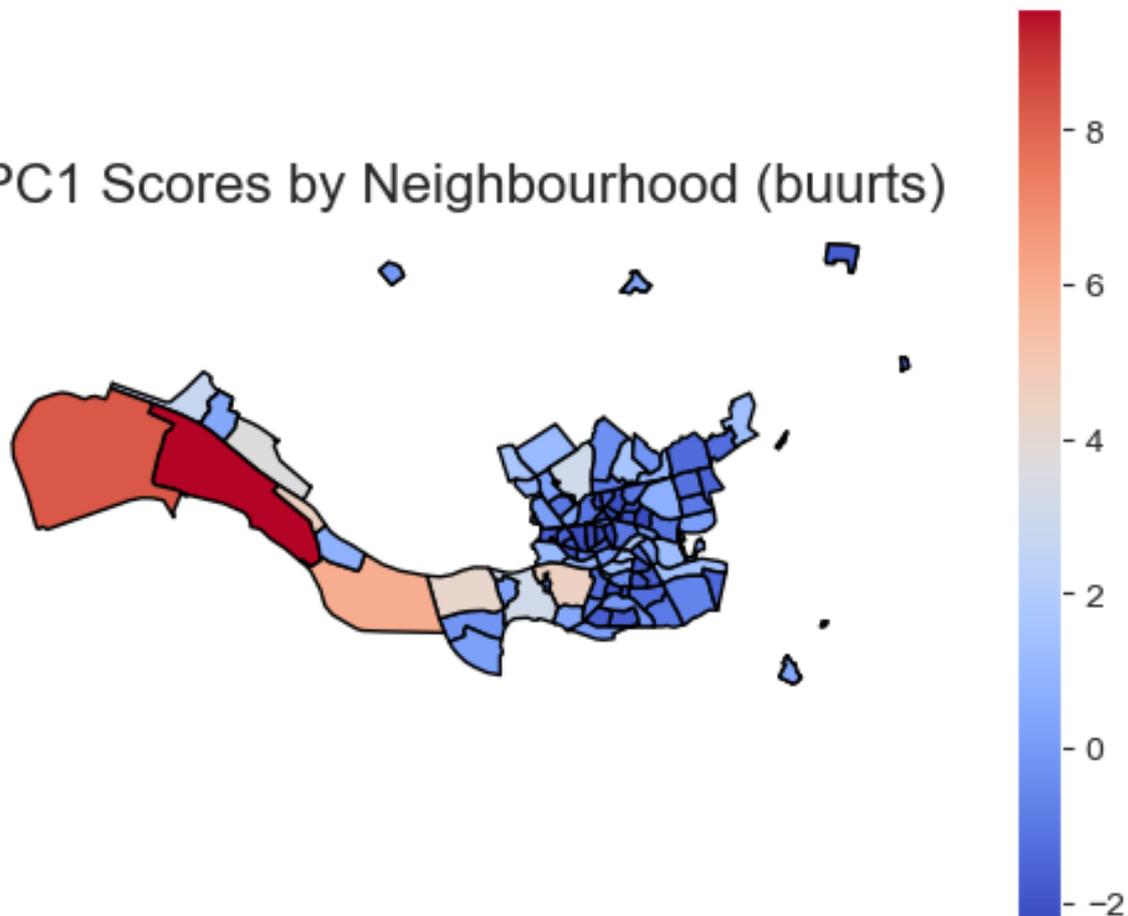

Figure 5: PC1 scores by Neighbourhood

Figure 6: PC1 Scores by Neighbourhood Mapped

6 Next Steps

With the progression of the project, the next steps will include a focus on refining the data analysis and modelling framework to ensure a comprehensive evaluation of green infrastructure and the impact on urban resilience.

The next immediate step is to build indicators from raw data. This involves transforming all the raw data that have been cleaned into meaningful indicators. These indicators as highlighted in the methodology, will cover environmental, biodiversity and morphological factors that may affect urban resilience. This involves normalising datasets, ensuring spatial consistency with coordinate reference systems, as well as aggregating features to both street and neighbourhood level.

Furthermore, while the initial focus has been on analysing indicators at neighbourhood level, this scale might not be sufficient in capturing the spatial variability within Rotterdam when performing predictive modelling. Moving forward, the aim of the analysis will expand to incorporate street-level data rather than neighbourhood level. In turn, this will give a finer spatial resolution to improve the predictive modelling sample size. This enables a more detailed examination of green infrastructure and the relationship to resilience indicators.

Finally, while using machine learning to predict urban resilience scores and perform classification of urban resilience levels, the project has come to two options, one may be to perform further machine learning on the features, before actual predictive modelling. This would be done to apply weights to different features in order to have higher level complex models. The second option would be to perform techniques like SHAP which was described in the methodology. This technique would be used post-predictive modelling to determine the importance of different features. This may help in prioritising which green infrastructure features may need direct interventions or implementations.

These next steps aim to bridge the gap between the raw data collected and the urban resilience predictions discussed previously. Through refining indicators, incorporating multi-scale spatial analysis, and understanding the importance of individual features, the project will advance towards creating a framework for optimising green infrastructure and enhancing urban resilience.

7 Time planning

Figure 7 shows an overview of the planned tasks and how they are split among the 30 weeks of this thesis.
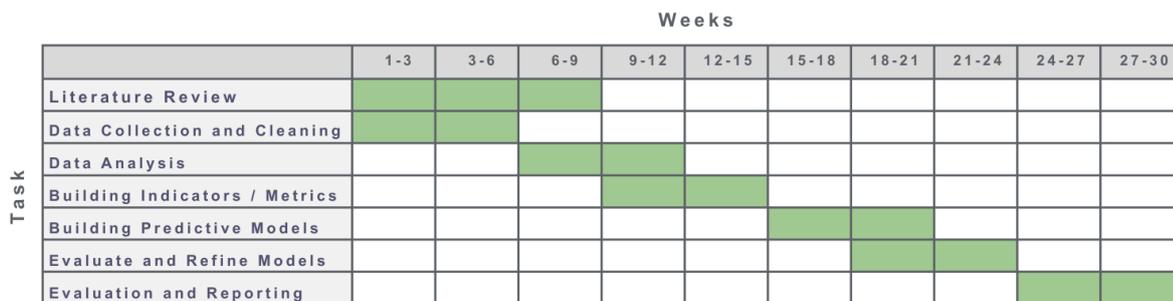

Figure 7: Task Distribution Gantt Chart

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