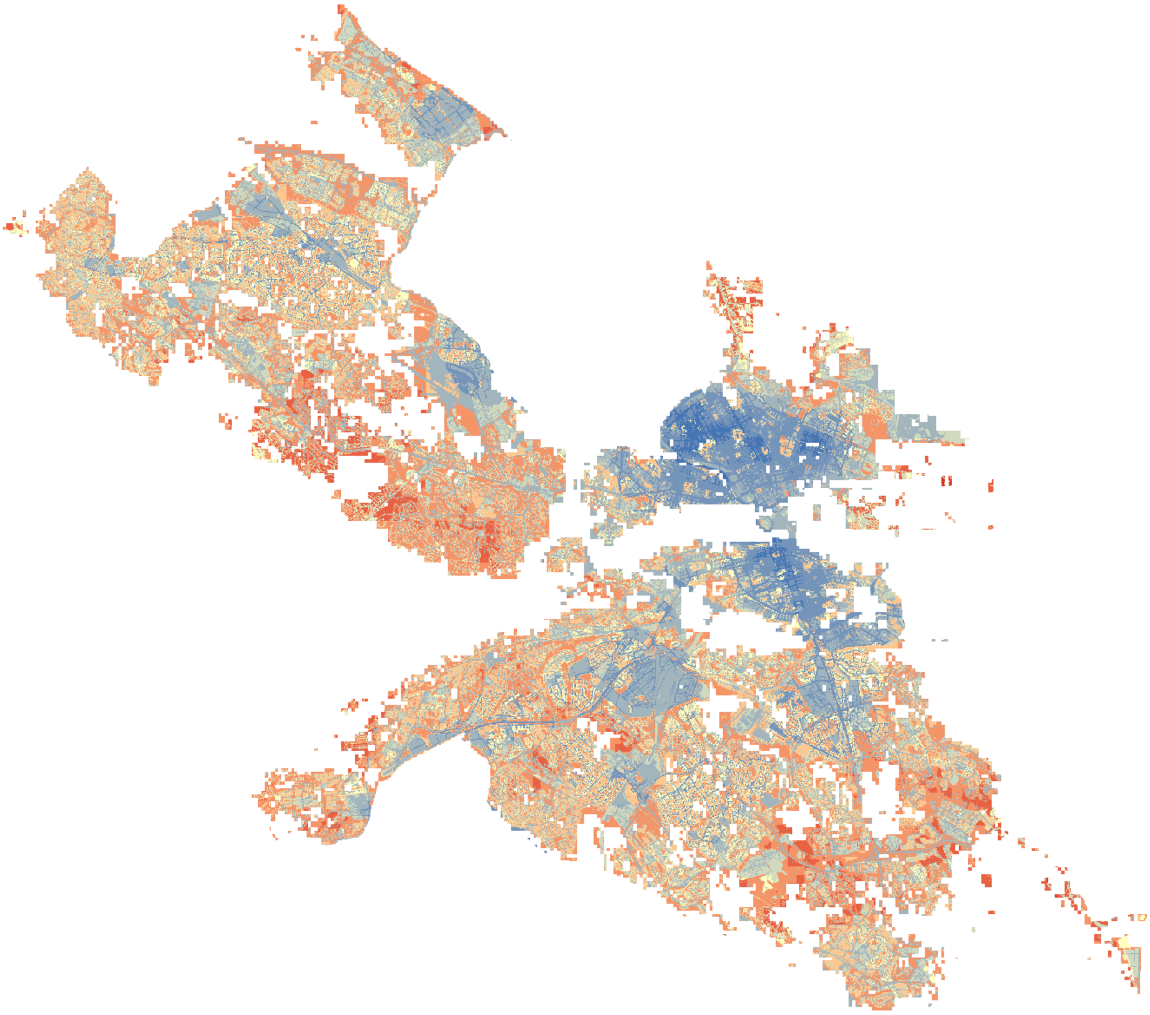

Ecosystem Services in Stockholm – Challenges and Opportunities

MASTER'S THESIS

Author Maurizia Puh
Study programme MSc Industrial Ecology
Universities Technical University Delft & Leiden University
First supervisor Dr. R. P. Remme, Leiden University
Second supervisor Dr. V. Barbarossa, Leiden University

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Abstract

Ecosystem services (ES), the benefits humans receive from nature, increasingly come under pressure in Stockholm, one of the fastest growing capitals in Europe. To enhance the amount of eco-efficient area, Stockholm developed the Green Space Index (GSI). It is not known which areas in Stockholm might be particularly vulnerable in terms of ES availability, or whether the GSI objectively improves ES availability.

The aim of this thesis was threefold. Firstly, to provide an overview of the current distribution of ES in the city; secondly, to test for a potential correlation between ES availability and socio-economic opportunity; thirdly, to test for differences in ES availability between an area where the GSI had been implemented, and areas without the GSI. Specifically, the ES of stormwater retention, annual water retention, heat mitigation, and nature access were assessed.

For quantifying ES, the Urban InVEST models from the Natural Capital Project were used. Results from the models were combined to form a heatmap of ES. A correlation between socio-economic opportunity and the availability of ES was assessed with a Spearman correlation test on the neighbourhood deprivation index (NDI) and the ES. The NDI measures income, education, population receiving social benefits, and employment. Differences between the areas with and without GSI were tested for with t-tests. All statistical analyses were conducted in RStudio.

The analysis revealed that the ES in Stockholm are available less in the city centre and increase towards the outskirts. Economic opportunity in a district is negatively correlated with stormwater retention, annual water retention, and nature access – the higher the socio-economic opportunity, the less of these services is available.

Where the GSI had been implemented was significantly different from all the areas it was compared to. Due to different types of land use both water retention services are lower in the GSI area compared with the situation prior to redevelopment, the residential area, and one of the three other areas that had been redeveloped without the GSI. For heat mitigation, the GSI area performed worse than two of the redeveloped areas.

While the outskirts seem to be better provided with ES, this does not mean that the demands are met everywhere. Large parts of the construction in the coming decades are planned to take place in these less well-off areas, potentially threatening the natural elements providing ES and affecting populations that are less well equipped to make up for the loss of ES. The GSI can be a powerful tool to combat this. However, the research uncovered some shortcomings that should be addressed: striving for a high GSI score is not sufficient, measures with which the GSI is achieved must be suitable for the needs of the location. A process focussed on uncovering these needs first, or splitting up the GSI into several assessment categories, could aide in this.

Future research should continue assessing the GSI, either in a scenario analysis, or by monitoring. With these findings, the present thesis hopefully contributes to an improved understanding of ES in Stockholm.

Acknowledgements

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Abbreviations

ES	Ecosystem Services
GFF-V	Green and Open Space Factor Vienna
GIS	Geographical Information System
GSI	Green Space Index
InVEST	Integrated Valuation of Ecosystem Services
LULC	Land Use/Land Cover
NatCap	Natural Capital Project
NDI	Neighbourhood Deprivation Index
SAMS	Small Area Market Statistics
SRS	Stockholm Royal Seaport
UC	Urban Cooling
UFRM	Urban Flood Risk Mitigation
UHI	Urban Heat Island
UNA	Urban Nature Access
USWR	Urban Stormwater Retention

1. Introduction

1.1. Problem statement

The main reason for building houses, as well as cities, has been to protect humans from nature.

Bolund & Hunhammar, 1999

In our ever-expanding cities, we are now fairly well protected from "nature"; harsh weather conditions, roads that are made structurally unsafe by vegetation, or attacks by wild animals are usually not a problem for city dwellers. Cities are – generally speaking – housing less animal and plant species than rural areas (Aronson et al., 2014), and urbanisation at large is then also considered one of the major threats to biodiversity (Millennium Ecosystem Assessment, 2005; Seto et al., 2012).

This is found to be increasingly problematic, however, as nature is recognized to provide humans with vital services: from food production to positive impacts on human health (see for a list of examples Frumkin et al., 2017), so-called ecosystem services (ES) are relevant to all aspects of society (Bolund & Hunhammar, 1999; Gómez-Baggethun et al., 2013). Without the necessary natural elements or ecosystems (like the garden depicted in Figure 1), these services are either absent or need to be substituted technologically.

Figure 1 Multifunctional greenspace, providing aesthetic value as well as stormwater protection (Stockholms Stad, 2022b).

The issue of threatened ES in cities and the risk this contains has come to the attention of city governments. Increasingly, efforts are made to catalogue, protect, and enhance these services. Mapping of ES is a preferred approach for many decision makers, since several layers of information can be incorporated into them (Burkhard et al., 2012). The distribution of service supply throughout the whole city can be mapped and combined with data on demand for these services. Thus, mapping can give valuable insights to researchers and practitioners alike.

Globally, there is a growing body of research on matching supply and demand for ES. An aspect of supply and demand relationships that is discussed frequently in literature is environmental justice. Simply put, environmental justice focuses on whether supply and demand relationships differ between population groups. In the context of ES, environmental justice is researched especially in the context of access to urban nature (Borelli et al., 2021; Dahlberg et al., 2022; Langhans et al., 2023). As benefits from nature should be accessible to everyone, environmental justice is a relevant field of research. Studies reviewing just distribution of services other than nature access were conducted for example in New York City (Herreros-Cantis & McPhearson, 2021) and in Strasbourg (Selmi et al., 2021). In both studies, runoff mitigation, and air purification were considered as ES. The study in New York City furthermore investigated local temperature regulation, while the French study considered atmospheric carbon reduction. A common way of categorizing advantaged and disadvantaged population groups is by socio-economic characteristics.

In order to stimulate a greener urban environment, the city of Stockholm recently developed its own planning tool for integrating multifunctional natural elements in its city scape. The Green Space Index (GSI) “promotes greenery that fulfils several functions, such as creating green spaces for recreation, delaying and purifying storm water, offering shade, contributing to pollination and being beautiful to behold” (Stockholms Stad, 2017). The index is expressed as a number between 0 and 1, with higher values indicating more eco-efficient surface, combining the services that make up the benefits of the area in question (Boverket, 2020).

The GSI for Stockholm was largely designed by the C/O City project during an early phase of redeveloping the Stockholm Royal Seaport (SRS) from an industrial area to a residential area (Stockholms Stad, 2022a). The municipality owns the area and has committed to an ambitious sustainability strategy, including application of the GSI (Lennartsson & Salmhofer, 2017). Planning of the redevelopment began in 2009 and construction started in 2011. As of June 2023, the SRS is the only area in Stockholm where the GSI has been applied (P. Qvist, personal communication, 30 May 2023).

Private construction projects in Stockholm are now required to calculate the GSI and strive for a value of 0.6 (Lundqvist et al., 2021). And in Stockholm, part of the fastest growing region in Europe, plenty of new construction projects are expected in the coming years; 140,000 new homes are to be built by 2030. The land is expected to come under further pressure as the number of inhabitants is expected to grow by almost a third in the coming two decades (Stockholms Stad, 2018). However, while 70% of the land in Stockholm is owned by the municipality (Stockholms Stad, 2021b), it is as of now not compulsory to work with the GSI when developing public land (Stockholms Stad, 2023).

Due to its novelty, the GSI has mostly been the subject of policy and guidance documents (C/O City, 2018; Lundqvist et al., 2021; Salmhofer & Ek, 2021). To assess the impact of the GSI, other studies were surveyed. One study available in English and dealing with the GSI was found, a work from Stange et al. (2022). In this study, the GSI is compared to two other green area factors, one in Berlin and one in Oslo. Apart from this study, in recent years some theses were published that research the GSI in Stockholm, for example Wikström (2020) or Hopkins (2021). However, peer-reviewed literature has not yet sufficiently focussed on critically assessing the impact of the GSI on the provision of ES. Even tools similar to the GSI, that have existed for longer periods of time, are usually not being monitored or assessed with external tools in their impacts (Juhola, 2018; Mendonça et al., 2021).

Apart from the potential effects of the GSI, the current distribution of ES and whether this distribution is correlated with socio-economic factors, has not been researched. It has, however, been noted that environmental justice issues are also present in the municipality in Stockholm (Adem Esmail et al., 2022). In 2003, the “Stockholm Urban Assessment” was conducted, when Stockholm found itself in a similar situation to today: faced with rapid population growth and urbanization (Colding et al., 2004). Studies since then have used Stockholm as a case study for conceptualizing new ES assessment methods (Baró et al., 2015; Goldenberg et al., 2017) or they investigate the future potential of ES under different scenarios, be it dependent on energy trajectories (Mörtberg et al., 2017) or land use change (Kain et al., 2016).

1.2. Research design

As Stockholm is faced with large-scale redevelopment in the coming decades, the city is currently at a crossroads of deciding on the distribution of natural elements and their benefits for the long term. While this poses a considerable challenge, it is also an opportunity. Knowledge about the current state of ES, potential injustices in the distribution, and an evaluation of the effectiveness of the GSI, a tool that is already in use, can enable the city of Stockholm to provide its citizens with the best possible provisioning of ES. As Bolund and Hunhammar (1999) rightfully say: "natural urban ecosystems contribute to public health and increase the quality-of-life of urban citizens", and these benefits should be available to all citizens.

Of course, there is a whole wealth of services to choose from. In the present study, the focus is on four ES: stormwater retention, annual water retention, heat mitigation, and nature access. All of these are relevant in the city of Stockholm. While under current climatic conditions storms are already a common occurrence in the Swedish summer, predictions are that these will only become more frequent in a warming climate. Damages related to these rainfall events are significant (Blumenthal et al., 2018). At the same time, Sweden already suffered from several particularly dry periods in the past decades, and these are also expected to become more severe with climate change. Effects of droughts in Sweden so far range from the need for water restrictions for private households, to wildfires and measures as extreme as killing off considerable numbers of livestock. The economic damage to the agricultural sector alone has been cited to be as high as €1 billion (Teutschbein et al., 2023). The potentially devastating effects of drought make it worthwhile to consider the annual water retained in Stockholm.

During heatwaves, mortality in Stockholm has been observed to increase (Oudin Åström et al., 2020), which warrants additional attention to the cooling effects of vegetation. With the planned 140,000 additional homes, the impervious surface is bound to increase, furthering the urban heat island (UHI) effect (Stewart & Oke, 2012). Already in 2013, reflecting upon the Stockholm Urban Assessment from 2003, Colding (2013) stated that nature in Stockholm was getting more fragmented, limiting the amount of nature for recreation. Access to nature is regarded to be a relevant factor for mental and physical health (Remme et al., 2021).

In this master's thesis the state of the ES stormwater retention, annual water retention, heat mitigation and nature access in the municipality of Stockholm are examined. This is first done in an assessment of the current situation for the municipality, analysing a potential correlation between the ecosystem service provisioning and the socio-economic deprivation of a district. Subsequently, the potential effect of the GSI is analysed in a "before and after" comparison in the SRS, as well as in a comparison between areas.

The research questions answered in this thesis are:

1. How are the ecosystem services of stormwater retention, annual water retention, heat mitigation and nature access currently distributed in Stockholm?
2. Is there a correlation between the ecosystem services' distribution and socio-economic opportunities in the different districts?
3. What is the effect of implementing the Green Space Index (GSI) on ecosystem services in the Stockholm Royal Seaport?
    a. How have the values and distribution of the ecosystem services in the Stockholm Royal Seaport changed after redevelopment with the GSI?
    b. How is the area redeveloped with the GSI different from the areas redeveloped without the GSI?

c. How is the area redeveloped with the GSI different from another residential area in the same district?

Answering these questions will shed light on different ES in Stockholm. These services represent at least two of the pillars of sustainability, namely social and environmental sustainability, assessed with models from the technological side of sustainability. Moreover, the analysis is conducted within the boundaries of the municipality of Stockholm, which can be considered a complex human-made system. By purposefully focussing on this scale, this thesis furthers the canvas of systems thinking-based research vital to the field of Industrial Ecology.

The following section (Theoretical background) explores the main concepts used in this thesis, followed by the Methods section. Afterwards, the Results of the research are presented and their implications, weaknesses and strengths are detailed in the Discussion. Finally, the research questions are answered in the chapter Conclusions.

2. Theoretical background

2.1. Ecosystem services

In this research, the following definition of ecosystem services (ES) is used: "the ecological characteristics, functions, or processes that *directly* or *indirectly* contribute to human wellbeing" (Costanza et al., 2017). Three types of ES are commonly distinguished: provisioning services, regulating services, and cultural services (Haines-Young & Potschin, 2013).

Apart from provisioning services, ES relevant for the urban sphere are generally used close to the ecosystems that generate them. For example, cooling provided by a park or a reduced flood risk from water buffering capacity provided by a garden.

To illustrate how benefits for people arise from ecosystems, the cascade model was developed by Haines-Young and Potschin (2010), displayed in Figure 2. Here, the distinction between services and benefits should be noted: ES are outputs of ecosystems which affect human wellbeing. These outputs may have been altered by human influence. Benefits are the products or experiences that humans derive from the services (Haines-Young & Potschin, 2013).

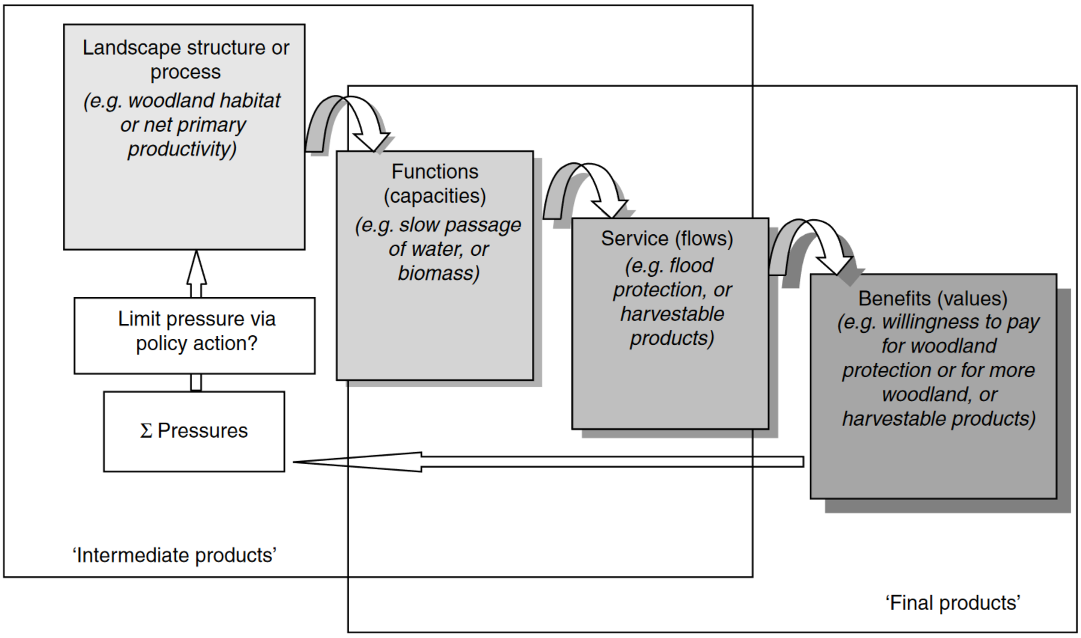

Figure 2 Ecosystem service cascade model, describing how benefits for humans arise from natural ecosystems (Haines-Young & Potschin, 2010).

The ES at the heart of this research are flood risk mitigation, annual water retention, heat mitigation, and nature access, as these are all services relevant in Stockholm and available in a coherent modelling framework in the InVEST models. The individual services are explained more in detail in the following sections.

2.1.1. Stormwater retention

When talking about stormwater retention in this thesis, it is concerning pluvial flooding, so flooding caused by an extreme rainfall event. Pluvial flooding in cities is mainly promoted by the interplay of two factors: urban areas are largely made up of impervious surfaces which do not allow for water to seep away. The water is then forced into the sewer system, which often is not equipped to deal with particularly heavy rainfalls. Figure 3 shows the pathways of rainwater in an urban environment. The storms for which the system's capacity was designed is likely to become more frequent in a changing climate (Huang et al., 2020).

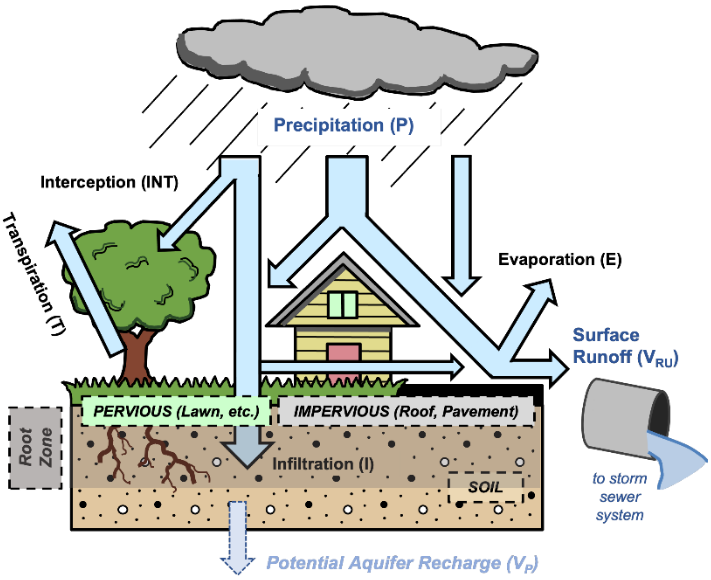

Figure 3 The (urban) water cycle, adapted from Natural Capital Project (2022).

Natural elements can help against flooding by slowing surface runoff and by offering additional water storage capacities. These elements might be introduced in the form of substituting impervious roofs with green roofs or by building rain gardens (Vojinovic, 2020).

2.1.2. Annual water retention

As the name implies, this service deals with the water balance on an annual basis. This focus is especially useful when exploring the potential for aquifer recharge in drought-prone regions, or when looking at the quality of the water present in an area. Also here, natural elements can promote water infiltration and thereby water retention rates (Natural Capital Project, 2022).

2.1.3. Heat mitigation

The urban heat island (UHI) effect is a phenomenon present in almost all urban areas. A UHI arises due to the structure of a city; cooling by convection is limited due to buildings, land cover is impervious, materials used often store heat, and natural vegetation, which could cool by providing shade and evapotranspiration, is limited. At the same time, cities are hotspots of human activity, which often releases even more heat (Stewart & Oke, 2012).

2.1.4. Nature access

Being in nature has many physical and mental health benefits (Frumkin et al., 2017; Remme et al., 2021). Especially being physically active in nature, be it by taking walks or by doing sports in natural areas, has been shown to offer a variety of health benefits, even exceeding the ones of being active indoors. Remme et al. (2021) identified two variables on which making use of natural spaces depends: access to nature and thereafter the choice to make use of the available nature.

While the choice to use urban nature is dependent on several factors on the individual level, and surely also on the quality of the nature offered, nature access can be defined more globally. According to Remme et al. (2021), nature access is the (perceived) opportunity of people to expose themselves to urban nature, which is dependent on distance, barriers, individual capabilities, and socio-economic factors.

2.2. The Green Space Index

The Green Space Index (GSI), as applied by the city of Stockholm, is “a tool that aims to support system solutions wherein urban greenery and storm water are managed in various ways to strengthen ecosystems and compensate for the negative effects of climate change while also creating attractive gardens and outdoor environments" (Stockholms Stad, 2017). Essentially, it is a measure of the eco-efficient surface compared to the overall area. Eco-efficient surface comprises "all green and blue surfaces that have a positive impact on the local ecosystem, contribute to a better microclimate, stormwater management and noise reduction and have social values linked to greenery and/or water" (Lundqvist et al., 2021 as translated by Google Translate).

In the following Table 1, translated and adapted from Boverket (2020), the calculation of a GSI is illustrated. Each surface type is assigned a value for eco-efficiency. This value is then multiplied with the total area of the surface in question to obtain the actual eco-efficient surface. In a last step, the eco-efficient area is calculated as a fraction of the total area for which the GSI is to be calculated.

Table 1 Exemplary calculation of the Green Space Index (GSI), as adapted from Boverket (2020).

Surface	**Value**	**Area (m^2)**	**Eco-efficient area (m^2)**
Soil and grass	0.4	30	12
Bushes and solitary trees	0.4	3	1.2
Sealed roof	0	40	0
Permeable hard surface	0.25	10	2.5
Sum	*not applicable*	83	15.7
GSI	$\frac{\mathbf{15.7}}{\mathbf{83}} = \mathbf{0.19}$		

Two GSIs are being distinguished: the GSI for private developments, literally translated the "neighbourhood level GSI", and the GSI for public land. For private developments, the calculation of the GSI is compulsory and generally a value of 0.6 has to be achieved (Lundqvist et al., 2021). On public land the GSI can be applied at a developer's volition. As of now, the GSI is only applied in the Hjorthagen area in the Stockholm Royal Seaport. Two development plans including GSI measures have been accepted, but are not yet constructed (P. Qvist, personal communication, 30 May 2023).

The GSI for private developments entails the services biodiversity, social and recreational values, and climate adaptation (including stormwater management and sound quality) (Boverket, 2021). For public land, the GSI additionally includes the services microclimate regulation and pollination (C/O City, 2018). The GSI is aggregated to represent all these services as a score between 0 and 1.

2.3. Case study: Stockholm Royal Seaport

The Stockholm Royal Seaport (SRS), or Norra Djurgårdsstaden in Swedish, is a former industrial area in the east of Stockholm, consisting of the neighbourhood of Hjorthagen, the two harbour areas Värthamnen and Frihamnen, and the area of Loudden. In 2009 the city council designated the SRS to become a flagship of sustainable urban development, a so-called "environmentally profiled city district" (Lennartsson & Salmhofer, 2017). Several measures are implemented for achieving a higher GSI: for example green roofs, courtyards, parks, as well as nests for insects and birds (Stockholms Stad, 2021a).

2.4. Socio-economic opportunity

Neighbourhood deprivation is a concept predominantly utilized in medical or sociological studies in Sweden, where it is investigated in correlation with the prevalence of diabetes (White et al., 2016), obesity in children (Li et al., 2014), mortality during heat waves (Oudin Åström et al., 2020), or drug abuse and crime rates (Sariaslan et al., 2013). Except for the latter study by Sariaslan and colleagues, all studies used a combination of level of education, unemployed population, income, and population receiving social benefits as indicators for neighbourhood deprivation. Sariaslan et al. add a few more factors relating to familial status and heritage. Information on the first four indicators can be found most easily. When applied in such a way, neighbourhood deprivation can be seen as a measure of socio-economic opportunity present in a district.

3. Methods

3.1. Approach

The conducted research can be divided into four general phases, as visualized in Figure 4. Phase 1 was the preparation phase in which the case study was decided upon, and data was collected for the baseline assessment and the case study. Phase 2 was the assessment of the baseline situation in the municipality of Stockholm for which the four different ES were quantified, resulting in a heatmap showing the distribution throughout the city. Moreover, a potential correlation between economic opportunity and ES distribution was tested for statistically. Phase 3 was dedicated to the case study, so all services were quantified for the situation in the SRS before 2011, when the GSI was not yet implemented. The before and after situations in the GSI area were compared for statistically significant differences, and tests for differences between the areas were conducted. Phase 4 finalized the project by bringing all the results together to draw conclusions and answer the research questions.

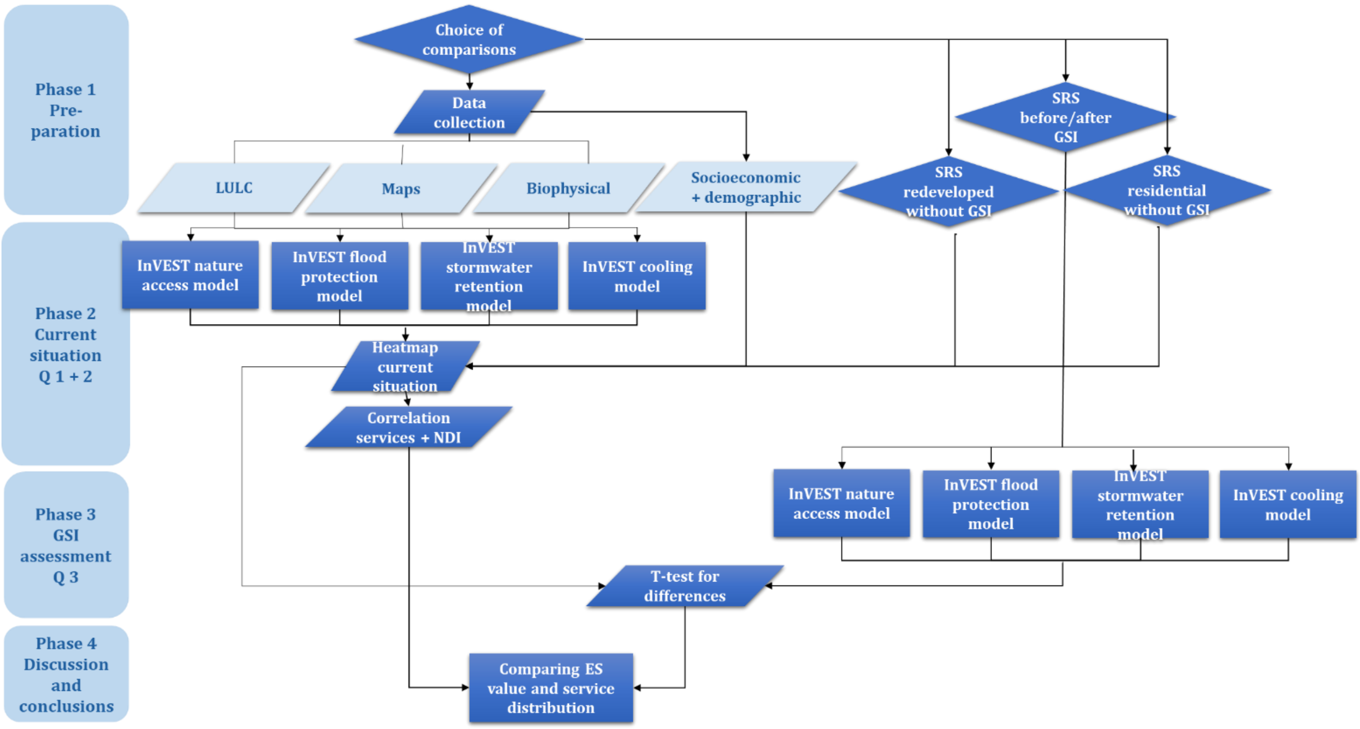

Figure 4 Research flow diagram, dividing the research into four different phases to answer the research questions. ES: Ecosystem services, GSI: Green Space Index, LULC: land use/land cover, NDI: measure of socio-economic opportunity, SRS: Stockholm Royal Seaport, InVEST: ES quantification software.

3.2. Software

In this project the InVEST 3.13.0 Workbench was used for running the InVEST models. Data visualization was done in ArcMap 10.6.1, as well as a part of the data processing. ArcCatalog 10.6.1 was also used for data processing. The biophysical tables were prepared in Excel. Statistical analyses were conducted in RStudio 4.2.1.

3.3. The InVEST models

Urban InVEST, a suite of models developed by the Natural Capital Project (NatCap), combines models that are relevant in the urban context and advances the development of models specific to the urban sphere for use by practitioners and researchers. NatCap is a collaboration that brings together several renowned institutions, such as the Stockholm Resilience Centre, the Chinese Academy of Sciences, or the University of Minnesota (Lewis, 2019). The models were developed in collaboration with municipalities in the United States and the Asia-Pacific region, and the first ones were released in 2020. As of May 2023, four urban models are publicly available: Flood Risk Mitigation, Stormwater Retention, Cooling, and Nature Access. More models are under development (Natural Capital Project, 2022).

Several studies have already been conducted using Urban InVEST. Hamel et al. (2021) introduce Urban InVEST in three case studies for Shenzhen (China), the Twin Cities (United States), and Paris (France). In each of the three, the models were used to investigate a different urban planning issue through the lens of ES, to showcase the versatility of the models.

The InVEST models make use of land use and land cover data in combination with biophysical data to quantify the benefits of nature. Examples of biophysical data are information on the albedo of different surfaces, evapotranspiration values, or stormwater runoff coefficients. For reference, the data for the models used in this research are listed in Appendix I: Model inputs. Results are best interpreted using geographical information systems (GIS).

The InVEST software is freely available for download on the website of NatCap, together with intensive documentation describing the workings of each model and including pointers towards potential data sources. NatCap also hosts an online forum for discussing questions and problems, where users and software developers alike participate. Moreover, the code behind the models is freely available on GitHub. In the following description of the individual models, information is taken from the User Guide (Natural Capital Project, 2022), unless specified otherwise.

3.3.1. Land Use/Land Cover raster

The land use/land cover (LULC) map is the basis of all the Urban InVEST models. For the current situation, the LULC map was made up of data from two sources. Wherever possible, data from Stockholm's mapping and geodata service was used for adding trees, waterbodies, roads, buildings, wetlands, green areas and forest areas, port areas, sports facilities, paved areas, and airport areas. Urban Atlas' 2018 tree cover map was added to that, green roofs in the SRS were added manually, and finally the Urban Atlas 2018 LULC map was used to fill any remaining gaps. All this data was available as a shapefile and had to be converted to raster with a cell size of 10 x 10 m. For the classification of the different LULC classes the system of Urban Atlas was retained, only two classes were added: "Green roofs" and "Buildings". The resulting map is displayed in Figure 5.

The Urban Atlas data had to be clipped to the extent of the subwatersheds intersecting the municipality of Stockholm. Clipping to the extent of the municipality would have been sufficient for the Urban Cooling and Urban Nature Access models, however clipping to the extent of the subwatersheds made the LULC file usable in all the models and made sure that effects of LULC types from outside the city boundaries were also partially considered. The subwatersheds overlapping the municipality of Stockholm were extracted from the regional subwatershed map using ArcMap's "Select by location" tool and by consequently making a new layer from the selected polygons. Wherever necessary, the files were reprojected to SWEREF99_TM. All these operations were done in either ArcMap 10.6.1 or in ArcCatalog 10.6.1. The ArcGIS tool "Mosaic to new raster" was then used to combine the different layers into one raster.

The extent of the Urban Atlas data ended shortly outside of the land area, resulting in large parts of the water bodies around Stockholm being classified as NoData. Since the presence of water impacts the different ES, this was rectified by reclassifying the NoData values to water with the "Reclassify" tool. The assumption was made that all NoData values in the LULC map within the relevant extent was water.

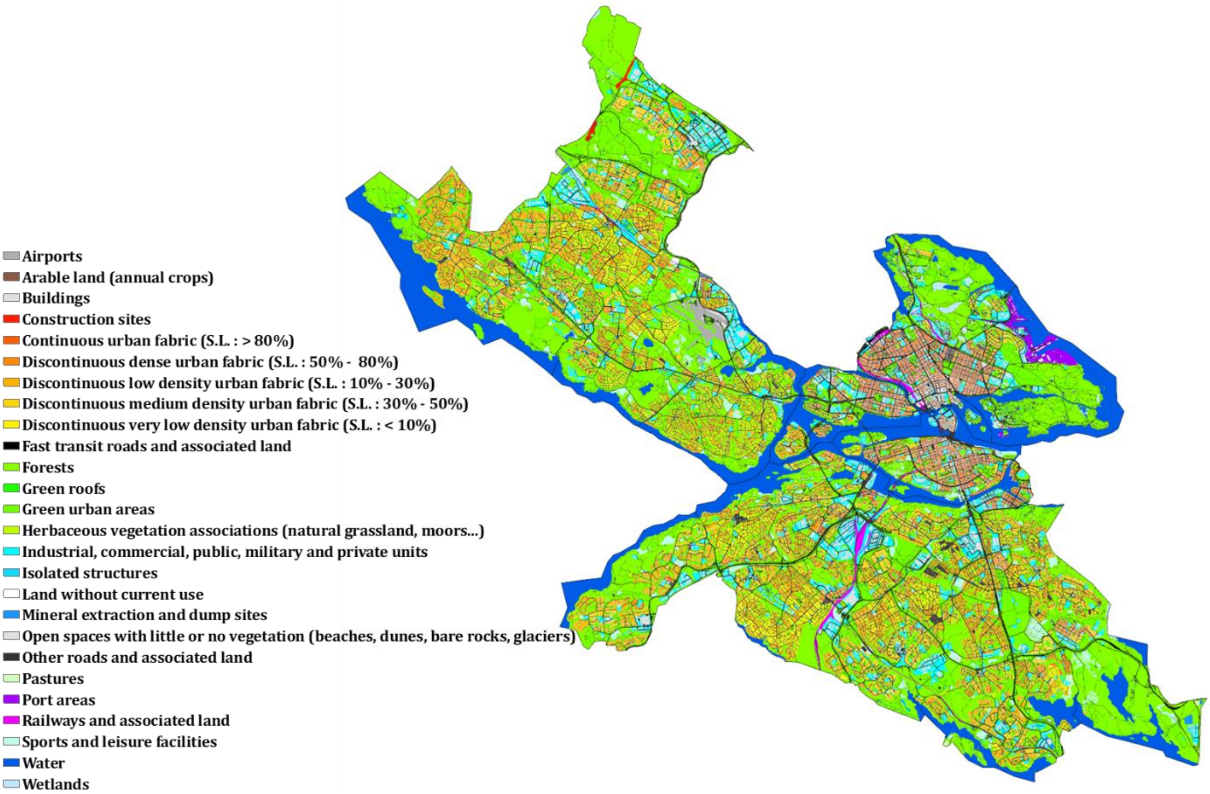

Figure 5 Land use/land cover map of the municipality of Stockholm used for the analysis of the current situation, made up from data from the municipality of Stockholm, Urban Atlas, and with manually added green roofs in the Stockholm Royal Seaport.

3.3.2. Urban Flood Risk Mitigation model

In InVEST's Urban Flood Risk Mitigation (UFRM) model, the service of water retention during a heavy downpour is quantified. Flooding is calculated as runoff volume. The model first estimates the runoff for each surface based on the curve number, which depends on the LULC class and the soil hydrologic group. Afterwards, the runoff retention is calculated by subtracting the runoff over total storm depth from 1, resulting in a fraction. Runoff retention volume is calculated by multiplying the runoff retention with the storm depth and the area.

The Urban Flood Risk Mitigation model for the current situation

The two water retention InVEST models operate on the level of watersheds or subwatersheds (the catchment area from which water is collected to flow into a single stream (United States Environmental Protection Agency, n.d.)). All raster files were fed to the model clipped to the extent of the subwatersheds and reprojected in SWEREF_99. Model output is only generated for pixels where data is present, for the UFRM model this means that cells where no information on soil hydrologic group is available, no water retention is calculated.

A relevant rainfall depth for the model was determined at a total volume of 105.7 mm. This number is based upon a stormwater model issued by the municipality of Stockholm (Thurin, 2018). 105.7 mm is the amount of rainwater expected in a "once-in-100-years" rainfall event in the city.

Curve numbers were obtained from several international sources, as local data specific per LULC type and soil group was not available. Most curve numbers stem from the United States Natural Resources Conservation Service (1986) and a study by Zeng et al. (2017). In both publications, the curve numbers of the LULC description resembling the one present in the LULC map for Stockholm most closely was chosen. All model inputs are listed in Table 3 in Appendix I: Model inputs.

3.3.3. Urban Stormwater Retention model

In the Urban Stormwater Retention (USWR) model, the annual water retention is calculated. These calculations are based on runoff coefficients, which are provided by the user and, like the curve numbers for the UFRM model, are defined per LULC class for each soil group. Based on these runoff coefficients, the model calculates how much water is retained, considering the annual precipitation in the location in question.

For additional realism, the model offers the option to consider the retention of areas in the vicinity. If areas within a certain radius are not considered to be connected to the stormwater sewer system, then the retention of the location in question is increased.

The Urban Stormwater Retention model for the current situation

The precipitation raster utilized in this research is made up of twelve separate rasters, each representing the average precipitation in the area for one month of the year. The rasters were summed up with ArcMap's "Raster calculator" tool. Then, the raster had to be reprojected to SWEREF_99 and clipped to the extent of Stockholm's subwatersheds. The same was done for the road centerlines file, obtained from Lantmäteriet. Lantmäteriet made data of different types of roads available, from highways to dirt roads. After sampling some data points in the different road layers and looking them up on Google Maps, the decision was made to only use the layer with the main roads because other road classifications also contained roads with pervious covers. As for the UFRM model, the USWR model is not generating output data for locations where input data is missing, specifically for the combination of the soil hydrologic group and precipitation rasters.

Just as for the curve numbers, also for the runoff coefficients local data at the necessary level of specificity was not available, and no international source offered all the correct combinations of LULC types and soil groups. Therefore, again, the closest resembling LULC category/soil group combination from several sources was chosen. The main source for this was Rawls et al. (1981).

Whether or not a LULC class is considered connected to the sewage system was determined based on the description of the LULC class in the Urban Atlas documentation (European Commission & Copernicus, 2020) and the definitions given in the InVEST User Guide (Natural Capital Project, 2022). All model inputs are listed in Table 4, Appendix I: Model inputs.

3.3.4. Urban Cooling model

In the Urban Cooling (UC) model, the heat mitigation index is calculated as follows. For each pixel in the LULC map, the effects of shade, evapotranspiration, and albedo are assessed. Next, potential effect of green areas on the pixel are considered. These effects are considered if there are green areas are larger than 2 ha within the user specified maximum cooling distance.

Local data on the maximum temperatures in the urban area and the temperature in the surrounding rural area (the difference of which is the UHI) enable the calculation of air temperatures. The average temperature and the temperature anomaly, compared to the rural reference, is calculated for each administrative unit.

The Urban Cooling model for the baseline assessment

All raster files were provided to the model for the extent of the Stockholm subwatersheds. The ArcMap input files were clipped to the desired extent and reprojected to SWEREF99_TM. The district boundaries of the municipality were used as the area of interest, since results are provided for the polygons in the layer provided.

The evapotranspiration raster showed some gaps which affected the results in such a way that no results were calculated for those raster cells. Therefore, NoData values in the raster were filled in by means of nearest neighbour analysis (Appendix II: Filling the gaps in the evapotranspiration raster).

Air blending distance and maximum cooling distance were both taken from the recommendations provided in NatCap's User Guide (2022). A brief sensitivity analysis on the effect of an air blending distance of 500m versus 600m (the User Guide recommends a value of 500 to 600m) was conducted, showing no difference in model outcome. Therefore, the 500m was adhered to in all model runs.

For the reference air temperature and the UHI effect, the hottest day in Stockholm in the past years was identified. This was on 21 July 2022 at 14:00 hours. Temperature data was taken for this time from a weather station in the city centre (Observatoriekullen A) and from a weather station in the surrounding rural areas (Tullinge A), south of Stockholm. The value for the relative humidity was also taken from this time at the city centre weather station.

The biophysical table was populated largely with data from Veerkamp et al. (2023), who report their process of assessing heat mitigation with the InVEST models for the city of The Hague using Urban Atlas LULC data. Albedo values and crop coefficients Veerkamp et al. had mainly taken from non-local sources. Shade and building intensity were calculated specifically for The Hague. Here, the assumption is made that The Hague and Stockholm are similar enough to allow for taking over these values in the present study. Moreover, a substantial proportion of buildings and trees are displayed individually in the LULC table of the current situation, instead of being grouped in the Urban Atlas classes. This facilitates a reliable analysis. A full list of data necessary for the UC model is available in Appendix I: Model inputs (Table 5).

3.3.5. Urban Nature Access model

In short, the InVEST Urban Nature Access (UNA) model compares the supply of nature to a given location to the demand for nature in that same location. Supply is defined as the area of nature in square meters within a specified distance from the location in question. Demand is calculated from multiplying the population in the location with the specified per capita nature demand (urban nature is thereby considered a rival good in InVEST). From this, the urban nature balance is calculated by subtracting the supply from the demand.

The Urban Nature Access model for assessing the current situation

Of the models used in this research, the UNA model was the one for which data was easiest to be found. Information of whether a lucode is considered nature (1) or not (0) was based upon the description of each LULC class in the Urban Atlas Mapping Guide (European Commission & Copernicus, 2020).

The population raster was available for the entire country of Sweden and had to be reprojected to SWEREF99_TM and then clipped to the extent of the municipality of Stockholm. For the UNA model, it was important to provide the population data for the extent of the municipality instead of the subwatersheds, as results are aggregated per polygon of the area of interest file. Also here, the UNA model only generates output for cells in which population data is provided.

For the decay function, the option "Gaussian" was selected based on two assumptions:

1. Urban green gets less attractive to people the further away they live (excluding the options "dichotomy" and "exponential")
2. The accessibility of the urban green right in front of someone's house is 1 (excluding the option "density").

Regarding the uniform search radius, the value of 800 m is based on this being the distance commonly walked during a 10-minute walk, in line with urban planning concepts such as the "10-minute city" (Emery & Thrift, 2021). Table 6 in Appendix I: Model inputs lists all the input data.

3.3.6. Modelling the 2006 situation

To assess the effects of the GSI on ecosystem service provisioning, a before and after comparison was done. For this, data from before 2011, when the reconstruction in the SRS started, had to be used. Throughout the models, the element that changes from the current situation to the "before" situation is the LULC map. This one is substituted with the LULC map from Urban Atlas for 2006 (European Union & European Environment Agency (EEA), 2015). No local data was added to the LULC map. The biophysical tables had to be adjusted according to the changes in the LULC map, resulting in removal of the categories buildings and green roofs. Moreover, in 2006 some agricultural, semi-natural and natural areas were still grouped together, which was accounted for in the biophysical table.

3.4. Neighbourhood Deprivation Index

As employed by Oudin Åström et al. (2020), the neighbourhood deprivation index (NDI) is an indicator based on mean disposable income, population with higher education, unemployed population, and population with social assistance within a neighbourhood. This definition was taken over in the present study and the NDI was calculated for each of the districts in Stockholm. Data was available from Statistik Sthlm's yearbook (2023).

To calculate the NDI, for each of the four indicators the minimum and maximum values were identified. All values were normalized based on the minimum and maximum values for each indicator and then divided by four to obtain a value between zero and one, as shown in Equation 1 (x_i being the value for the indicator in question in the district). It must be noted that this NDI is a relative measure, as it indicates a district's performance between the least deprived (NDI = 0) and the most deprived (NDI = 1) district for each indicator.

$$NDI_{district} = \frac{\Sigma_i \frac{x_i - max}{max - min}}{4} \qquad \textit{Equation 1}$$

3.5. Data analysis

To show hot and cold spots of ecosystem service provisioning in the current situation, a heatmap of the four ES was produced. Table 2 specifies which layer from each model was used for aggregation. For this, the values in each raster were reclassified on a scale from 0 to 10 from least ecosystem service provided to most ecosystem service provided and then overlayed using the "Weighted overlay" tool. Each raster was assigned equal weight (25%). Values are only displayed in the heatmap if all underlying layers have values in that location – for this, mostly the UNA layer was the limiting factor.

Table 2 Result layers per model incorporated in the heatmap for the current situation in Stockholm.

Model	Results layer used
Urban Flood Risk Mitigation (UFRM) model	Runoff retention (fraction per pixel)
Urban Stormwater Retention (USWR) model	Adjusted retention ratio (fraction per pixel)
Urban Cooling (UC) model	Heat mitigation index (ratio per pixel)
Urban Nature Access (UNA) model	Urban nature balance total population (m^2 nature over-/undersupply per pixel)

For assessing a potential correlation between the NDI and ES, zonal statistics were calculated for each of the services under the current situation per district in Stockholm, using ArcMap's "Zonal statistics as table" tool. This was done since the NDI is calculated on district level. From this, the means of each service in each district were extracted. Spearman's correlation coefficient rho, expressing the magnitude of correlation and the directionality (positive or negative), was then calculated using RStudio. RStudio also delivered the corresponding p-values, the likelihood of a difference being due to chance. A correlation was considered significant at a threshold of $p = 0.05$.

To assess a potential correlation between GSI implementation and delivery of ES, first the area in which the GSI was considered during construction was identified. Since no exact information was found on where the GSI had been implemented, areas where the official website of the SRS mentions sustainability considerations are counted as part of the GSI area (Stockholms Stad, n.d.).

This GSI area was then subjected to a before-and-after comparison. The ES values per pixel for the current situation and for the 2006 Urban Atlas data were extracted and then compared in RStudio by calculating the t-test statistics. Differences were considered significant at a threshold of $p = 0.05$.

Apart from the temporal comparison, also a spatial comparison was made. Within the SRS, three more areas have been fully redeveloped since 2011. However, sustainability was not a focal point there. To assess whether changes in ES might come about when areas are simply redeveloped according to current standards, the GSI area was compared to each of the three other redeveloped areas. Also here, ES values per pixel were extracted and the t-test statistics were calculated in RStudio. Finally, a comparison between the GSI area and another residential area in the SRS was conducted. The residential area has not been redeveloped, is of a similar size as the GSI area, and in close vicinity, meaning it is exposed to similar environments, which might influence the provision of ES. The different areas are marked in Figure 6.

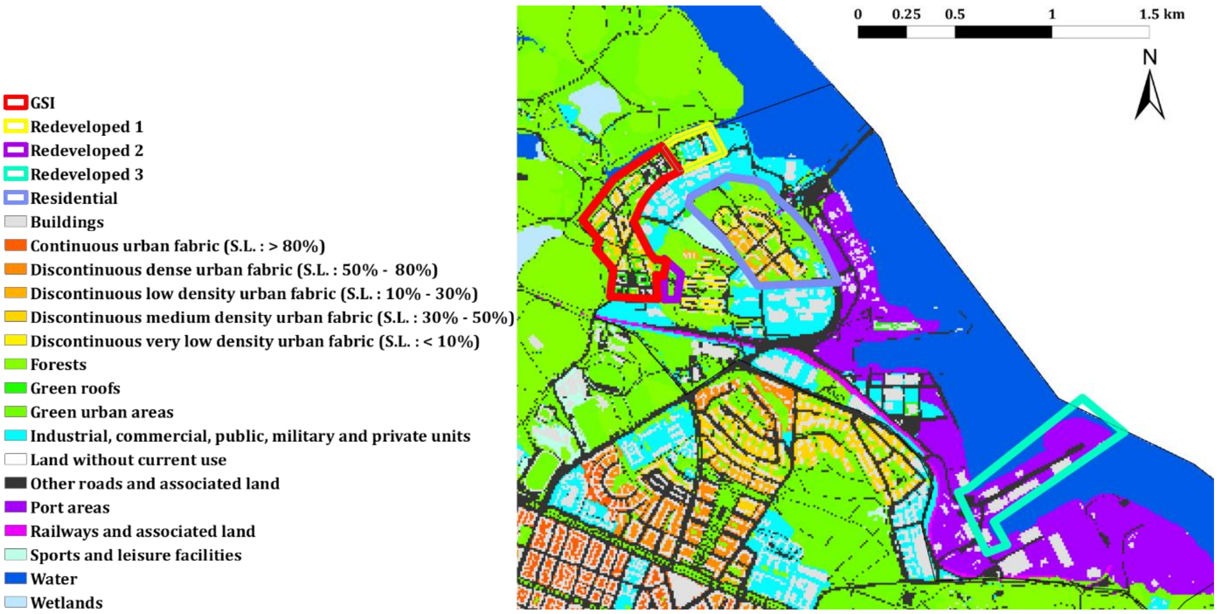

Figure 6 The different areas compared with each other for assessing the effect of the GSI (Green Space Index) within the Stockholm Royal Seaport Area, and the land use/land cover classes present in the area.

4. Results

4.1. Distribution of services in Stockholm

Stockholm city centre (defined as the districts of Norrmalm, Östermalm, Kungsholmen and Södermalm) is rather deprived of ES, as shown in the heatmap in Figure 7. Apart from the low availability in the centre, the ES appear to be evenly distributed in the remainder of the municipality. These general patterns also reappear in the maps of the services that are underlying the heatmap (Figure 8). Some cold spots outside of the city centre are noticeable in all the maps. This includes the Bromma/Stockholm airport in the northeast of the district Bromma. Industrial areas are typical cold spots: these are present in Rinkeby-Kista (including extensive parking lots), in the northwest of Spånga-Tensta, with a railway line leading towards the airport from there, the Västberga industrial area in Hägersten-Älsvjö, and the industrial area next to a highway in Enskede-Årsta-Vantör. The area of the Stockholm trade fair ("Stockholmsmässan") in Hägersten-Älsvjö is also visible as a cold spot.

Obvious hotspots of ES provisioning are in Bromma where extensive green structures are located: two nature reserves and a golf course. Moreover, Bromma has a focus on nature recreation with an allotment colony and a camping site. Apart from those, there are residential areas with single family homes and gardens. In Farsta, there is a wooded area designated for physical exercise ("Fagersjö motionsspår"). Östermalm has two natural areas: one in the north, the other in the south. The south part of Skarpnäck is occupied by one large nature reserve, which reappears in the maps as hotspots of ES availability. On large parts of the municipality's borders, Stockholm is surrounded by water and other natural areas such as forests, leading to high provision of ES at the borders. The UFRM model, the USWR model and the UNA model visually share these similarities most clearly, whereas in the UC model they are displayed more diffusely. However, the general trends are also visible there.

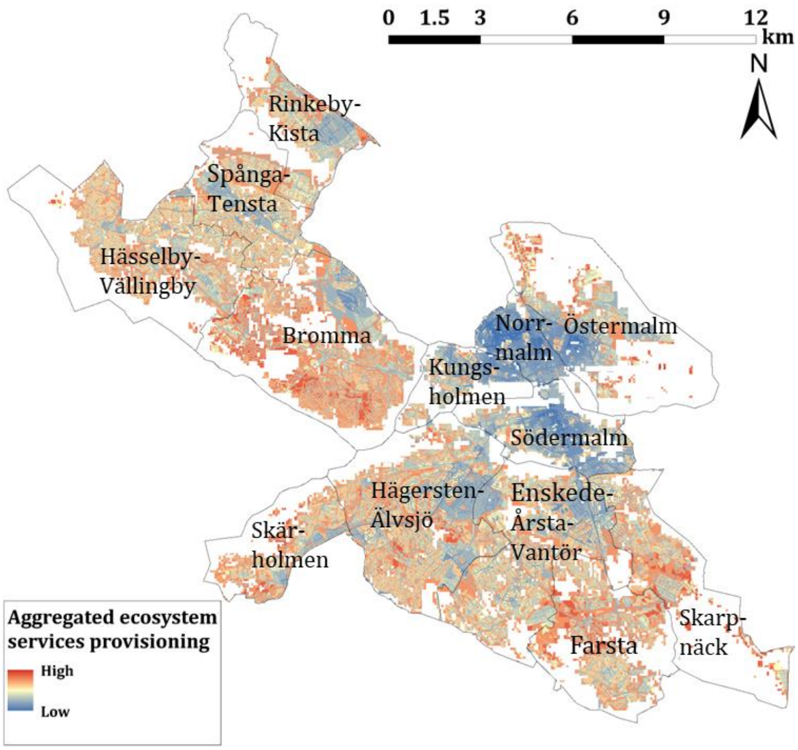

Figure 7 Heatmap combining the four ecosystem services (stormwater runoff retention, annual water retention, heat mitigation, and nature access) for the city of Stockholm. The results for all ecosystem services were classified according to the same scale before being overalyed, resulting in this map indicating where ecosystem services are present to a low or high extent.

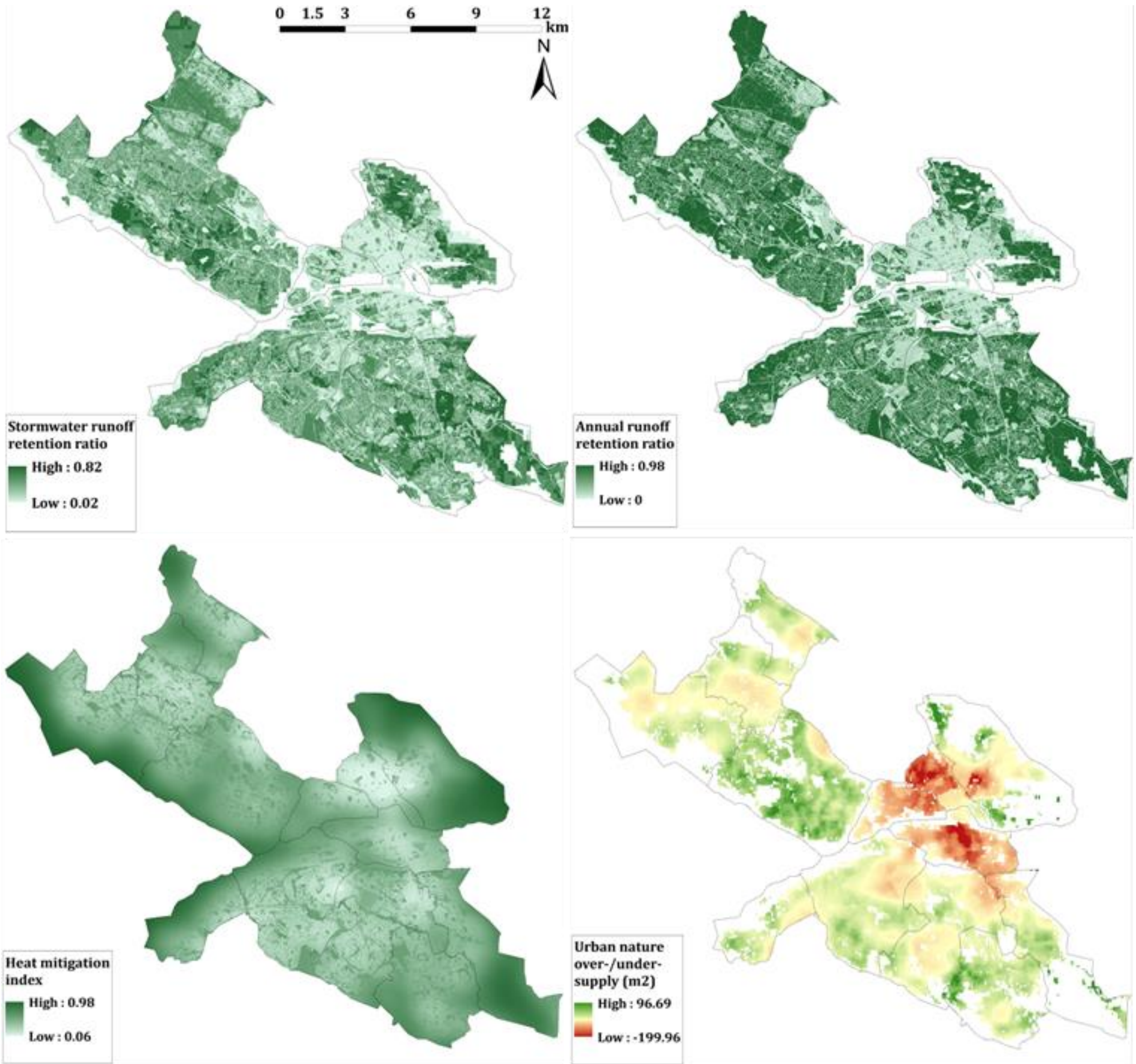

Figure 8 The four ecosystem services that make up the heatmap shown previously in Figure 6. Overall, trends visible in the individual maps are similar and come back in the combined heatmap.

4.2. Correlation between services and socio-economic opportunity

All services except for heat mitigation show a significant (p = 0.05) positive correlation between the service and the NDI values in each district (Figure 9, for correlation coefficients and exact p-values please refer to Table 7 in Appendix III: Results from the statistical analyses), indicating that districts with higher socio-economic opportunity are less well provided with stormwater retention, annual water retention, and nature access. At an aggregated score for the four different ES ("Mean service provisioning" in Figure 9), the correlation is not significant (p = 0.07). Since three of the four services individually do show a correlation, this is probably due to the influence of the heat mitigation index.

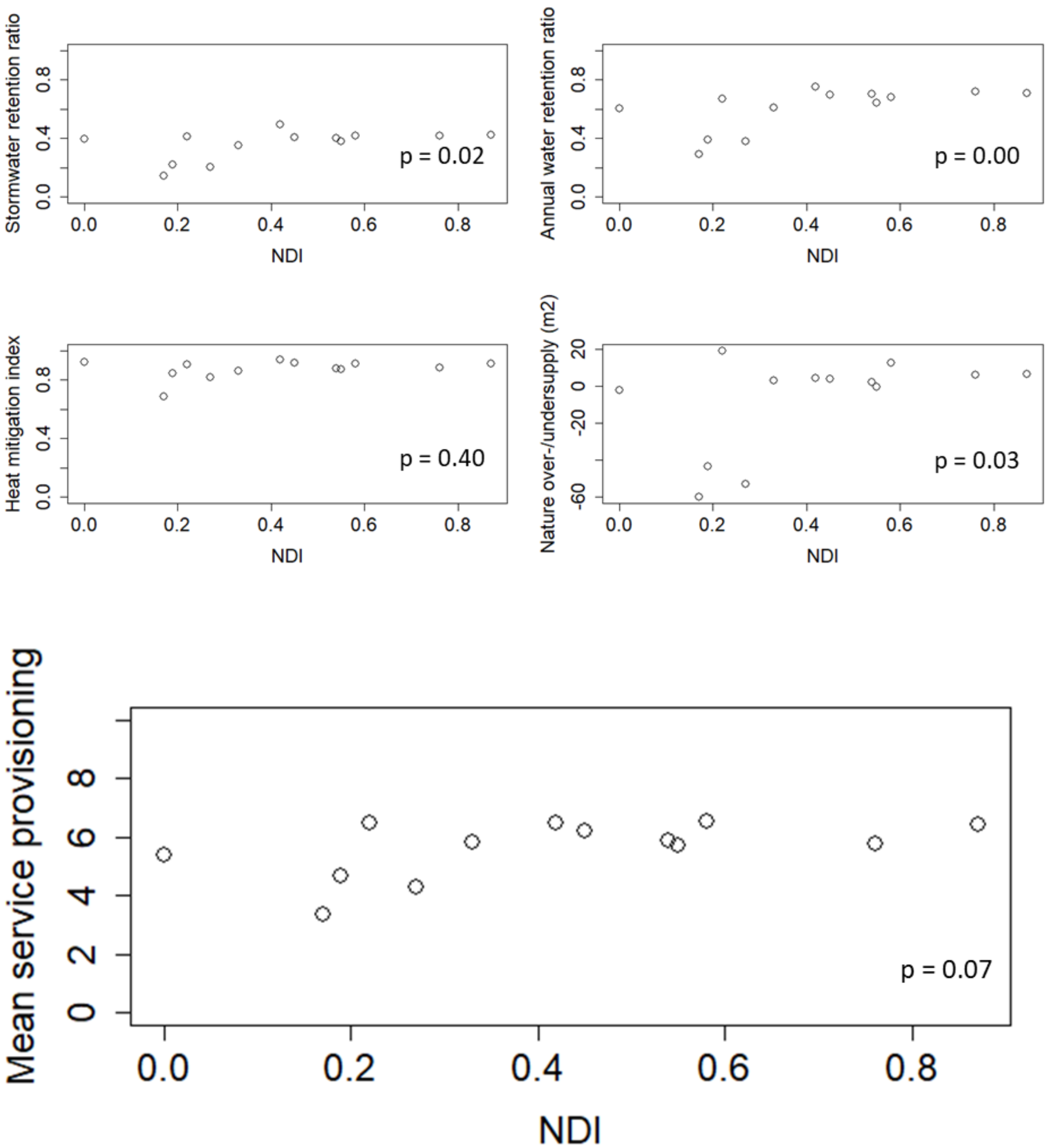

Figure 9 Bivariate scatter plots for each of the services versus the socio-economic opportunity in each district, expressed as neighbourhood deprivation index (NDI). The higher the NDI, the less socio-economic opportunity is present in a district. Mean service provisioning is an aggregate score of all the four services between 1 and 10, with higher values indicating more ecosystem services provided.

4.3. Effects of the Green Space Index

All comparisons to assess the effect of the GSI – before and after redevelopment of the area with the GSI and between the different areas – resulted in significant differences (see Appendix III: Results from the statistical analyses, Table 8 for correlation coefficients and p-values). As shown in Figure 10, the GSI area is performing worse for both water retention-related services when comparing with the situation before redevelopment, the residential area, and the second redeveloped area. The GSI area is also offering less heat mitigation than the first and the third redeveloped area. Only in terms of access to nature is the GSI area consistently performing better than the areas it is being compared to.

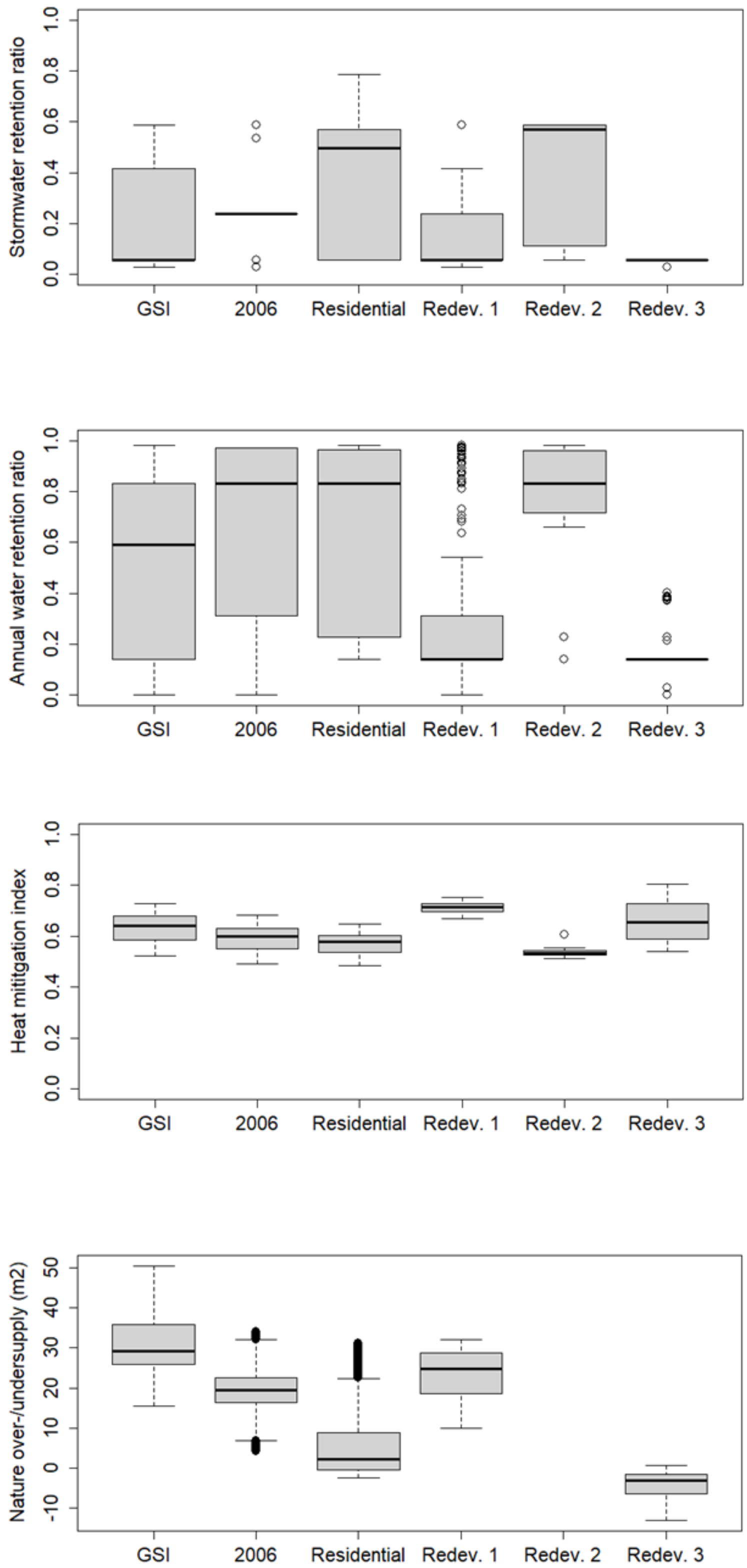

Figure 10 Boxplots of the four ecosystem services for all the different areas that are being compared for assessing the effect of the Green Space Index (GSI). Without exception, all comparisons made between the GSI and other areas resulted in significant (p = 0.05) differences. GSI: area that has been redeveloped as a residential area with sustainability criteria, 2006: GSI area before redevelopment, Residential: residential area in the same neighbourhood that has not been redeveloped, Redev. 1-3: three different areas in the same neighbourhood that have been redeveloped but without the GSI. The absence of a boxplot for nature over-/undersupply in Redev. 2 is due to a lack of data for that area.

5. Discussion

5.1. Assessment and implications of results

The analysis has revealed that ES in Stockholm are provided along a gradient from the city centre towards the outskirts of the city, with the centre having the lowest ES provided to them and the outskirts higher values. Given that ES by definition are provided by natural elements (Costanza et al., 2017), it is not surprising that districts with relatively large amounts of nature also have more ES present in them. The Stockholm city centre is densely developed and has therefore little space for natural elements (Stockholms Stad, 2018), thus little ES are available here.

The gradient from inner to outer city is mirrored in the gradient from high economic opportunity in the city centre to low economic opportunity in the outskirts. The results indicate that high economic opportunity in a district is correlated with low provisioning of stormwater retention, annual water retention, and nature access, since a higher NDI means that less socio-economic opportunity is present in a district. This is in line with studies in other European cities, such as in Bristol (Jones et al., 2009), Barcelona (Baró et al., 2015, 2016), Paris (Cohen et al., 2012), or Strasbourg (Selmi et al., 2021). All these studies found either a neutral or negative correlation between indicators of socio-economic wellbeing and the ES studied, underscoring the findings from this master's thesis.

Conversely, three studies with more ambiguous results were found. These studies entail Lakes et al. (2014) who investigated the distribution of green space and noise pollution in Berlin, and found a positive relationship between green space availability and economic opportunity. Regarding noise pollution, however, they also found a negative relationship. Two studies on Porto (Graça et al., 2017, 2018) also did not offer clear-cut results. While green spaces seem to be more abundant in socio-economically disadvantaged neighbourhoods, the quality of the ES these spaces offer is lower. Considering the results presented here, these findings imply caution – green spaces must not be equated directly with ES, and therefore the assessment of a green space as "eco-efficient" should be done carefully and critically, and ideally based on independent, quantitative assessments.

To further tie into the focus on the quality of green space, the generally higher provisioning of green spaces, and in many cases ES, in socio-economically more deprived neighbourhoods is no reason for immediate celebratory acts. As Jones et al. (2009) report from Bristol, even though less affluent citizens might have more green spaces close by, they make use of these spaces much less than their richer counterparts. This is explained by factors such as an overall poorer quality of the green spaces present, a reduced feeling of safety in these green areas, and limited walkability. Jennings et al. (2016) unearthed similar patterns in the United States and summarized these factors influencing green space usage under the term "social accessibility". This is rather more specific to cultural and recreational ES but shows that green spaces need to be explicitly designed for the function they are supposed to fulfil, with the services at the core: the mere presence of a green area will not suffice.

Moreover, a generally higher availability of ES in socio-economically disadvantaged districts does not automatically translate to all demands for ES being met. While more affluent citizens may substitute absent natural elements and their perks with technological solutions, for example air conditioning to combat the UHI effect, less affluent citizens may not have this opportunity (Wilkerson et al., 2018). In Stockholm, large quantities of the new developments from the coming decades are not planned in the affluent city centre, but in the outer districts (Stockholms Stad, 2018). The city planning must pay close attention to not compromise ES. Spatial planning must be done in such a way that ES are provided in communal spaces, so that also households in which ES cannot be substituted technologically or otherwise, are not disadvantaged.

In this context, it is also worthwhile to spend some time on the potential problem of green gentrification. Green gentrification is taking place when the introduction of green elements in a neighbourhood leads to increased living prices, driving socio-economically disadvantaged citizens out of said neighbourhood (Anguelovski et al., 2018). In their study of Barcelona, Anguelovski and colleagues identified former industrial areas that are being redeveloped to residential areas as being at a particular threat of gentrification. This redevelopment from industrial to residential area is happening in the SRS as well. With 140,000 new homes to be built throughout the whole city in the coming decades, it is likely that more formerly industrial areas are to be converted. Considering the findings of Anguelovski et al., the city of Stockholm should pay close attention to limiting gentrification when pushing for an increase in eco-efficient area.

The idea behind implementing a policy such as the GSI is that natural elements enhance multiple aspects of human wellbeing (Slätmo et al., 2019). However, there are very few studies on the actual impact of green area factors, such as the GSI, on ES. This lack of monitoring and evaluation of green area factors or similar policies in peer-reviewed literature was already noted by Juhola (2018) and Mendonça et al. (2021). But even in 2023, the situation has not changed much, as has become evident from a literature review. The present study in Stockholm therefore lays important groundwork for assessing the effectiveness of green area factors by quantifying the effect of a green space policy on the provisioning of ES with an external tool, after the green area factor has been implemented.

There are reasons for ES not yet being widely adopted in urban planning. A study by Kaczorowska et al. (2016) looked into (perceived) barriers to taking up ES in Stockholm's land use planning. The barriers include that a large quantity of development projects take place on private land, an existing gap between theory and practice, limited data accessibility for decision making, and the perception that workloads might increase considerably with taking up ES consideration. To all these barriers, the GSI may be seen as a solution. In the municipality of Stockholm, the GSI is obligatory for private developers, and the GSI can be interpreted as a translation of theoretical knowledge into practice. The way the Stockholm GSI is structured, it provides a comprehensive assessment of the eco-efficiency of a space, with relatively little data and work input necessary, as described by Stange et al. (2022). Moreover, when Stange and colleagues compared the Stockholm GSI to similar policy tools in Berlin and Oslo, it was found that it was hardest for an area to score high on the GSI. This finding implies that while the GSI is a tool with a relatively low application threshold, it is still strict and high scores are not easily achieved.

However, while the GSI is a good starting point, it is by no means a perfect solution. As became apparent from the Results, the area redeveloped with the GSI is performing worse for three out of the four ES, compared to both the residential and other redeveloped areas. The fact that the area developed with the GSI is performing worse in terms of water management is especially interesting, given that stormwater management is a vital driving force behind the development of green area factors in general (Stange et al., 2022).

Since precipitation values and soil groups do not differ much between the compared locations, the key to the differences between areas stems from the LULC categories assigned (see also Figure 6). Where the GSI has been applied, large areas are classified as road and medium density residential areas. The residential area has more mixed land uses, medium and low-density residential areas, forest, and green urban areas. The three redeveloped areas are classified on a spectrum from mostly green areas in redeveloped area 2 to a purely harbour area in redeveloped area 3. We then also see that the residential area and the redeveloped area 2, in which there is so much green space, are the ones performing better than the GSI area in terms of water retention.

These results show that the GSI, as it is expressed as one single number, must be applied with caution. It should be tailored to local needs, for example by first analysing which ES are in highest demand in an area and then choosing interventions to tackle that demand. Kaczorowska and Pont (2019; as described in Kaczorowska, 2020) already describe a comprehensive process of using several tools existing in Stockholm's city planning in concert to identify local needs. With this approach, the GSI interventions could be targeted to tackle the most pressing challenges in a neighbourhood. This is especially relevant as there will always be synergies as well as trade-offs between ES, and a single green area will not be able to address all local needs (Depietri, 2022).

As it is, the GSI is currently not directly valuing ES, but only does so "implicitly through qualitative weighting of blue-green surfaces and structures" (Stange et al., 2022). Transparency on trade-offs and synergies is lacking. Apart from incorporating additional tools in the GSI process based upon Kaczorowska and Pont (2019; as described in Kaczorowska, 2020), another approach could be to make the scoring of the GSI more transparent. This could be done following the example of the Green and Open Space Factor Vienna (GFF-V) (Ring et al., 2021), which in the opinion of the author has two main advantages over the GSI.

Firstly, the GFF-V is disaggregated into three different assessment categories (climatic factors, biodiversity, and wellbeing). These are not necessarily the categories that are most relevant to Stockholm, but disaggregating into several categories can give practitioners more insight into what they are influencing when faced with several GSI options. Secondly, the GFF-V is considering building façades and rooftops separately from the total area. Especially green façades may contribute substantially to ES such as biodiversity, noise reduction, or cooling. This could be a useful addition to the GSI and should be considered in future reviews of the tool.

5.2. Limitations and recommendations for future research

The Urban InVEST models have the potential to quantify more information on the different services than included in the present study. Especially the two water-related models could have yielded more insights on flood damage costs (UFRM model), water quality and potential replacement costs for water retention technology (USWR model). Due to unavailability of flood damage cost data and time constraints, these options were not exhausted. If this type of data can be obtained in the future, running the models with all capabilities will give more insight into the services provided by natural elements in Stockholm. As it is, the two water-based models yield rather similar results.

Data availability was also an issue in the core models. While it was possible to find suitable data from the United States, international sources or from studies done in similar contexts to the city of Stockholm (as in the case of data for the UC model), local data was often not readily available. In some cases, data might have been available, but a language barrier or a paywall prevented the researcher from accessing it. In future studies, having a researcher on the case who speaks the local language and who has closer connections with the local authorities who handle the kind of environmental data necessary as model input would be beneficial.

Especially in the case of the LULC maps, data availability might have affected the outcome of the models. For assessing the current situation, different sets of local data were combined to paint a rather comprehensive picture of the present moment, with any gaps being filled by the Urban Atlas data. Completely relying on the Urban Atlas data was not possible since mistakes in the LULC classification were present. For example, the area redeveloped with the GSI in the 2018 Urban Atlas was still classified as the broad category "Industrial, military and private units". Elements that were introduced due to the GSI, such as green roofs, were not represented at all in the Urban Atlas data, making it unsuitable for assessing effects of tools such as the GSI.

However, for assessing the situation prior to implementing the GSI (before 2011), data was scarce. Therefore, it was chosen to make use of the Urban Atlas 2006 dataset for running the models for the before scenario. The level of detail of the 2006 Urban Atlas map and the LULC map for the current situation are vastly different, and results obtained from this comparison should be considered under this lens. Any differences might give an indication of changes but might also for a considerable part be due to differences in input data. Future research should ascertain to make use of as much specific, fine grain data as possible to build any LULC map. Data from sources such as Urban Atlas should only be used as a last resort, if at all.

Correlation between ES and economic opportunity in this study was analysed on a district level, with each district having between 37,000 and 124,000 inhabitants. Other research considering neighbourhood deprivation in Sweden makes use of the unit of "small area market statistics" (SAMS), in which around 1,000 inhabitants are grouped together by Statistics Sweden (Li et al., 2014; Sariaslan et al., 2013; White et al., 2016). This was not done in the present research, as information on the SAMS was not readily available. However, since it has been applied successfully in other peer-reviewed research and offers a more fine-scale division of the city of Stockholm, it is recommended to make use of the SAMS in future research on neighbourhood deprivation.

Assessing the effect of implementing the GSI is currently only possible on a case study basis, and therefore only limited general conclusions about the GSI can be drawn. This is due to the SRS being the only location in which developments adhering to the GSI have been built (P. Qvist, personal communication, 30 May 2023). Since the same GSI score can be achieved with several different measures, it is not possible to make statements such as the GSI being beneficial or detrimental to a particular service. The sample size is also too small to assess any "dosage-effect" relationships, whether a higher GSI score always coincides with a higher provisioning of ES.

Before more resources and time are spent on developments that adhere to strict GSI scores, and effects of this are experienced only in the aftermath, it is recommended that scenario analyses are made which quantify the effect of these interventions with external models. This way, the usefulness of the GSI as a tool can be assessed, and conclusions can be drawn on whether the GSI by itself is sufficient to promote ES. Such a scenario analysis could be modelled after the study of Kain et al. (2016), where scenarios mostly consist of land use changes according to rules based on development plans, policies, and expert input.

Currently, achieving a GSI score of 0.6 is obligatory for any new private developments in Stockholm. However, developments on public land, which makes up 70% of the municipality's area, do not need to adhere to GSI targets. Conducting a scenario analysis in which public land is redeveloped with a certain GSI, in addition to being able to assess the effects of the GSI, has the benefit of providing a basis on which the Stockholm authorities could decide on whether GSI targets should also be made compulsory for public land developments. After all, if positive effects on the provisioning of ES become apparent from such an analysis, it would seem a logical first step to make it compulsory for public land.

Finally, the assessment in the present study was focussed on the ES of stormwater retention, annual water retention, heat mitigation and nature access. While these are relevant in the urban context in general as well as in Stockholm specifically, the GSI itself was designed to deal with social and recreational ES, stormwater management, noise pollution, microclimate regulation, and pollination. Therefore, in future assessments it would be fair to assess the GSI by its own standards and research the effect it is having on this particular set of ES.

6. Conclusions

The aim of this thesis was threefold. Firstly, to provide an overview of the current distribution of ecosystem services (ES) in the city of Stockholm; secondly, to test for a potential correlation between ES availability and socio-economic opportunity; and thirdly, to test for differences in ES availability between an area where the Green Space Index (GSI) had been implemented, and areas without the GSI. Specifically, the ES of flood risk mitigation, annual water retention, heat mitigation, and nature access were assessed.

The analysis revealed that ES in Stockholm are present along a gradient, from low availability in the city centre to higher availability towards the outskirts. Districts with more natural areas offer a higher availability of ES, while in areas with more industrial activity the quantity of services provided is lower. Moreover, it was found that economic opportunity in a district is correlated with stormwater retention, annual water retention, and nature access. The higher the economic opportunity in a district, the less of these three services is available.

The area in which the GSI had been implemented is significantly different from all the areas it was compared to, be it the before-after-comparison, the comparisons with the three other areas that were redeveloped without considering the GSI, or the other residential area in the vicinity. Due to different types of land uses, however, water retention (both, stormwater and annual) is lower in the GSI area compared with the situation prior to redevelopment, the residential area, and one of the three other redeveloped areas. For heat mitigation, the GSI area performs worse than two of the redeveloped areas. Only in the case of nature access does the GSI area consistently perform better than the other areas.

These findings lead to several relevant conclusions. While in the current situation socio-economically disadvantaged districts seem to profit from a higher availability of natural elements and their benefits, it should be ascertained that the quality of natural elements in these districts is sufficient to provide ES, and that demands for ES are being met. This monitoring is especially vital in the coming decades, when 140,000 new homes are to be built, mainly in the outer districts.

In its current form the GSI is rather untransparent, as it is an aggregated score of multiple services. Therefore, is recommended to embed the GSI in a workflow in which first the needs of an area in terms of ES are determined, before deciding on the most suitable GSI measures to meet these needs. Alternatively, the GSI could be disaggregated into several assessment categories, to give developers more insights into which ES are affected by which GSI measure.

Future research should focus on assessing the effects of the GSI. This could be done either in the form of scenario analysis to assess potential effects, or by repeating the comparison of different areas, with and without GSI, once more developments with the GSI have been built. This way, its effectiveness in not only increasing eco-efficient surface in Stockholm, but in satisfying demand for ES can be assessed. Satisfying demand for ES should then also be considered the main objective of applying the GSI. Depending on the outcome of this assessment, recommendations can be given as to whether the GSI should be made compulsory for developments in public space.

The present thesis has identified potentially vulnerable locations for ES availability. Moreover, Stockholm's GSI has been assessed in a first case study, pointing to some weaknesses in the design of the tool. It is hoped that this research can contribute to a more complete picture of ES provisioning in Stockholm and that it can support the city administration in effectively promoting urban design solutions for meeting demand for ES.

References

© Lantmäteriet. (2021). *Fastighetskartan Kommunikation latest, Property map Transport networks* [Vector, shapefile].

Adem Esmail, B., Cortinovis, C., Suleiman, L., Albert, C., Geneletti, D., & Mörtberg, U. (2022). Greening cities through urban planning: A literature review on the uptake of concepts and methods in Stockholm. *Urban Forestry & Urban Greening*, *72*, 127584. https://doi.org/10.1016/j.ufug.2022.127584

Anguelovski, I., Connolly, J. J. T., Masip, L., & Pearsall, H. (2018). Assessing green gentrification in historically disenfranchised neighborhoods: A longitudinal and spatial analysis of Barcelona. *Urban Geography*, *39*(3), 458–491. https://doi.org/10.1080/02723638.2017.1349987

Aronson, M. F. J., La Sorte, F. A., Nilon, C. H., Katti, M., Goddard, M. A., Lepczyk, C. A., Warren, P. S., Williams, N. S. G., Cilliers, S., Clarkson, B., Dobbs, C., Dolan, R., Hedblom, M., Klotz, S., Kooijmans, J. L., Kühn, I., MacGregor-Fors, I., McDonnell, M., Mörtberg, U., … Winter, M. (2014). A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1780), 20133330. https://doi.org/10.1098/rspb.2013.3330

Baró, F., Haase, D., Gómez-Baggethun, E., & Frantzeskaki, N. (2015). Mismatches between ecosystem services supply and demand in urban areas: A quantitative assessment in five European cities. *Ecological Indicators*, *55*, 146–158. https://doi.org/10.1016/j.ecolind.2015.03.013

Baró, F., Palomo, I., Zulian, G., Vizcaino, P., Haase, D., & Gómez-Baggethun, E. (2016). Mapping ecosystem service capacity, flow and demand for landscape and urban planning: A case study in the Barcelona metropolitan region. *Land Use Policy*, *57*, 405–417. https://doi.org/10.1016/j.landusepol.2016.06.006

Baryła, A., Karczmarczyk, A., Wróbel, M., & Kożuchowski, P. (2017). WATER RETENTION ON THE EXTENSIVE GREEN ROOF MODELS. *Infrastruktura i Ekologia Terenów Wiejskich / Infrastructure and Ecology of Rural Areas*, *IV/2/2107*, 1649–1658. https://doi.org/10.14597/infraeco.2017.4.2.124

Blumenthal, B., Haas, J., & Andersson, J.-O. (2018). *A GIS-based multivariate approach to identify flood damage affecting factors* [Preprint]. Risk Assessment, Mitigation and Adaptation Strategies, Socioeconomic and Management Aspects. https://doi.org/10.5194/nhess-2018-286

Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics*, *29*(2), 293–301. https://doi.org/10.1016/S0921-8009(99)00013-0

Bondarenko, M., Kerr, D., Sorichetta, A., & Tatem, A. (2020). *Census/projection-disaggregated gridded population datasets for 189 countries in 2020 using Built-Settlement Growth Model (BSGM) outputs* [Data set]. University of Southampton. https://doi.org/10.5258/SOTON/WP00684

Borelli, S., Conigliaro, M., & Salbitano, F. (2021). The Social Impacts of NBS: Access to and Accessibility of Green Spaces As a Measure of Social Inclusiveness and Environmental Justice. In E. Croci & B. Lucchitta (Eds.), *Nature-Based Solutions for More Sustainable Cities – A*

Framework Approach for Planning and Evaluation (pp. 211–224). Emerald Publishing Limited. https://doi.org/10.1108/978-1-80043-636-720211018

Bosch, M., Locatelli, M., Hamel, P., Remme, R. P., Chenal, J., & Joost, S. (2021). A spatially explicit approach to simulate urban heat mitigation with InVEST (v3.8.0). *Geoscientific Model Development*, *14*(6), 3521–3537. https://doi.org/10.5194/gmd-14-3521-2021

Boverket. (2020, December 23). *Grönytefaktor – räkna med ekosystemtjänster*. Boverket. https://www.boverket.se/sv/PBL-kunskapsbanken/teman/ekosystemtjanster/verktyg/gronytefaktor/

Boverket. (2021, July 14). *Grönytefaktor för kvartersmark*. Boverket. https://www.boverket.se/sv/PBL-kunskapsbanken/teman/ekosystemtjanster/verktyg/gronytefaktor/kvartersmark/

Burkhard, B., Kroll, F., Nedkov, S., & Müller, F. (2012). Mapping ecosystem service supply, demand and budgets. *Ecological Indicators*, *21*, 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019

C/O City. (2018). *Grönytefaktor för allmän platsmark 2.0*. https://www.cocity.se/wp-content/uploads/2018/06/gyf-ap-20-manual_lagupplost.pdf

Cohen, M., Baudoin, R., Palibrk, M., Persyn, N., & Rhein, C. (2012). Urban biodiversity and social inequalities in built-up cities: New evidences, next questions. The example of Paris, France. *Landscape and Urban Planning*, *106*(3), 277–287. https://doi.org/10.1016/j.landurbplan.2012.03.007

Colding, J. (2013). Chapter 17—Local Assessment of Stockholm: Revisiting the Stockholm Urban Assessment. In T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, S. Parnell, M. Schewenius, M. Sendstad, K. C. Seto, & C. Wilkinson (Eds.), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities* (pp. 313–336). Springer Netherlands. https://doi.org/10.1007/978-94-007-7088-1

Colding, J., Elmqvist, T., Lundberg, J., Ahrné, K., Andersson, E., Barthel, S., Borgström, S., Duit, A., Ernstsson, H., & Tengö, M. (2004). Beijer Discussion Paper 182: The Stockholm Urban Assessment (SUA-Sweden). *Beijer Discussion Paper Series*.

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., & Grasso, M. (2017). Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosystem Services*, *28*, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008

Dahlberg, A., Borgström, S., Rautenberg, M., & Sluimer, N. (2022). A Nearby Park or Forest Can Become Mount Everest. Access to Urban Green Areas by People in Wheelchair from an Environmental Justice Perspective: A Stockholm Case. In B. Plüschke-Altof & H. Sooväli-Sepping (Eds.), *Whose Green City? : Contested Urban Green Spaces and Environmental Justice in Northern Europe* (pp. 19–40). Springer International Publishing. https://doi.org/10.1007/978-3-031-04636-0_2

Depietri, Y. (2022). Planning for urban green infrastructure: Addressing tradeoffs and synergies. *Current Opinion in Environmental Sustainability*, *54*, 101148. https://doi.org/10.1016/j.cosust.2021.12.001

Emery, T., & Thrift, J. (2021). *20-Minute Neighbourhoods—Creating healthier, active, prosperous communities. An introduction for council planners in England*. Town and Country Planning Association (TCPA). https://www.tcpa.org.uk/wp-content/uploads/2021/11/final_20mnguide-compressed.pdf

European Commission & Copernicus. (2020). *Mapping Guide v6.3 for a European Urban Atlas*. European Union. https://land.copernicus.eu/user-corner/technical-library/urban_atlas_2012_2018_mapping_guide_v6.3

European Union & European Environment Agency (EEA). (2015). *Urban Atlas 2006—Copernicus Land Monitoring Service* [Land item]. https://land.copernicus.eu/local/urban-atlas/urban-atlas-2006

European Union & European Environment Agency (EEA). (2021a). *Street Tree Layer (STL) 2018—Copernicus Land Monitoring Service* [Land item]. https://land.copernicus.eu/local/urban-atlas/street-tree-layer-stl-2018

European Union & European Environment Agency (EEA). (2021b). *Urban Atlas 2018—Copernicus Land Monitoring Service* [Land item]. https://land.copernicus.eu/local/urban-atlas/urban-atlas-2018

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302–4315. https://doi.org/10.1002/joc.5086

Frumkin, H., Bratman, G. N., Breslow, S. J., Cochran, B., Kahn, J. P. H., Lawler, J. J., Levin, P. S., Tandon, P. S., Varanasi, U., Wolf, K. L., & Wood, S. A. (2017). Nature Contact and Human Health: A Research Agenda. *Environmental Health Perspectives*, *125*(7), 075001. https://doi.org/10.1289/EHP1663

Goldenberg, R., Kalantari, Z., Cvetkovic, V., Mörtberg, U., Deal, B., & Destouni, G. (2017). Distinction, quantification and mapping of potential and realized supply-demand of flow-dependent ecosystem services. *Science of The Total Environment*, *593–594*, 599–609. https://doi.org/10.1016/j.scitotenv.2017.03.130

Gómez-Baggethun, E., Gren, Å., Barton, D. N., Langemeyer, J., McPhearson, T., O'Farrell, P., Andersson, E., Hamstead, Z., & Kremer, P. (2013). Urban Ecosystem Services. In T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, S. Parnell, M. Schewenius, M. Sendstad, K. C. Seto, & C. Wilkinson (Eds.), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment* (pp. 175–251). Springer Netherlands. https://doi.org/10.1007/978-94-007-7088-1_11

Graça, M. S., Alves, P., Gonçalves, J., Nowak, D. J., Hoehn, R., Farinha-Marques, P., & Cunha, M. (2018). Assessing how green space types affect ecosystem services delivery in Porto, Portugal. *Landscape and Urban Planning*, *170*, 195–208. https://doi.org/10.1016/j.landurbplan.2017.10.007

Graça, M. S., Gonçalves, J. F., Alves, P. J. M., Nowak, D. J., Hoehn, R., Ellis, A., Farinha-Marques, P., & Cunha, M. (2017). Assessing mismatches in ecosystem services proficiency across the urban fabric of Porto (Portugal): The influence of structural and socioeconomic variables. *Ecosystem Services*, *23*, 82–93. https://doi.org/10.1016/j.ecoser.2016.11.015

Haines-Young, R., & Potschin, M. (2010). The links between biodiversity, ecosystem services and human well-being. In D. G. Raffaelli & C. L. J. Frid (Eds.), *Ecosystem Ecology* (1st ed., pp. 110–139). Cambridge University Press. https://doi.org/10.1017/CBO9780511750458.007

Haines-Young, R., & Potschin, M. (2013). *Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012* (p. 34).

Hamel, P., Guerry, A. D., Polasky, S., Han, B., Douglass, J. A., Hamann, M., Janke, B., Kuiper, J. J., Levrel, H., Liu, H., Lonsdorf, E., McDonald, R. I., Nootenboom, C., Ouyang, Z., Remme, R. P., Sharp, R. P., Tardieu, L., Viguié, V., Xu, D., … Daily, G. C. (2021). Mapping the benefits of nature in cities with the InVEST software. *Npj Urban Sustainability*, *1*(25), Article 1. https://doi.org/10.1038/s42949-021-00027-9

Herreros-Cantis, P., & McPhearson, T. (2021). Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. *Ecological Applications*, *31*(6), e02390. https://doi.org/10.1002/eap.2390

Hopkins, R. A. (2021). *Public urban green space: Exploring priorities and challenges for managing and valuing green space, using Stockholm as a case study*. KTH Royal Institute of Technology.

Huang, Y., Tian, Z., Ke, Q., Liu, J., Irannezhad, M., Fan, D., Hou, M., & Sun, L. (2020). Nature-based solutions for urban pluvial flood risk management. *WIREs Water*, *7*(3), e1421. https://doi.org/10.1002/wat2.1421

JayantaPoddar. (2021, July 4). *Fill Raster holes with nearest neighbour*. Esri Community. https://community.esri.com/t5/arcgis-spatial-analyst-questions/fill-raster-holes-with-nearest-neighbour/m-p/1077176#M11363

Jennings, V., Larson, L., & Yun, J. (2016). Advancing Sustainability through Urban Green Space: Cultural Ecosystem Services, Equity, and Social Determinants of Health. *International Journal of Environmental Research and Public Health*, *13*(2), Article 2. https://doi.org/10.3390/ijerph13020196

Jones, A., Hillsdon, M., & Coombes, E. (2009). Greenspace access, use, and physical activity: Understanding the effects of area deprivation. *Preventive Medicine*, *49*(6), 500–505. https://doi.org/10.1016/j.ypmed.2009.10.012

Juhola, S. (2018). Planning for a green city: The Green Factor tool. *Urban Forestry & Urban Greening*, *34*, 254–258. https://doi.org/10.1016/j.ufug.2018.07.019

Kaczorowska, A. (2020). Urban Transformation and Implementation of Green Development Strategies – Case of Gothenburg. *IOP Conference Series: Earth and Environmental Science*, *588*(5), 052004. https://doi.org/10.1088/1755-1315/588/5/052004

Kaczorowska, A., Kain, J.-H., Kronenberg, J., & Haase, D. (2016). Ecosystem services in urban land use planning: Integration challenges in complex urban settings—Case of Stockholm. *Ecosystem Services*, *22*, 204–212. https://doi.org/10.1016/j.ecoser.2015.04.006

Kaczorowska, A., & Pont, M. B. (2019). Modelling Urban Environments to Promote Ecosystem Services and Biodiversity: Case of Stockholm. *International Journal of E-Planning Research*, *8*(3), 1–12. https://doi.org/10.4018/IJEPR.2019070101

Kain, J.-H., Larondelle, N., Haase, D., & Kaczorowska, A. (2016). Exploring local consequences of two land-use alternatives for the supply of urban ecosystem services in Stockholm year 2050. *Ecological Indicators*, *70*, 615–629. https://doi.org/10.1016/j.ecolind.2016.02.062

Kart- och geodataservice. (2023). *Stadskarta* [Map]. Stockholms stadsbyggnadskontor Stadsmätningsavdelningen. https://dataportalen.stockholm.se/dataportalen/Data/Stadsbyggnadskontoret/Stockholm.zip

Lakes, T., Brückner, M., & Krämer, A. (2014). Development of an environmental justice index to determine socio-economic disparities of noise pollution and green space in residential areas in Berlin. *Journal of Environmental Planning and Management*, *57*(4), 538–556. https://doi.org/10.1080/09640568.2012.755461

Langhans, K. E., Echeverri, A., Daws, S. C., Moss, S. N., Anderson, C. B., Chaplin-Kramer, R., Hendershot, J. N., Liu, L., Mandle, L., Nguyen, O., Ou, S. X., Remme, R. P., Schmitt, R. J. P., Vogl, A., & Daily, G. C. (2023). Centring justice in conceptualizing and improving access to urban nature. *People and Nature*, *n/a*(n/a). https://doi.org/10.1002/pan3.10470

Lennartsson, M., & Salmhofer, C. (2017). *Stockholm Royal Seaport—Road Map*. Stockholms Stad. https://vaxer.stockholm/globalassets/omraden/-stadsutvecklingsomraden/ostermalm-norra-djurgardsstaden/royal-seaport/a-sustainable-urban-district/road-map/srs_roadmap_20170927.pdf

Lewis, T. C. (2019, May 13). *The Natural Capital Project* [Text]. Natural Capital Project. https://naturalcapitalproject.stanford.edu/who-we-are/natural-capital-project

Li, X., Memarian, E., Sundquist, J., Zöller, B., & Sundquist, K. (2014). Neighbourhood Deprivation, Individual-Level Familial and Socio-Demographic Factors and Diagnosed Childhood Obesity: A Nationwide Multilevel Study from Sweden. *Obesity Facts*, *7*(4), 253–263. https://doi.org/10.1159/000365955

Lundqvist, D., Ek, A., Olsson, G., & Brännlund, F. (2021). *Uppdatering av GYF för kvartersmark 2021*.

Mendonça, R., Roebeling, P., Fidélis, T., & Saraiva, M. (2021). Policy Instruments to Encourage the Adoption of Nature-Based Solutions in Urban Landscapes. *Resources*, *10*(8), Article 8. https://doi.org/10.3390/resources10080081

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis*. Island Press.

Mörtberg, U., Goldenberg, R., Kalantari, Z., Kordas, O., Deal, B., Balfors, B., & Cvetkovic, V. (2017). Integrating ecosystem services in the assessment of urban energy trajectories – A study of the Stockholm Region. *Energy Policy*, *100*, 338–349. https://doi.org/10.1016/j.enpol.2016.09.031

Natural Capital Project. (2022). *InVEST 3.13.0.post6+ug.g6b07b42 User's Guide*. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, and Stockholm Resilience Centre. https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/en/index.html

Natural Resources Conservation Service (NRCS). (1986). *Urban hydrology for small watersheds. Technical release 55*. US Department of Agriculture. https://www.nrc.gov/docs/ML1421/ML14219A437.pdf

Oudin Åström, D., Åström, C., Forsberg, B., Vicedo-Cabrera, A. M., Gasparrini, A., Oudin, A., & Sundquist, K. (2020). Heat wave–related mortality in Sweden: A case-crossover study investigating effect modification by neighbourhood deprivation. *Scandinavian Journal of Public Health*, *48*(4), 428–435. https://doi.org/10.1177/1403494818801615

Qvist, P. (2023, May 30). *Application of the GYF* [Personal communication].

Rawls, W. J., Wong, S. L., & McCuen, R. H. (1981). *Comparison of Urban Flood Frequency Procedures*. US Department of Agriculture. https://export.amlegal.com/media/

3bff82e2e68ab02700e98a44f427d3ad62f44c27/DATAOBJECTS/0-0-0-1543.pdf

Remme, R. P., Frumkin, H., Guerry, A. D., King, A. C., Mandle, L., Sarabu, C., Bratman, G. N., Giles-Corti, B., Hamel, P., Han, B., Hicks, J. L., James, P., Lawler, J. J., Lindahl, T., Liu, H., Lu, Y., Oosterbroek, B., Paudel, B., Sallis, J. F., … Daily, G. C. (2021). An ecosystem service perspective on urban nature, physical activity, and health. *Proceedings of the National Academy of Sciences*, *118*(22), e2018472118. https://doi.org/10.1073/pnas.2018472118

Ring, Z., Damyanovic, D., & Reinwald, F. (2021). Green and open space factor Vienna: A steering and evaluation tool for urban green infrastructure. *Urban Forestry & Urban Greening*, *62*, 127131. https://doi.org/10.1016/j.ufug.2021.127131

Roehr, D., & Kong, Y. (2010). Runoff Reduction Effects of Green Roofs in Vancouver, BC, Kelowna, BC, and Shanghai, P.R. China. *Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques*, *35*(1), 53–68. https://doi.org/10.4296/cwrj3501053

Ross, C. W., Prihodko, L., Anchang, J., Kumar, S., Ji, W., & Hanan, N. P. (2018). *Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling* [Data set]. ORNL Distributed Active Archive Center. https://doi.org/10.3334/ORNLDAAC/1566

Russo, A., & Cirella, G. T. (2018). Modern Compact Cities: How Much Greenery Do We Need? *International Journal of Environmental Research and Public Health*, *15*(10), 2180. https://doi.org/10.3390/ijerph15102180

Salmhofer, C., & Ek, A. (2021). *GYF-Grönytefaktor för kvartersmark. Norra Djurgårdsstaden*. Stockholms Stad.

Sariaslan, A., Långström, N., D'Onofrio, B., Hallqvist, J., Franck, J., & Lichtenstein, P. (2013). The impact of neighbourhood deprivation on adolescent violent criminality and substance misuse: A longitudinal, quasi-experimental study of the total Swedish population. *International Journal of Epidemiology*, *42*(4), 1057–1066. https://doi.org/10.1093/ije/dyt066

Selmi, W., Selmi, S., Teller, J., Weber, C., Rivière, E., & Nowak, D. J. (2021). Prioritizing the provision of urban ecosystem services in deprived areas, a question of environmental justice. *Ambio*, *50*(5), 1035–1046. https://doi.org/10.1007/s13280-020-01438-1

Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*(40), 16083–16088. https://doi.org/10.1073/pnas.1211658109

Slätmo, E., Nilsson, K., & Turunen, E. (2019). Implementing Green Infrastructure in Spatial Planning in Europe. *Land*, *8*(4), Article 4. https://doi.org/10.3390/land8040062

Stange, E. E., Barton, D. N., Andersson, E., & Haase, D. (2022). Comparing the implicit valuation of ecosystem services from nature-based solutions in performance-based green area indicators across three European cities. *Landscape and Urban Planning*, *219*, 104310. https://doi.org/10.1016/j.landurbplan.2021.104310

Statistik Sthlm. (2023, January 11). *Statistisk årsbok—Stockholms stad*. https://start.stockholm/om-stockholms-stad/utredningar-statistik-och-fakta/statistik/statistisk-arsbok/

Stewart, I. D., & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Stockholms Stad. (n.d.). *City development map*. Stockholm Royal Seaport 2030. Retrieved 6 June 2023, from https://www.norradjurgardsstaden2030.se/map

Stockholms Stad. (2017). *The City of Stockholm's Environmental Work*. https://miljobarometern.stockholm.se/content/docs/tema/Environmental-Work-Stockholm-2017.pdf

Stockholms Stad. (2018). *Stockholm City Plan*. https://vaxer.stockholm/globalassets/tema/oversiktplan-ny_light/english_stockholm_city_plan.pdf

Stockholms Stad. (2021a). *Stockholm Royal Seaport Sustainability Report 2020*.

Stockholms Stad. (2021b, May 27). *Stadens byggnader och mark—Stockholms stad*. https://start.stockholm/om-stockholms-stad/utredningar-statistik-och-fakta/stadens-byggnader-och-mark/

Stockholms Stad. (2022a, November 23). *C/O City: Green structures as active components in the urban environment*. Stockholm Royal Seaport 2030. https://www.norradjurgardsstaden2030.se/innovations/cocity

Stockholms Stad. (2022b, November 24). *Sustainable Urban Development*. Norra Djurgårdsstaden 2030. https://www.norradjurgardsstaden2030.se/results/let-nature-do-the-work#structures%20

Stockholms Stad. (2023, February 16). *Hållbarhetskrav vid byggande—Stockholms stad*. https://tillstand.stockholm/tillstand-regler-och-tillsyn/lokal-och-fastigheter/hallbarhetskrav-vid-byggnation/

Susca, T., Gaffin, S. R., & Dell'Osso, G. R. (2011). Positive effects of vegetation: Urban heat island and green roofs. *Environmental Pollution*, *159*(8), 2119–2126. https://doi.org/10.1016/j.envpol.2011.03.007

Sveriges meteorologiska och hydrologiska institut (SMHI). (n.d.-a). *Ladda ner meteorologiska observationer: Stockholm—Observatoriekullen A | SMHI*. Retrieved 6 June 2023, from https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=core,stationid=98230

Sveriges meteorologiska och hydrologiska institut (SMHI). (n.d.-b). *Ladda ner meteorologiska observationer: Stockholm—Observatoriekullen A | SMHI*. Retrieved 6 June 2023, from https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airHumidity,stations=core,stationid=98230

Sveriges meteorologiska och hydrologiska institut (SMHI). (n.d.-c). *Ladda ner meteorologiska observationer: Tullinge A | SMHI*. Retrieved 6 June 2023, from https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=core,stationid=97100

Sveriges meteorologiska och hydrologiska institut (SMHI). (2022). *Utforskaren—Öppna data*. https://www.smhi.se/data/utforskaren-oppna-data/huvud-och-delavrinningsomraden-vattendelare-svar2012-datamangd

Teutschbein, C., Albrecht, F., Blicharska, M., Tootoonchi, F., Stenfors, E., & Grabs, T. (2023). Drought hazards and stakeholder perception: Unraveling the interlinkages between drought severity, perceived impacts, preparedness, and management. *Ambio*, *52*(7), 1262–1281. https://doi.org/10.1007/s13280-023-01849-w

Thurin, S. (2018). *Skyfallsmodellering Stockholm Stad*. Stockholm Vatten och Avfall. https://miljobarometern.stockholm.se/content/docs/tema/klimat/skyfall/skyfallsmodellering/WSP-Rapport-uppdaterad-skyfallsmodellering-Stockholm-2018.pdf

Trabucco, A., & Zomer, R. (2022). *Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database v3* (p. 6086879943 Bytes) [Data set]. figshare. https://doi.org/10.6084/M9.FIGSHARE.7504448.V4

United States Environmental Protection Agency. (n.d.). *Principles of Watershed Management | Watershed Academy Web | US EPA*. Retrieved 5 July 2023, from https://cfpub.epa.gov/watertrain/moduleFrame.cfm?parent_object_id=465&object_id=468

Veerkamp, C. J., Loreti, M., Benavidez, R., Jackson, B., & Schipper, A. M. (2023). Comparing three spatial modeling tools for assessing urban ecosystem services. *Ecosystem Services*, *59*, 101500. https://doi.org/10.1016/j.ecoser.2022.101500

Vojinovic, Z. (2020). 6. NBS for flood mitigation and coastal reslience. In T. Freitas, S. Vandewoestijne, & T. Wild (Eds.), *Nature-based solution—State of the art in EU funded projects* (pp. 105–137). Publications Office of the European Union. https://data.europa.eu/doi/10.2777/236007

White, J. S., Hamad, R., Li, X., Basu, S., Ohlsson, H., Sundquist, J., & Sundquist, K. (2016). Long-term effects of neighbourhood deprivation on diabetes risk: Quasi-experimental evidence from a refugee dispersal policy in Sweden. *The Lancet Diabetes & Endocrinology*, *4*(6), 517–524. https://doi.org/10.1016/S2213-8587(16)30009-2

Wikström, A. (2020). *The Green Area Factor, Green Infrastructure and Biodiversity*. KTH Royal Institute of Technology.

Wilkerson, M. L., Mitchell, M. G. E., Shanahan, D., Wilson, K. A., Ives, C. D., Lovelock, C. E., & Rhodes, J. R. (2018). The role of socio-economic factors in planning and managing urban ecosystem services. *Ecosystem Services*, *31*, 102–110. https://doi.org/10.1016/j.ecoser.2018.02.017

Zeng, Z., Tang, G., Hong, Y., Zeng, C., & Yang, Y. (2017). Development of an NRCS curve number global dataset using the latest geospatial remote sensing data for worldwide hydrologic applications. *Remote Sensing Letters*, *8*, 528–536. https://doi.org/10.1080/2150704X.2017.1297544

Appendices

Appendix I: Model inputs

Table 3 InVEST Urban Flood Risk Mitigation model inputs and data sources for modelling the current situation.

Input	Format	Input value (if applicable)	Source
Area of interest	Vector file		Sveriges meteorologiska och hydrologiska institut (SMHI) (2022)
Rainfall depth	Number	105.7 mm	Thurin (2018)
Land use/land cover (LULC) map	Raster file, resolution 10 x 10 m		European Union & European Environment Agency (EEA) (2021a, 2021b,) and Stockholm's mapping service (Kart- och geodataservice, 2023)
Biophysical table	csv file Columns: - lucode (integer) - cn_x curve number (cn) per soil group (x) for each LULC class		Curve numbers based on Natural Capital Project (2022), Natural Resources Conservation Service (NRCS) (1986) and Zeng et al. (2017)
Soil hydrologic group	Raster file, resolution 1/480 decimal degrees		Ross et al. (2018)

Table 4 InVEST Urban Stormwater Retention model inputs and data sources for modelling the current situation.

Input	Format	Input value (if applicable)	Source
Land use/land cover (LULC) map	Raster file, resolution 10 x 10 m		European Union & European Environment Agency (EEA) (2021a, 2021b,) and Stockholm's mapping service (Kart- och geodataservice, 2023)
Soil hydrologic group	Raster file, resolution 1/480 decimal degrees		Ross et al. (2018)
Precipitation	Raster file, resolution 30 seconds		Fick and Hijmans (2017)
Biophysical table	csv file Columns: - lucode (integer) - is_connected (boolean) - rc_x - runoff coefficients (rc) per LULC class and soil group (x)		is_connected based on European Commission & Copernicus (2020) and Natural Capital Project (2022) Runoff coefficients from Baryła et al. (2017), Hamel et al. (2021), Natural Capital Project (2022), and Rawls et al. (1981)
Adjust retention ratios	Option: yes/no	yes	
Retention radius	Number	10	
Road centerlines	Vector file		© Lantmäteriet (2021)
Area of interest	Vector file		Sveriges meteorologiska och hydrologiska institut (SMHI) (2022)

Table 5 InVEST Urban Cooling model data input and sources for modelling the current situation.

Input	Format	Input value (if applicable)	Source
LULC	Raster file, resolution 10 x 10 m		European Union & European Environment Agency (EEA) (2021a, 2021b) and Stockholm's mapping service (Kart- och geodataservice, 2023)
Evapotranspiration	Raster file, resolution 30 arc-seconds		Trabucco & Zomer (2022)
Area of interest	Vector file		Kart- och geodataservice (2023)
Biophysical table	csv file Columns: - lucode (integer) - kc (number) - green_area (boolean) - shade (ratio) - albedo (ratio) - building intensity		Bosch et al. (2021), European Commission & Copernicus (2020), Hamel et al. (2021), Roehr & Kong (2010), Susca et al. (2011), Stewart & Oke (2012), and Veerkamp et al. (2023)
Reference air temperature	Number	34°C	Sveriges meteorologiska och hydrologiska institut (SMHI) (n.d.-c)
UHI effect	Number	3.9°C	Sveriges meteorologiska och hydrologiska institut (SMHI) (n.d.-a)
Air blending distance	Number	500 m	Natural Capital Project (2022)
Maximum cooling distance	Number	450 m	Natural Capital Project (2022)
Cooling capacity calculation method	Option: factors/intensity	Factors	
Run energy savings valuation	Option: yes/no	No	
Run work productivity valuation	Option: yes/no	Yes	
Average relative humidity	Number	21	Sveriges meteorologiska och hydrologiska institut (SMHI) (n.d.-b)

Table 6 InVEST Urban Nature Access model inputs and data sources for modelling the current situation.

Input	Format	Input value (if applicable)	Source
Land use/land cover (LULC) map	Raster file, resolution 10 x 10 m		European Union & European Environment Agency (EEA) (2021a, 2021b,) and Stockholm's Kart- och geodataservice (2023)
LULC attribute table	csv file Columns: - lucode (integer) - urban_nature (boolean)		urban_nature based upon descriptions in European Commission and Copernicus (2020)
Population	Raster file, resolution 100 x 100 m		Bondarenko et al. (2020)
Administrative boundaries	Vector file		Stockholm's Kart- och geodataservice (2023)
Sociodemographic information per administrative unit	Vector file		Statistik Sthlm (2023)
Urban nature demand per capita	Number	50 m^2	Russo & Cirella (2018)
Aggregate by population groups	Option: yes/no	No	
Search radius mode	Selection	Uniform radius	
Decay function	Selection	Gaussian	Assumptions
Uniform search radius	Number	800 m	Emery & Thrift (2021)

Appendix II: Filling the gaps in the evapotranspiration raster

NoData are gaps within the raster (evapotranspiration raster), to be reclassified according to the median of the nearest neighbours by using the ArcMap's Raster Calculator (JayantaPoddar, 2021):

Con(IsNull("raster"), FocalStatistics("raster", NbrRectangle(5,5, "CELL"), "MEDIAN"), "raster")

Appendix III: Results from the statistical analyses

Table 7 Spearman correlation coefficient rho and p-value for the correlation analysis of each ecosystem service and the neighbourhood deprivation index (NDI), indicating a significant correlation between three of the services (stormwater retention, annual water retention, and nautre access) and the NDI.

Service	**Stormwater retention**	**Annual water retention**	**Heat mitigation**	**Nature access**	**All services combined**
Correlation test	*Mean runoff retention ratio per district – NDI*	*Mean adjusted retention ratio per district – NDI*	*Mean heat mitigation index per district – NDI*	*Mean urban nature balance per district – NDI*	*Mean aggregated services per district - NDI*
rho	0.632	0.736	0.253	0.593	0.516
p-value	0.0237	0.00579	0.404	0.036	0.074

Table 8 t- and p-values for the comparison between the residential area redeveloped with the Green Space Index (GSI), the situation before redevelopment ("2006"), a residential area that has not been redeveloped and is in the same neighbourhood ("Residential"), and three areas in the same neighbourhood that have been redeveloped, but without the GSI ("Redeveloped 1-3"). The absence of a values for nature over-/undersupply in Redev. 2 is due to a lack of data for that area.

Service		**Stormwater retention**	**Annual water retention**	**Heat mitigation**	**Nature access**
Model		*Urban flood risk mitigation*	*Urban stormwater retention*	*Urban cooling*	*Urban nature access*
2006 – GSI	*t-value*	-10.698	-17.041	212.4	142.88
	p-value	< 2.2e-16	< 2.2e-16	< 2.2e-16	< 2.2e-16
Residential – GSI	*t-value*	-19.363	-12.804	40.993	85.95
	p-value	2.2e-16	< 2.2e-16	< 2.2e-16	< 2.2e-16
Redeveloped 1 without GSI - GSI	*t-value*	6.402	24.398	-51.269	21.311
	p-value	2.707e-10	< 2.2e-16	< 2.2e-16	< 2.2e-16
Redeveloped 2 without GSI - GSI	*t-value*	-11.917	-7.8688	36.884	
	p-value	< 2.2e-16	3.737e-13	< 2.2e-16	
Redeveloped 3 without GSI - GSI	*t-value*	34.98	40.496	-13.91	158.51
	p-value	< 2.2e-16	< 2.2e-16	< 2.2e-16	< 2.2e-16