Towards climate just nature-based solutions

A social vulnerability framework for mapping ecosystem service demand

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Abstract

Nature-based solutions (NbS) are increasingly being used around the globe as a climate action tool. In the Global South, which faces significant climate risks, higher urbanisation rates emphasise the importance of climate justice. While social valuations and interactions with nature-based solutions have been well researched, the relationships between nature-based solutions and social vulnerability to climate change remain difficult to capture. Furthermore, there exist little support for decision-makers to integrate social vulnerability into NbS planning. In this thesis, a social vulnerability framework to determine ecosystem service demand is presented using principal component analysis (PCA), and used with an NbS matching model to determine the types and locations of NbS to be prioritised, applied to a case study of Cape Town, South Africa. The presented framework allows for leveraging openly available quantitative data sets and incorporating different risk factors, while depending on expert interviews to contextualise the model and emphasize its limitations. Three potential policy considerations are recommended for the city of Cape Town to facilitate climate just NbS implementation: cooperation with conservation, potential for climate adaptation and justice, and the importance of community involvement. Using this method of prioritisation and selection, decsion-makers of the city of Cape Town can incorporate climate justice into its urban planning for NbS, while taking consideration of the framework limitations and restrictions.

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List of abbreviations

NbS	Nature-based solutions
ES	Ecosystem services
EJ	Environmental justice
CJ	Climate justice
PCA	Prinicpal Component Analysis
SoVI	Social Vulnerability Index
CCCT	City Council of Cape Town

1. Introduction

Cities in the Global South are growing at unprecedented rates. It is expected that more than half of the population in the Global South will live in cities by the year 2025 (Smit 2021). This increasing urban population compounds with increasing negative impacts of climate change (figure 1.1 (a)), particularly in Global South cities (Mahesh et al. 2009). Additionally, local governments and citizen organisations are looking more towards nature for solutions (Gómez-Baggethun and Barton 2013), especially with regard to climate change (Demuzere et al. 2014; Kabisch et al. 2016). Often, ecosystems of varying scopes and sizes are used as tools in cities to address specific problems.

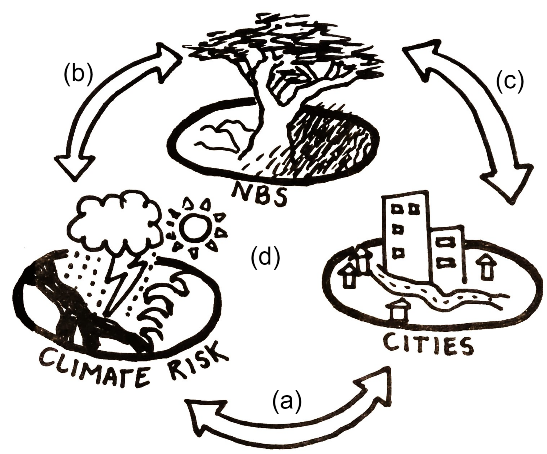


Figure 1.1: Relationships between NbS, cities and climate change

These so-called nature-based solutions (NbS) provide potential solutions to societal challenges through nature-supported and nature-inspired approaches (IUCN 2016; Raymond et al. 2017; Roe 2021) (figure 1.1 (b)) that leverage ecosystems to derive benefits and increase urban resillience. The many interactions that occur between urban communities and these ecosystems, pre-existing or not, result in benefits and disservices (figure 1.1 (c)). These benefits and disservices can be measured and assessed through a concept known as ecosystem services (ES) (Andersson et al. 2015; Constanza 1992; de Groot et al. 2002). While some of the ES of NbS can be measured directly, such as carbon sequestration by street trees (Keeler et al. 2019), other factors – especially those that include socio-cultural factors – are more difficult to capture (McPhearson et al. 2022).

1.1 Nature-based solutions and justice

Governments, from local to national levels, often have to implement climate mitigation strategies with limited resources and in socially vulnerable communities. This leads to two significant challenges: firstly prioritising the implementation (Enserink et al. 2022) of urban NbS to ensure efficient use of resources, and secondly incorporating integrated decision-making (Enserink et al. 2022) into NbS urban planning to account for complex dynamics in vulnerable communities. Indeed, the benefits and disadvantages of urban NbS are often disproportionately distributed – particularly across vulnerable and disadvantaged communities – and have not been studied in-depth (Herreros and McPhearson 2021). Incorporating justice into NbS planning can be better understood through three different concepts of justice: distributional, procedural and representational justice (Cousins 2021). Populations that are socially vulnerable to climate change require equitable access to resources (distributional justice), decision-making processes that are equitably executed and inclusive (procedural justice) as well as fair representation in data and decision-making (representational justice).

The scale of urban NbS is also an important factor that affects implementation, benefits and disservices. How NbS are often classified into distinct categories, while useful for analysis and understanding, simplifies NbS to a point where important aspects, both practical and conceptual, are excluded. This includes how different NbS implementations interact with each other on local and national scales, but also how these implementations are undertaken and planned (Bridges et al. 2021; Slinger 2021). Additionally, many contextual factors influence NbS implementations and the ES that they generate. These contextual factors include political will and public opinion of urban NbS, but also geographic and ecological factors that influence NbS implementation.

To support integrated and multi-scale decision-making and prioritisation for climate just NbS, the social demand for ecosystem services can be leveraged as tool to inform NbS selection and prioritisation. This requires establishing a framework for understanding social vulnerability in terms of ecosystem service demand, which allows for more just selections of NbS and prioritisation of NbS projects. Particularly, addressing distributional and representational justice consideration ensures that vulnerable communities will have more equitable access to necessary resources and infrastructure, as well as visibility to decision-makers regarding decisions and policies that might affect them directly. The role of contextualisation in such a framework is essential, as generalised findings might not capture local features and might lead to a higher risk of eventual implementation failure. This also mitigates challenges of NbS related to scale; NbS are generalised to enable easier analysis, but require contextualisation to provide more accurate and applied results.

1.2 Nature-based solutions in Cape Town

To evaluate the effectiveness of this decision-support approach, it is applied to a case study of Cape Town, South Africa. Cape Town is an excellent example of a city where NbS are being used and planned for use to mitigate climate change effects, particularly to increase drought resiliency (City Council of Cape Town 2020a; Orimoloye et al. 2021). The City's biodiversity is also unique in the world (Cilliers et al. 2013; City Council of Cape Town 2019; O'Farrell et al. 2012), which contributes to complexity through conservation, national and international pressure to prevent biodiversity loss, as well as other biodiversity concerns.

Cape Town is a notably spatially segregated city, with many inequalities still entrenched from its Apartheid-past. These inequalities extend to access to and benefits from NbS (Venter et al. 2020). The City Council of Cape Town (CCCT) is establishing the importance of drought resilience and exploring the utility of NbS as a tool to do so (City of Cape Town 2018). Planning NbS as part of climate action, however, lacks integrated and justice-based support for the CCCT (AFD Consulting 2019; City Council of Cape Town 2020a; City of Cape Town 2018).

1.3 Research gap: Climate justice of nature-based solutions

The majority of current NbS analyses, while using ES to determine impacts and to later (occasionally) evaluate justice concerns, do not incorporate explicit concepts of climate justice. While more socially-inclusive methods have allowed for NbS value to be more realistically mapped (Fagerholm et al. 2012), the lack of explicit consideration for the impacts of NbS on social vulnerability to climate change prevents meaningful steps towards climate justice, as is the case in South Africa (Venter et al. 2020). This is further exacerbated by a considerable lack of decision-support approaches for NbS planners (City Council of Cape Town 2020a; City of Cape Town 2018) that incorporate multi-dimensional strategic support for NbS planning.

1.4 Research question

The research gap identified above, leads to the following research question:

Box 4: Main research question

How can climate justice be incorporated in the urban planning and policy of nature-based solutions in the city of Cape Town, South Africa?

The above research question can be further specified by breaking it into several sub-questions, based sequentially on the steps taken in this decision-support approach, shown in Box 5. Firstly, the current extent of inequality and vulnerability in Cape Town was assessed, which allowed for better being able to assess the potential impacts of NbS on these communities. Once a clear understanding was obtained of the relationships between NbS and climate justice, this was applied to Cape Town to understand where NbS were most preferred from a social and ecological perspective. Finally, the contextualised results and approach were used in determining the implications for decision-makers in using this approach.

Box 5: Sub-questions

1. What are the current socio-spatial inequalities in Cape Town?
2. What are the impacts of nature-based solutions in terms of climate justice, and how can they be assessed?
3. Which locations are the most ecologically and socially suitable for NbS in Cape Town?
4. What are the implications of introducing climate justice into urban planning for NbS?

The value derived from certain NbS and its ES are highly contextual, making qualitative understanding and contextualisation (see section 3.4) essential in providing the lens through which the results can be interpreted. Using the sub-research questions in Box 5, a broad research approach was followed based on four main stages of the thesis process (shown in figure 1.2), namely gathering data (A), modelling and analysis (B), contextualisation (C) and concluding based on the results and approach (D).

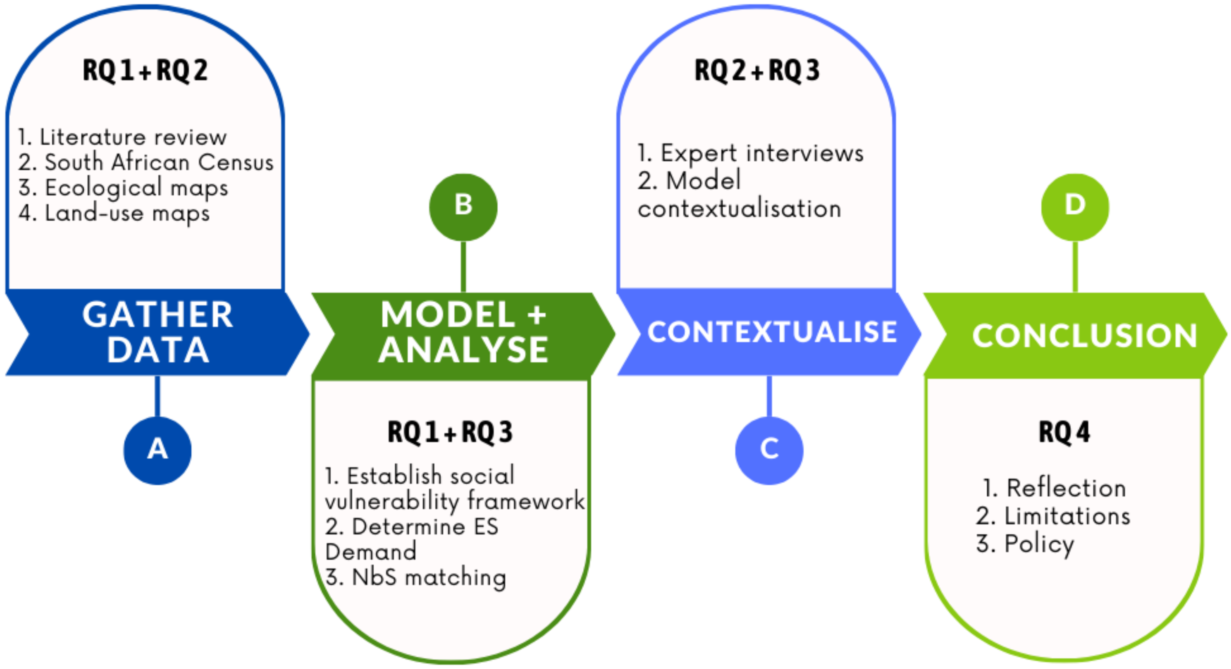


Figure 1.2: Initial research plan

In this thesis, a decision-support approach is developed to achieve more climate-just urban NbS, applied to Cape Town, South Africa. As this thesis involved also the creation of a model for selecting and mapping NbS, an approach similar to that of a modelling cycle was followed (Slinger et al. 2008). Although different terms were used, this approach loosely incorporates various elements of the modelling cycle, including problem description, conceptualisation, model specification, verification as well as describing use of the model. This thesis is organised as illustrated in figure 1.3. In section 2, the current literature around social vulnerability frameworks for urban NbS and state-of-the-art decision-support approaches are investigated.

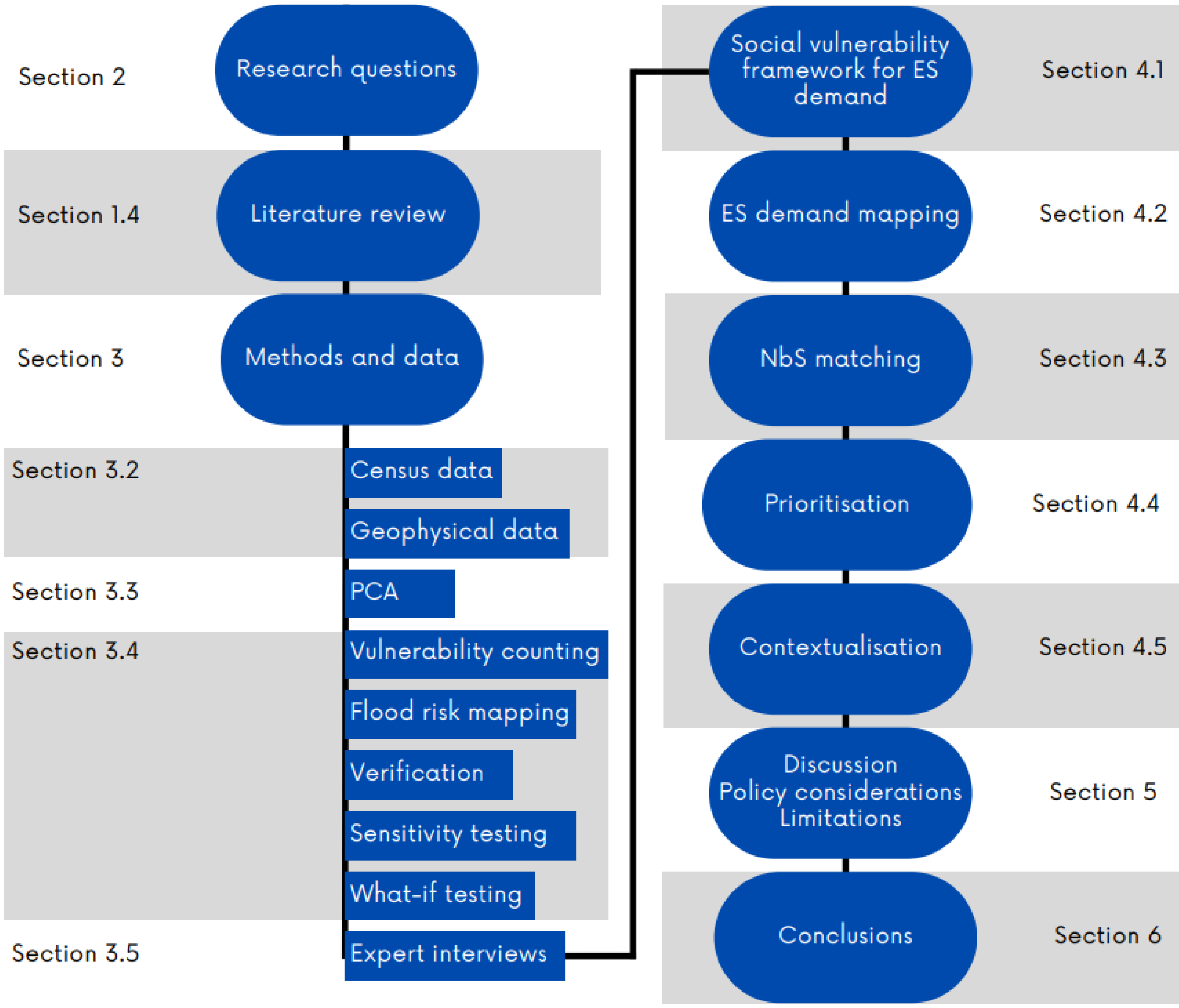


Figure 1.3: Thesis approach

Based on the research gap identified in that section, section 3 describes the methods used in developing this decision-support approach: a social vulnerability framework for mapping ES demand, selection and prioritisation of climate-just NbS, verification and validation techniques, and contextualisation methodologies. In section 4, the methodologies are applied to the case study of Cape Town, South Africa. Insights from the results for policy and decision-makers are discussed in section 5, as well as important implications and limitations of the provided approach. Finally, conclusions and recommendations for future work are provided in section 6.

2. Literature review

This chapter summarises the state of the art for the research domains surrounding the dilemma of justice effects of urban NbS. More specifically, to better understand the current state-of-the-art of incorporating social vulnerability to climate change in urban NbS planning, as well as to be aware of current decision-support approaches and tools.

Box 1: Terminology

Nature-based solution: Nature-based solutions are actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature (IUCN, 2019).

Climate justice: Local impacts and experience, inequitable vulnerabilities, the importance of community voice, and demands for community sovereignty and functioning in light of climate change (Schlosberg and Collins 2014).

Social vulnerability to climate change: Closely related to climate justice, but focuses on the associated risks and adaptive capacity to climate risk for populations (Vincent 2004).

The literature research was conducted along three dimensions, each covering a core research domain:

1. Nature-based solutions — while Cape Town often focuses on drought-related NbS, the more general concept of NbS is used, as this general analysis may then be more applicable to other cases and solutions (Kabisch et al. 2016),

2. Ecosystem services — particularly the extent to which the concept is used, the limitations and how communities' demands for ES vary. ES is a commonly used method for determining the impacts, usefulness and benefits derived from NbS – and is a core part of this study.
3. Climate justice — as a way of investigating the intersection between vulnerability and NbS intervention.

These three research domains were chosen so as to identify other frameworks that incorporate justice, and specifically climate justice, into urban NbS planning.

2.1 Literature methodology

The literature review was conducted by using several online tools, such as *Google Scholar*, *Scopus* and *IEEE* and literature review methodologies, such as "snowballing", in order to obtain a comprehensive overview of the current state of the art of urban NbS, how they are measured through ecosystem services, as well as the justice effects they have in cities where they are implemented. Through conversation with field experts, foundational papers within the field were identified. Online tools, such as *Connected Papers*, aided significantly in the "snowball" process, as it clearly visualises paper cross-citations in a network topology. The box below provides the SCOPUS commands that were used:

Box 2: SCOPUS Search Strategy

Research direction 1: NbS ((nature AND based AND solutions) OR (green AND infrastructure)) AND (cape AND town)

Research direction 2: ES (ecosystem AND services) AND ((trade AND offs) OR (spatial))

Research direction 3: Climate Justice (ecosystem AND services) AND ((social AND vulnerability) OR (environmental AND justice) OR (climate AND justice))

After a general body of related literature was obtained, consisting of 76 papers, this was trimmed down by filtering papers based on direct relevance through several different criteria:

1. A relatively high number of citations (unless it was published in the previous year),
2. Recent date of publication (not from longer than 10 years ago — except in exceptional cases or for papers that are considered foundational in the field).

Using the above criteria, a final body of literature was obtained that consisted of around 62 papers.

2.2 Nature-based solutions

Nature-based solutions (NbS) have been steadily increasing in popularity as a concept describing non-manmade solutions to a wide array of problems (Frantzeskaki et al. 2019), particularly for climate adaptation (Gill et al. 2007). Of course, along with increasing adoption, there is also an increasing number of ways in which to define it. Definitions vary from comprehensive and even elaborate (Dorst et al. 2019) to more concise, such as that provided by Raymond et al. (2017), which broadens the NbS to be any nature-supported solution to a societal challenge. Such broad solutions, while readily understood, essentially shift the complexity down the line, as these broad definitions often lead to difficulty in establishing generalised conclusions. The definition given by the IUCN (2019) (see Box 1), often credited with first defining the NbS concept, emphasizes the role that ecosystems play in such solutions, and stipulates its mutually beneficial relationship for both people and nature. This definition will enjoy precedence in this thesis.

2.2.1 The goal of nature-based solutions

NbS are often preferred as a tool for urban resilience and climate adaptation due to the holistic nature through which a multitude of benefits can be obtained by a single, albeit often complex, solution (Dorst et al. 2019). In the case of Cape Town, drought-based NbS are specifically being investigated as alternatives to mitigate future droughts (Holden et al. 2022; Orimoloye et al. 2021). Interestingly, Orimoloye et al. (2021) found that certain types of human activity (such as deforestation leading to loss of trees), as well as natural phenomena (such as natural drought resulting in plant-loss), negate some benefits from NbS – indicative of the complex relationship between human activity and NbS. This finding was confirmed in studies in Eastern Africa where Kalantari et al. (2018) emphasised the need to plan for feedback mechanisms that might arise between the resulting population expansion (and land-use changes associated with it) and the benefits from NbS. Most of these studies, however, fail to consider existing inequalities explicitly, despite mentioning the link between disadvantaged populations and flood and drought vulnerability (Kalantari et al. 2018).

2.2.2 Modelling and planning nature-based solutions

NbS have been modelled in past applications through a variety of models and data analysis techniques. These models often aid decision-makers in determining appropriate locations for NbS, while also providing insights into the expected impacts of specific implementations. Chang et al. (2021) developed the GISP (Green Infrastructure Spatial Planning) model and applied it to the Yanshuei river basin, Taiwan, to be able to model the impacts of flood-based NbS on the surrounding communities. The model could predict co-benefits that arose due to differing dynamics acting simultaneously but was area-specific, reducing its generalisability. This generalisability proves to be a persistent problem in NbS modelling. Another typical modelling technique involves simulating land-use and its associated impacts (Sun et al. 2018), which, while excluding some interactive dynamics and co-benefits that occur between different nature-based and other systems, is particularly useful due to the general availability of land-use maps. Land-use modelling is incorporated in this approach, as it provides a valuable basis for practical and legal feasibility of NbS implementations. For cases where proximity plays a large role, simple land use models often offer an appropriate trade-off between simplicity and usefulness (Ernstson 2013). Connectivity and interactions between different NbS is, however, a crucial and often overlooked dynamic (Raymond et al. 2017). Other models, such as that developed by Ernstson (2013), indeed make use of ecological network models to capture ecological flows that result in co-benefits. Much uncertainty exists over the benefits provided by NbS, however, as these are often difficult to measure or quantify.

2.2.3 Nature-based solutions in Cape Town

While many different nature-based solutions can be implemented in many different contexts, a catalogue of NbS was created for Cape Town in interest of yielding practical and more realistic scenarios and results. This was based on literature of NbS in Cape Town and South Africa (Cilliers et al. 2013; Holden et al. 2022; Orimoloye et al. 2021; Venter et al. 2020) as well as the World Bank's catalogue of NbS (World Bank 2021). It is important to note the multi-scale facets of NbS. Classifications made by institutions such as the World Bank, the World Resources Institute and the Army Corps of Engineers (Bridges et al. 2021; Tye et al. 2022; World Bank 2021), provide useful bases for analysing and planning implementations, but introduce limitations into planning. Larger scale benefits, disservices, and implementation considerations can be excluded using such classifications. In this decision-support approach, such classifications are still used for the following reasons:

- Using vocabulary that is already known to decision-makers helps in reducing the distance of understanding, and facilitates this approach in supporting decision-making and planning,
- Much of the existing body of research makes use of similar classifications, allowing characterisations to be made for different NbS classifications.

This selected catalog was further verified by expert interviews. The NbS that were considered for this analysis are shown in Box 3. Marine NbS, such as aquaculture and fisheries, have notably been excluded from this analysis. While the ocean ecosystem undoubtedly contributes significantly to Cape Town's biodiversity, it was excluded from this analysis to maintain focus on proximity-based ES from terrestrial NbS for vulnerable communities.

Box 3: Catalogue of NbS for Cape Town

- Green buildings (including green roofs),
- Beach and dune strengthening projects,
- Wetlands (constructed and natural),
- Urban open green space (such as public parks and fields),
- River projects (including river renaturation and flood plain management),
- Urban agriculture (on small and large scales), and
- Urban forests.

2.2.4 Biodiversity

Biodiversity plays a core role in the health, resilience, and adaptation of ecosystems, and so, NbS. Particularly in Cape Town, biodiversity is often emphasized as a core asset to the city in its conservation efforts (O'Farrell et al. 2012). Indeed, Cilliers et al. (2013) emphasized the importance of using biodiversity as rationale for conservation rather than ES, as in Cape Town's ecological landscape many areas with high irreplaceability values do not necessarily include areas with high values of ecosystem services (O'Farrell et al. 2012). This biodiversity conservation approach has been studied in literature (Cilliers et al. 2013; Colléony and Shwartz 2019), but its exact impacts and relations on social vulnerability to climate change remain unclear. Additionally, these potentially conflicting approaches represent an ethical value conflict between the valuation of nature and biodiversity, and of social justice and poverty reduction. Further complicating the arena, is the national and even global importance of Cape Town's biodiversity. As the Cape Floristic Region within Cape Town is considered a global biodiversity hotspot, and South Africa is a signatory to international biodiversity conservation protocols (Holmes et al. 2012), decision-makers face an added layer of consideration, but also external pressure, when considering urban planning for NbS. This consideration was reflected in the decision-support approach through the inclusion of conservation areas in the NbS matching model (see section 3.3).

2.3 Ecosystem services

As previously mentioned, one of the most pressing challenges of planning potential NbS, is determining the eventual impact on the neighbouring society. Ecosystem services is a concept that is capable to capture such impacts (de Groot et al. 2002; Seppelt et al. 2011). Ecosystem services describe all the benefits and disservices provided to human societies by a specific ecosystem (McPhearson et al. 2022), as illustrated in figure 2.1. These ecosystem services can also eventually be translated into financial terms (Costanza et al. 1997).

As ecosystem services cover a wide range of benefits that are not necessarily independent from one another, trade-offs and co-benefits are inevitable (Maes et al. 2012). Seppelt et al. (2011) therefore emphasize the need to undertake holistic approaches to ecosystem services, ranging from understanding data and model realism, trade-offs and side-effects, to assess impacts on stakeholders. There exists a large body of research that aims to improve understanding of these trade-offs and co-benefits (Demuzere et al. 2014; Raymond et al. 2017). This body of research helps in understanding how different ecosystem services interact with each other, the environment, and how they are degraded and/or amplified by either human or natural phenomena (Kalantari et al. 2018). Most of

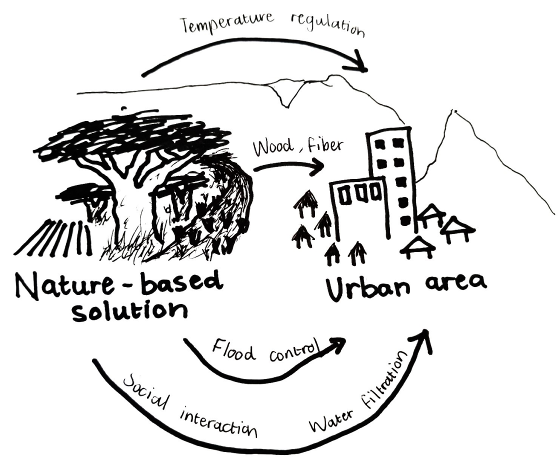


Figure 2.1: *Examples of ecosystem services, based on Andersson et al. (2015)*

these analyses do not, however, incorporate social interactions, and how demographics and segregation affect co-benefits and trade-offs (Langemeyer and Connolly 2020). The field has also not remained isolated from social sciences. On the contrary, much progress has been made towards accurately mapping and capturing the social value of ecosystem services (Gómez-Baggethun and Barton 2013) through methods such as participatory mapping and community involvement (Fagerholm et al. 2012).

While capturing the social value of separate ES or even NbS potentially reflects group-specific variations in how these concepts are valued, they do not explicitly address inequality or discrimination dynamics. To this effect, Langemeyer and Connolly (2020) found the incorporation of justice into ES, a concept they called *inclusive ecosystem services*, lacking. Similarly, Cousins (2021) reflected on the peripheral role that justice often plays in NbS implementations and ES impact measurement. Additionally, while adoption of ecosystem services as a urban planning tool has seen some success in Europe and North America (Hansen et al. 2015), many academic papers still rarely actually quantify ecosystem services of NbS, as in the case of green stormwater management solutions (Prudencio and Null 2018).

2.4 Climate justice

Climate justice (CJ) is a concept that explains how a changing climate affects certain populations differently, and how climate adaptation interventions can be used to address these inequalities (Schlosberg and Collins 2014). A vital component of understanding CJ and planning climate action, is the concept of social vulnerability, particularly with regards to populations' adaptive capacity when reacting to climate risks (Katic 2017; Tapia et al. 2017; Vincent 2004). With the increasing necessity of climate resilience in urban areas, and the increasing magnitude and reach of climate action and related projects, it is important to understand how these interventions affect existing inequalities (Kabisch et al. 2016). This is particularly important in cities with deeper inequalities, such as Cape Town, where many of Apartheid's entrenched inequalities still affect ecosystem benefits, such as access to green infrastructure (Venter et al. 2020).

As mentioned in this literature review, concepts of justice – across distributive, procedural and representational dimensions (Ernstson 2013) – have rarely been included as a core component in most NbS research (Cousins 2021; Grabowski et al. 2022; Herreros and McPhearson 2021), while its importance in NbS as a key consideration for societal well-being has been made clear (Colléony and Shwartz 2019; Kabisch et al. 2016; McPhearson et al. 2022). Indeed, in the explanation of their Social-Ecological-Technical System (SETS) approach to NbS, McPhearson et al. (2022) explain the necessity for considering the multi-dimensional impacts that NbS have when operating in systems that are as complex as urban areas. Parallel to climate justice, is the concept of *environmental justice* (EJ), which is credited as providing the foundation of CJ (Schlosberg and Collins 2014). Some recent studies have been done on the EJ impacts of urban NbS, such as by Kato-Huerta and Geneletti (2022), but do not incorporate quantitative analyses, and instead rely on in-depth literature reviews. Here, the term of *just NbS* is borrowed from Cousins (2021) to reflect NbS that focus on addressing inequalities and injustices. This term is expanded to *climate-just NbS*, however, to reflect the need for justice consideration in climate action, particularly for populations vulnerable to climate change.

Various frameworks have been used in literature to capture the social vulnerability of individuals or group through calculation of a social vulnerability index (SoVI) from socio-demographic data (Cutter et al. 2003; Mavhura et al. 2017; Vincent 2004). While these indicators do seem to be significantly contextual (Katic 2017), they are still useful in making relative comparisons among contextually similar areas, such as over national, inter-, or intra- urban scales. The relationships between these vulnerabilities and the consumption of ecosystem services, although researched (Karrasch et al. 2014; Seddon et al. 2020), is often not approached quantitatively. Social Impact Assessment (SIA) has been used to determine the relationship between ecosystem services and communities where they have been implemented (Karrasch et al. 2014), but these assessments depend predominantly on qualitative methods such as expert interviews. While this is useful for understanding qualitative impacts of NbS on EJ, and accordingly CJ, it neglects the spatial dimension that plays a vital role in determining access and distribution of ES benefits. Additionally, this significantly raises the barrier of conducting research in these domains, as primary data has to be collected where secondary (and often open) data sources often already exists. This qualitative, contextualising component is still necessary however, and is considered a necessary step in the decision-support approach presented here. The European Commission has, however, released its guidebook for evaluating the impact of NbS (European Commission and Directorate-General for Research and Innovation 2021), which provides a useful framework of recommended indicators to capture the holistic impacts of NbS. This can be used to build analyses on, but should be used with caution as the valuation of different factors and domains are unclear. This framework was used in cooperation with other sources to determine indicators of importance, but did not provide meaningful framing in terms of how this could support decision-makers towards climate-just NbS.

It has been found that poorer and more vulnerable communities make more use of certain provisioning ES, such as food and medicine (Cilliers et al. 2013). There does indeed seem to be a differing access to ES and inverse dependence on certain ES along a socio-economic gradient (Cilliers et al. 2013). From a planning perspective, it is important to understand these differences and varying demands for ES across the city-scape, as it enables policy-makers to make more informed decisions for prioritising limited resources in multi-stakeholder environments (Enserink et al. 2022). Thus, understanding the ecosystem services with the highest demands in vulnerable community requires a multi-dimensional understanding of the vulnerabilities present in that community. Some practical frameworks have been suggested to use vulnerability impact assessment to determine the impacts of climate vulnerability to ecosystem service service supply (Munroe et al. 2015), but these remain focused on ES supply on a case-by-case basis, making larger scale comparisons difficult. Additionally, these frameworks are either mostly theoretical in nature (Ernstson 2013; McPhearson et al. 2022) which are difficult for policy-makers to implement, or mostly practical (European Commission and Directorate-General for Research and Innovation 2021; Katic 2017; World Bank 2021) that exclude important justice-specific considerations. This results in vulnerability frameworks often not being used to guide the planning and implementation of NbS.

2.5 Research gap and summary of findings

Thus, there is a significant gap in research in that there exist few quantitative frameworks for determining ecosystem service demand from a climate justice and social vulnerability perspective. This lack of available frameworks also leads to a lack in decision-support for policy makers and urban planners concerning urban NbS and its impacts on social vulnerability.

The concept of ES has often been used in literature to evaluate the effects and usefulness of NbS (Andersson et al. 2015; de Groot et al. 2002; Demuzere et al. 2014; Sun et al. 2018), but, importantly, mostly without the explicit inclusion of climate justice or social vulnerability. Related to this is how the benefits and disadvantages of urban NbS are often disproportionately distributed across vulnerable and disadvantaged communities – and have not been studied in-depth (Herreros and McPhearson 2021). Quantitative SoVI calculation is extensively used in literature (Apotsos 2019; Cutter et al. 2003; Vincent 2004), however, based on this literature review, it has not been used to evaluate the social demands for ES or NbS. This also applies for creating social vulnerability to climate change frameworks, where most academic papers do differentiate between different dimensions of vulnerability (Tapia et al. 2017), but do not differentiate to an ES demand level. Here, leveraging social vulnerability and climate justice concepts (Cutter et al. 2003; Kabisch et al. 2016; Schlosberg and Collins 2014) towards a unified approach potentially allows for directly incorporating distributional and representational justice into NbS planning. Finally, existing approaches toward indicator selection (Katic 2017), land use-based NbS modelling (Ernstson 2013), and contextualisation through expert interviews (Karrasch et al. 2014), have, according to this literature review, not been combined in an approach that simultaneously supports decision-makers and holistically promotes climate-just NbS.

For this thesis, methods, approaches and frameworks were used based on the literature considered in this chapter, but combined and applied in a novel way to develop a decision-support approach for more climate-just urban NbS. To address the research gap, the concepts of the SoVI and social demand for ES were connected to allow for calculation of the social demand for ES through socio-demographic and land feature data. This approach allows for leveraging openly available data sets to obtain an in-depth view into the social demand landscape of the area under question. Additionally, this allows for matching areas to suitable NbS, based on the ecosystem services that they provide – allowing for social vulnerability for climate, and so climate justice, to be directly incorporated into the planning of urban nature-based solutions in a decision-support approach for policy-makers.

3. Method

A extensive set of methods were used to address the research gap towards creating a decision-support approach for climate-just NbS, and are explained in this section. The section is structured as shown in figure 3.1. Data collection from quantitative and qualitative sources are described in section 3.1, creation of the social vulnerability framework for ES demand in section 3.2, using ES to determine suitability and priority of NbS implementations in section 3.3, and finally how the approach was contextualised in section 3.4.

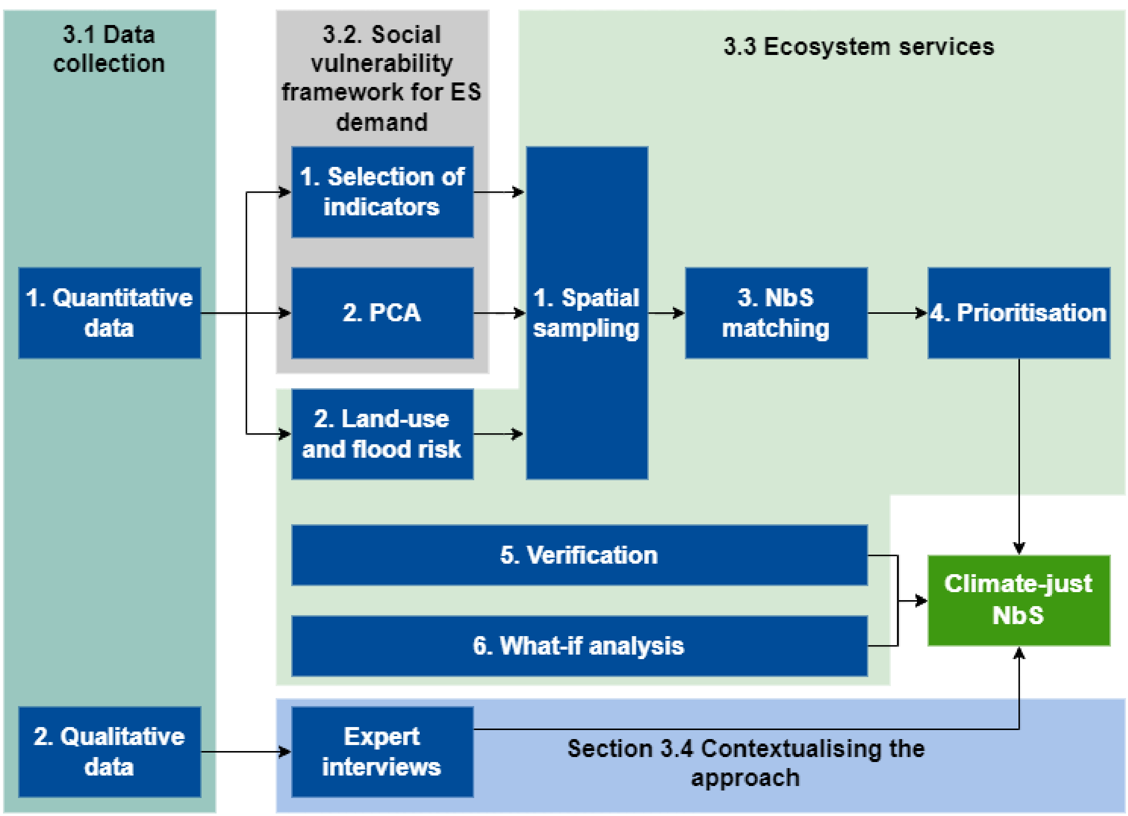


Figure 3.1: Methods used in creating decision-support approach

3.1 Data collection

In order to create a framework for mapping ES demand to social vulnerability to climate change, several different data sources were used for various steps of the approach. Here, these data sources and collection methods will be discussed based on the type of data.

3.1.1 Quantitative data

Social vulnerability and different dimensions of ES demand were determined based on both socio-demographic and geographic data. After the indicators were selected (see section 3.2.1), a list of the required data fields and proxies were obtained. Two main data sources were used here:

1. StatisticsSA's online portal (StatsSA 2011), for obtaining ward-level socio-demographic data, and
2. The Cape Town Open Data Portal (City Council of Cape Town 2020b) for geographic features such as land use and proxied flood risk.

The data from the first source, Statistics SA, were provided at a **ward**-level (see box 4). Using the respective portals, either Microsoft Excel (.xlsx-files) or shapefiles (.shp-files) were used to obtain the raw data. Here, several indicators were grouped in files based on their location in the census, allowing for related data to be grouped together. The respective files were cleaned so that they all used similar formats to easily read and process them into Python *pandas* dataframes.

Box 4: Wards and neighbourhoods

The South African Census of 2011 (StatsSA 2011) aggregates data to a ward level. A ward is a geopolitical area used as voting district, and represents multiple neighbourhoods joined together. Each ward elects its own ward councillor to the city council. For the data set used in this analysis, the City of Cape Town consists of 116 wards, of which 35 were used for further analysis in the Cape Flats and surrounds. While all socio-demographic data are provided per ward, wards do not always represent useful neighbourhood groupings (leading to, for example, relatively rich and poor neighbourhoods being combined in one ward), but still provide useful information.

3.1.2 Qualitative data

In order to contextualise the decision-support approach to the case study of Cape Town, some sort of qualitative data is required. Expert interviews (see section 3.4) were conducted to create a contextual evaluation of the approach. Practically, these interviews were used to determine important dynamics, for the applied domain of Cape Town - outlining the important dynamics that were either incorporated or not considered in the modelling approach.

Further contextualisation was required in terms of the NbS that are typically considered as viable in the Cape Town region, as well as which ES they provide. To facilitate understanding of the model to decision-makers, as well as to support existing research, NbS classifications from the World Bank (2021) were used. Importantly, these classifications discretise NbS into set entities with uniform characteristics, which is unrealistic and potentially lead to scaling-issues.

3.2 Social vulnerability framework for ES demand

Social demand for different ES was mapped in terms of social vulnerability to climate change - resulting in the social vulnerability framework for ES demand. The framework, shown in figure 3.2, shows how different ecosystem services were grouped under five dimensions of social vulnerability to climate change. Social vulnerability to climate change can be divided into many different dimensions, but here the scoping of vulnerability dimensions by Tapia et al. (2017) was applied due to its clear definition. Viewing the demand of different ecosystem services as part of different dimensions of social vulnerability allows for conceptually connecting NbS, and the ES they provide, to social vulnerability to climate change.

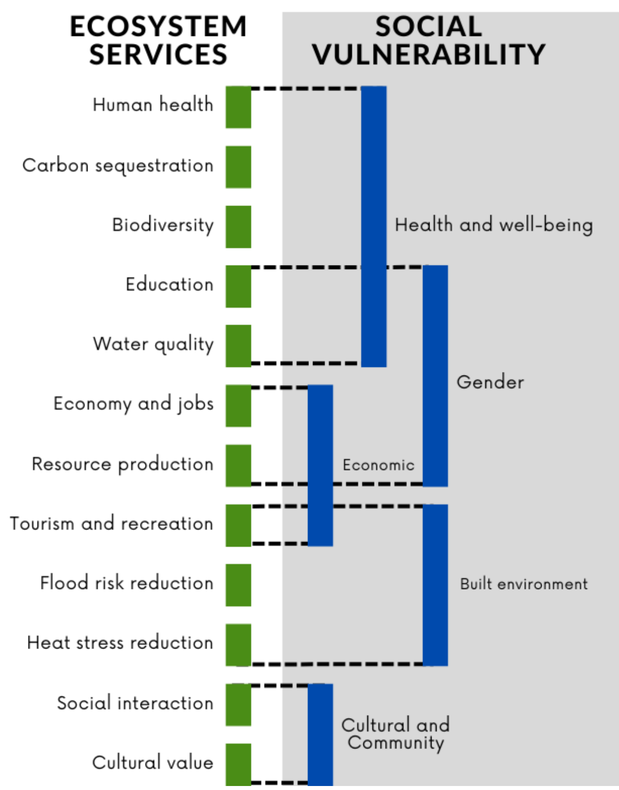


Figure 3.2: Social vulnerability framework for ES demand

There exist many different approaches towards capturing social vulnerability. In this thesis, a social vulnerability index is calculated using principal component analysis (PCA).

PCA is often used for such as applications (Cutter et al. 2003; Mavhura et al. 2017), as it allows for capturing the joint variance in multiple, related indicators. This allows for measurable indicators, which are often already available through census data, to be leveraged to determine social vulnerability (Apotsos 2019). How these indicators are selected, however, becomes an important factor in the eventual result of the SoVi (see sub-section 3.2.1). By framing different ES demands in terms of different dimensions of social vulnerability, ES-demand-indicators were selected based on existing literature. This method has been applied before in determining *ES supply* using PCA (Clec'h et al. 2016; García-Nieto et al. 2013), but (according to the author's literature review) never before for determining the social demand for ES.

3.2.1 Selection of indicators

As mentioned earlier, the selection of indicators becomes significantly important when determining SoVi indices, and here thus also for determining social demand for ES. The indicators for calculating demand for different ecosystem services were systematically selected as shown in figure 3.3. First, different ecosystem services are framed as part of different dimensions of social vulnerability (already shown in figure 3.2). The study of Apotsos (2019) provides valuable support here, as they evaluated SoVi indices for multiple South African cities. Secondly, based on this mapping, other literature sources are used to substantiate indicator choices for each ecosystem service. While other methods often include expert guidance for such indicator selections (Bucherie et al. 2022; Katic 2017), using literature allows for broader, more un-biased selection of indicators. Finally, once indicators have been selected, the correlation among them are evaluated. Correlation between different indicators are known to be important when being used in PCA, and must thus be accounted for when selecting indicators.

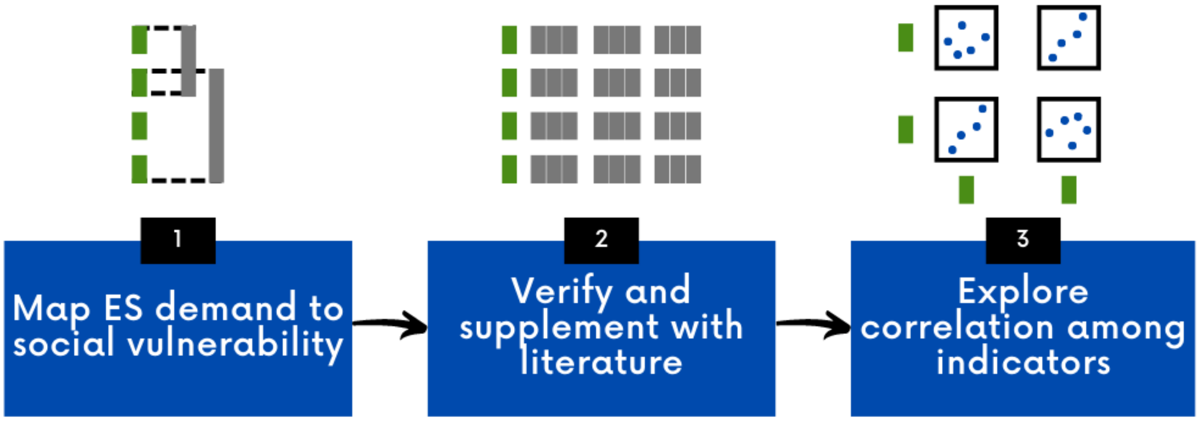


Figure 3.3: Selection of indicators for determining ES demand

Applying this method, indicators were selected that were eventually used to determine the ES demand. These indicators are shown in table 3.1 with the ES they represent and the literature that supports this categorisation. These indicators were selected based on past studies done for similar vulnerability groupings (Apotsos 2019; Cutter et al. 2003; Eisenman et al. 2016; Tapia et al. 2017), as well as the indicators that were measured and available from the 2011 South African census (StatsSA 2011).

Table 3.1: Indicators used to determine social demand for ecosystem service

Ecosystem service	**Indicators**	**Relevant literature**
Human health	Concentration difficulty, selfcare difficulty, physical difficulty, Household size, Parents alive, Total under 15 years old, Total over 65 years old	Cutter et al. (2003); Eisenman et al. (2016); Otto et al. (2017)
Carbon sequestration	Not considered	Reynolds et al. (2017)
Biodiversity	Indigenous vegetation	Seddon et al. (2020)
Education	Good education, Poor education, No internet, Concentration difficulty	Apotsos (2019); Tapia et al. (2017)
Water quality	Piped water inside the house, Access to city water, Flush toilet	Ngarava et al. (2022); Tapia et al. (2017)
Economy and jobs	Low income, Unemployed, Rented house, Car ownership, Satellite TV, No internet, Internet at home, Average income	Tapia et al. (2017); Vanclay (2002)
Resource production	Non-electric light source, Fuel for cooking, Trash removed, Unemployed, Informal house	Apotsos (2019); Ngarava et al. (2022); Vanclay (2002)
Tourism and recreation	Included in Economy and jobs, and Human health	Not directly considered
Flood risk reduction	Fluvial, pluvial and coastal flood maps	Reckien et al. (2017)
Heat stress reduction	Total over 65 years old, Informal house, Piped water inside the house, Total under 15 years old, Low income	Eisenman et al. (2016); Reckien et al. (2017)
Social Interaction	Car ownership, Cellphone ownership, Internet at home, African Language speaker, African (non-Zulu, Xhosa) speaker, Non citizen, Recent arrival, no internet	Apotsos (2019); Tapia et al. (2017); Vanclay (2002)
Cultural value	Black African, Coloured, Indian or Asian, African (non-Zulu, Xhosa) speaker	Tapia et al. (2017); Vanclay (2002)

3.2.2 Principal component analysis

Principal Component Analysis (PCA) is a method to make data more interpretable while maintaining as much information as possible. By reducing the number of input dimensions, the common variation between several different factors is captured - which makes it attractive to determine the SoVI. In selecting multiple related indicators, PCA allows for capturing the joint variation of these indicators, in principal capturing the underlying factor that causes these variations (Cutter et al. 2003). Here, this approach is applied to also determine ES demand instead of only social vulnerability. With the required indicators selected to determine the social demand for each ES, each *demand factor* (see box 5) could be determined.

Box 5: Demand factor

As PCA has not been used to determine social demand for ES in literature, the term of “demand factor” is used in this thesis to describe the single PCA-calculated index that represents social demand for a specific ES. Thus, with PCA, a demand factor for each ward is calculated for each ES, that also forms part of explaining the ward’s social vulnerability through its *aggregated ES demand*.

Using Python’s *scikit-learn* library, the selected indicators were first scaled and normalised (with max-min scaling) to fall between the interval of $(0, 1]$. This scaling is an important step for effective PCA (Cutter et al. 2003). As a PCA model had to be created for each ES, Python’s object-orientated support proved to be beneficial. For each ES, a PCA object was created from the different selected indicators per ES with 2 principal components. As is done for SoVi calculation, the first principal component was used to determine the demand factor for the specific ES in question. The amount of variance explained by this demand factor was also evaluated, as this provided additional insight into how effectively the calculated demand factor captured the variance of the selected indicators.

3.3 Ecosystem services

Ecosystem services provide a useful framework for measuring the impact of NbS usually from a supply perspective, but is used here to determine the suitability of NbS from a demand perspective. With ES demand determined as described in section 3.2.2, this suitability was evaluated, and used to evaluate the most suitable NbS locations. In figure 3.4, the flow diagram for the NbS model is given. First, the social demand for ES is determined using PCA based off several indicators used in calculating social vulnerability (based on Apotsos (2019)). This is calculated per ward, and is also compared to an alternative to PCA to evaluate its performance. The calculated demand factors are then scaled down to $100m$ by $100m$ square cells, and is also populated with different geo-physical layers of data, such as the land-use, flood risk, and biodiversity values in the corresponding cells. The size of these cells were selected based on a trade-off of granularity of results, and computational complexity – while taken physical features such as building size and roads into account. All values were normalised between 0 (a low, or minimum-level demand) and 1 (a high, or maximum-level demand) to allow for better comparing these different demands. Then, based on the ES supply profiles of each NbS (shown in figure A.14), as well as physical constraints such as land use (shown in table A.3) the most suitable NbS is selected.

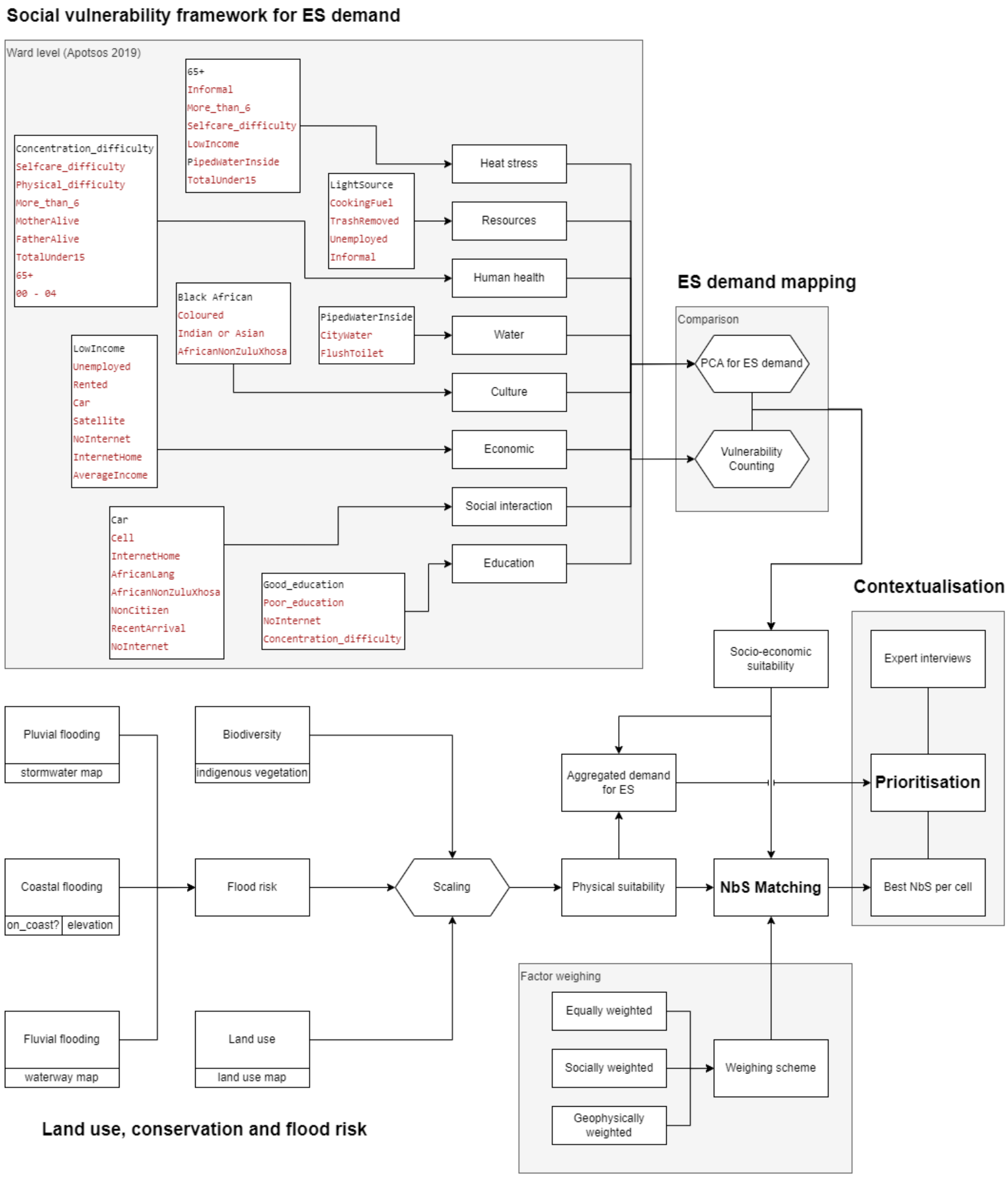


Figure 3.4: NbS matching model flow diagram

3.3.1 Spatial sampling

As some data sets provided granular data, such as the various flood risk maps, and others provided data on ward level, such as the socio-demographic data, all data were spatially sampled into uniform square cells of $100m$ by $100m$. As mentioned earlier, this square size allows for capturing multiple households and geographic features, while still yielding useful insights and remaining computationally feasible. These square cells were then populated with data from the various sources described throughout this chapter. For a summarised table of all data used and data sources, see appendix A table A.1. As ward-level data was normalised, each cell directly inherited the same data values from the ward it was located in. For cells that were located over multiple wards, the data values were averaged proportionally to the area of each ward present in the cell. This allowed also for smoother transitions between ward boundaries.

3.3.2 Land-use and flood risk

While the demand for certain ES were informed by social vulnerability indicators from socio-demographic data (the so-called social demand for ES), certain ES demand factors were determined based on geophysical features. This included determining the flood risk for each cell. The City of Cape Town is affected by three types of flood risk (City Council of Cape Town 2020a):

1. Pluvial flooding (rain),
2. Fluvial flooding (rivers), and
3. Coastal flooding (ocean).

Each of these three types of flooding have different dynamics regarding frequency, damage and mitigation – emphasising the value of considering these dynamics as separate risk types, particularly as different NbS address different flood risk types. The field of flood risk modelling is a well-developed research field, with many complex models being able to establish flood risk maps from various different sources (AFD Consulting 2019). For this analysis, however, simplified versions of these maps were used as proxies, as the main focus of the analysis lies in understanding the impacts of climate justice considerations. For all three types of flooding, geographic maps provided by the Cape Town Open Data Portal (City Council of Cape Town 2020b) were used, as shown in table 3.2.

Table 3.2: Data sources and proxies for mapping flood risk in Cape Town

Flood risk type	Data/ proxy used	Literature
Pluvial	Stormwater body layer	City Council of Cape Town (2020b)
Fluvial	Watercourses layer	City Council of Cape Town (2020b)
Coastal	Elevation above sea-level	City Council of Cape Town (2020b)

Furthermore, land-use plays a role in the legal and administrative feasibility of NbS placement. Based on zoning regulations from the City of Cape Town (City Council of Cape Town 2016), certain NbS were allowed in certain zones, whereas others were not.

3.3.3 NbS matching

Using a set catalogue of NbS for Cape Town, an ES provision profile for each was created based on literature and existing frameworks (World Bank 2021). This greatly simplifies the complexity behind the benefits provided by different NbS, and the complexity of the nature of NbS themselves, but also provides a practical simplification for this thesis. With a ES provision profile for each NbS, shown in figure A.14, the NbS was matched to the ES demand. A matching algorithm was developed that, based on a predetermined weighting of ES, determines which NbS is best able to accommodate the varying ES demands of a given area. Differently put, the NbS matching model compared the ES demand of each cell, and matched it to the NbS whose ES supply best meets these demands. A predetermined weighting was used to create different value-scenarios (see section 3.3.6 for more information) and captured the relative importance of each ES. For the base scenario, however, all ES were equally weighted. Here, practical limitations, such as proximity to the shore for beach and dune projects, and restrictions for conservation areas, were also taken into account. This coastal restriction is important to prevent the NbS model from selecting beach and dune NbS in regions far from the coast, where they would be practically infeasable. The conservation restriction is also necessary, as conserved land is often not available for redevelopment with NbS, and has a more complex relationship in providing certain ES.

With the implementation of the NbS matching model, social vulnerability to climate change is incorporated into NbS selection in two important ways:

1. Using different dimensions of social vulnerability, framed in terms of ecosystem service demand, the NbS that would most adequately meet the demand profile in question is selected, and
2. Using the aggregated social vulnerability to climate change (equivalent to the aggregated ecosystem service demand) to prioritise locations where NbS are most needed, or where demand for them is the highest.

This allows for capturing two important factors of climate justice, namely distributional and representational justice by matching to NbS ES profiles to the communities that need them, and prioritisation of vulnerable communities. This prioritisation of vulnerable groups has been mentioned before as an important factor for climate mitigation efforts in Cape Town (Mukheibir and Ziervogel 2007).

3.3.4 Prioritisation

Prioritisation is an important step in urban planning where resources and capacity are limited- (Enserink et al. 2022). By looking at which areas had the highest aggregated social demand, a better understanding can be gained into which areas are the most vulnerable, and which areas should be prioritised in terms of urban planning of NbS. Making such decisions, that often significantly impact livelihoods, based on mathematically calculated data-informed indices, risks giving false confidence into the decisions made. Any and all prioritisations must be done in full consideration of the limitations inherent in using calculated social vulnerability indices. Selecting the number of areas or cells to be prioritised, while often done arbitrarily, potentially impacts the results of the model. In order to prioritise, a proportion with the highest aggregated ES demand of all areas are used. When changing the size of this proportion, the prevalence of different NbS in the prioritised proportion was also expected to change. By looking at how these NbS prevalences changed in the analysed space as the number of priority cells changed, a greater understanding was gained of how sensitive this prioritisation factor is and how it should be used.

This change in prevalence of different NbS can be represented using an error calculation to establish sensitivity (Christopher Frey and Patil 2002). This error is calculated through

$$E_p = \frac{1}{N} \sum_{N}^{NbS} (NbS_p - NbS_{p-1}), \tag{3.1}$$

with E_p being the error for the priority iteration p (from all samples to only the top 1% of samples in 1% increments), N being the number of nature-based solutions considered for this analysis, NbS_p being the ratio of coverage of a particular nature-based solution for this priority iteration and NbS_{p-1} for the previous priority iteration. Using this error factor E_p, the sensitivity of changing the prioritisation factor could be analysed and evaluated.

In these decisions, there lie ethical assumptions towards the prioritisation of certain communities over others. Indeed, only selecting areas with the highest social vulnerability to climate change, assumes maximising benefits overall, instead of looking at how these benefits are spread across the whole urban area. While representational and distributional justice considerations are taken into account here, procedural justice is still not addressed. Furthermore, the calculation of a social vulnerability indicator is never objective or complete, and might therefore also include potential bias in the results (see section 5.4 for more information about these and other limitations).

3.3.5 Verification and comparison

To ensure the usability of the social vulnerability-informed NbS matching model, several verification tests were conducted on different parts of the model. Verification of the model performance was conducted through a purpose-built model-specific test. This test changed model parameters in a way that would yield a simple, easy-to-predict output for given inputs. Specifically, weights that were assigned to different ES demand factors were set equal to the provisioned ES of a specific NbS - with the expected output to be that the specific NbS be the selected NbS for all cells.

The social vulnerability framework was also compared with two other sources:

1. Comparing the PCA-derived demand factors with a different, more direct form of vulnerability measurement called **direct vulnerability counting** (see below),
2. Evaluating the aggregated social demand for ES (a new metric developed in this thesis) in comparison with existing, researched social vulnerability indices calculated for the same area.

Direct vulnerability counting involves a different method to convert indicators into a single index. Where, in PCA, indicators were grouped based on ecosystem service demand, and then processed into a single index through dimensionality reduction, here indicators are aggregated directly. For example, when calculating demand for heat stress reduction, persons aged 65 and higher will be counted, but also those that live in informal settlements. The unit of measure becomes the vulnerability itself, allowing for an individual to be counted twice if they are vulnerable in more than one way (in this case, being older than 65 and living in an informal settlement). This does require, however, that household-level data be converted to individual data through multiplication of the average household size. Making such a comparison provides greater insight into how different vulnerability-measuring methods might provide varying results – and under which circumstances this is likely to occur.

3.3.6 What-if analysis

To understand the potential risks and limitations of the model and approach presented in this thesis, as well as how decision-makers might make use of it, a *What-if* analysis was conducted. This also allowed for better understanding how different valuations of different ES affected model results. The What-if analysis was based on different value-weightings for different ES demands. Three scenarios were selected to illustrate differing views on the value of NbS. These scenarios included the following: a base case, with all ES factors equally weighted, a social valuation case, where more socio-economically related ES were given larger weights, and one geophysical valuation case, where only physical ES such as flood risk were considered. This analysis also evaluated the impact of decision-makers differing valuations of social factors and geo-physical factors.

3.4 Contexualising the approach

In order to contextualise the developed framework and model to the case study of Cape Town, the perspectives of experts in the fields of Cape Town governance, conservation, and nature-based solutions were obtained through semi-structured interviews. The interview participants were identified by leveraging the author's professional network, as well as using referrals on this basis in a snowball approach. Interview participants were chosen based on their experience within the following domains: Cape Town governance, inequality and vulnerabilities in the city, and nature-based solutions and social-ecological system management.

In this way five interviewees were identified. The five interviewees had, respectively, experience in large conservation and nature-promoting non-governmental organisations, research experience into the Cape Town socio-spatial landscape, legal and local government experience, technical experience in the implementation of NbS, as well as political and activist experience in the Cape Town urban area. All interview participants were also asked to rate their own experience in terms of three topics: governance in Cape Town, NbS, and Cape Town's vulnerabilities and inequalities through which all reported previous experience with NbS implementations.

An interview protocol (appendix B table B.2) was created so that semi-structured interviews could be held in order to facilitate the flow of conversation, and to allow participants to expand on areas of their expertise. The questions in the interview protocol were mainly aimed at establishing three concepts:

- Barriers and considerations towards implementing NbS in Cape Town,
- The interactions of NbS with vulnerable populations,
- Governance of Cape Town as part of this case study.

Interview participants were also shown a visual aid to explain the three concepts, their relation to each other and the thesis. This visual aid, shown in figure 3.5, proved to be a valuable conceptual starting point and aided in scoping the interview and thesis (yellow-white dot).

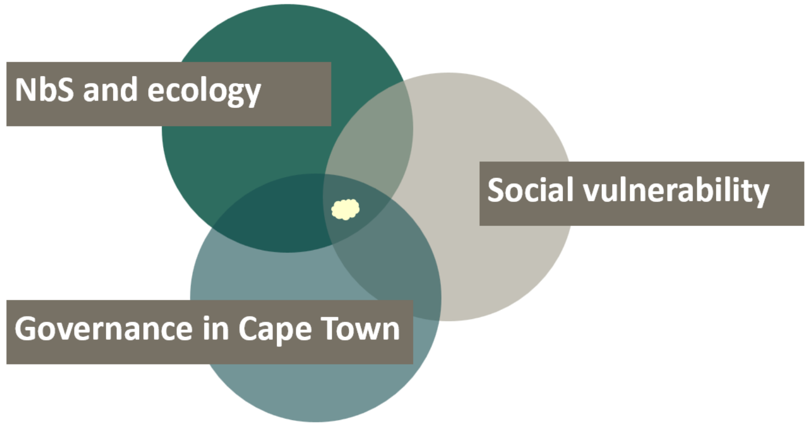


Figure 3.5: Visual aid to explain concepts related to the interview

Interviews were conducted between April and June 2023 in-person or virtually. After the interviews were conducted, they were transcribed and the transcriptions coded through a grounded theory approach, while observing regulations and protocols of TU Delft's Human Research Ethics Committee. This helped to identify the main problems surrounding NbS implementations in Cape Town, as well as capturing specific contextual factors that would otherwise not have been captured. For more information on the coding process, see appendix B.

4. Results

This chapter provides results for the proposed approach. Firstly, results of creating a social vulnerability framework for ES demand is presented to allow for using SoVI methods to determine ES demand in section 4.1. This is followed by the results of geo-physical data collection and flood risk estimation in section 4.2. The results of applying the NbS matching and prioritisation model to the mapped ES demand is presented in section 4.3, and is followed by results of verification, validation and comparison tests in section 4.4. Finally, results from expert interviews are presented and framed in terms of the climate-just NbS approach presented here for contextualisation in section 4.5.

4.1 Social vulnerability framework for ES demand

The framework presented in section 3.2, introduces explicit consideration of representational and distributional justice in the analysed areas. The ES demand of these vulnerable communities are directly taken into account for NbS selection and prioritisation concerns - representing their needs in this decision-support approach. Furthermore, through the prioritisation feature (of which results are shown in section 4.3), the approach allows for distributing limited resources to those who are most vulnerable. In this framework, all ES demand factors were weighted equally for the base case, although one could argue that some must be weighted more heavily, as they represent multiple dimensions of social vulnerability.

To evaluate the usefulness of the selected indicators (provided in section 3.2.1) in explaining variance for different ES demand factors, the correlation between them was determined. In interest of brevity, only the correlation for the indicators of the *water quality* ES is shown in figure 4.1. Correlations are visible between all the parameters. The distributions of the three water quality indicators also show that most wards have access to piped water, city water and flush toilets in the city. These strong correlations indicate that we could expect the PCA-calculated index to capture a large amount of variance which is more desirable for meaningful demand factors.

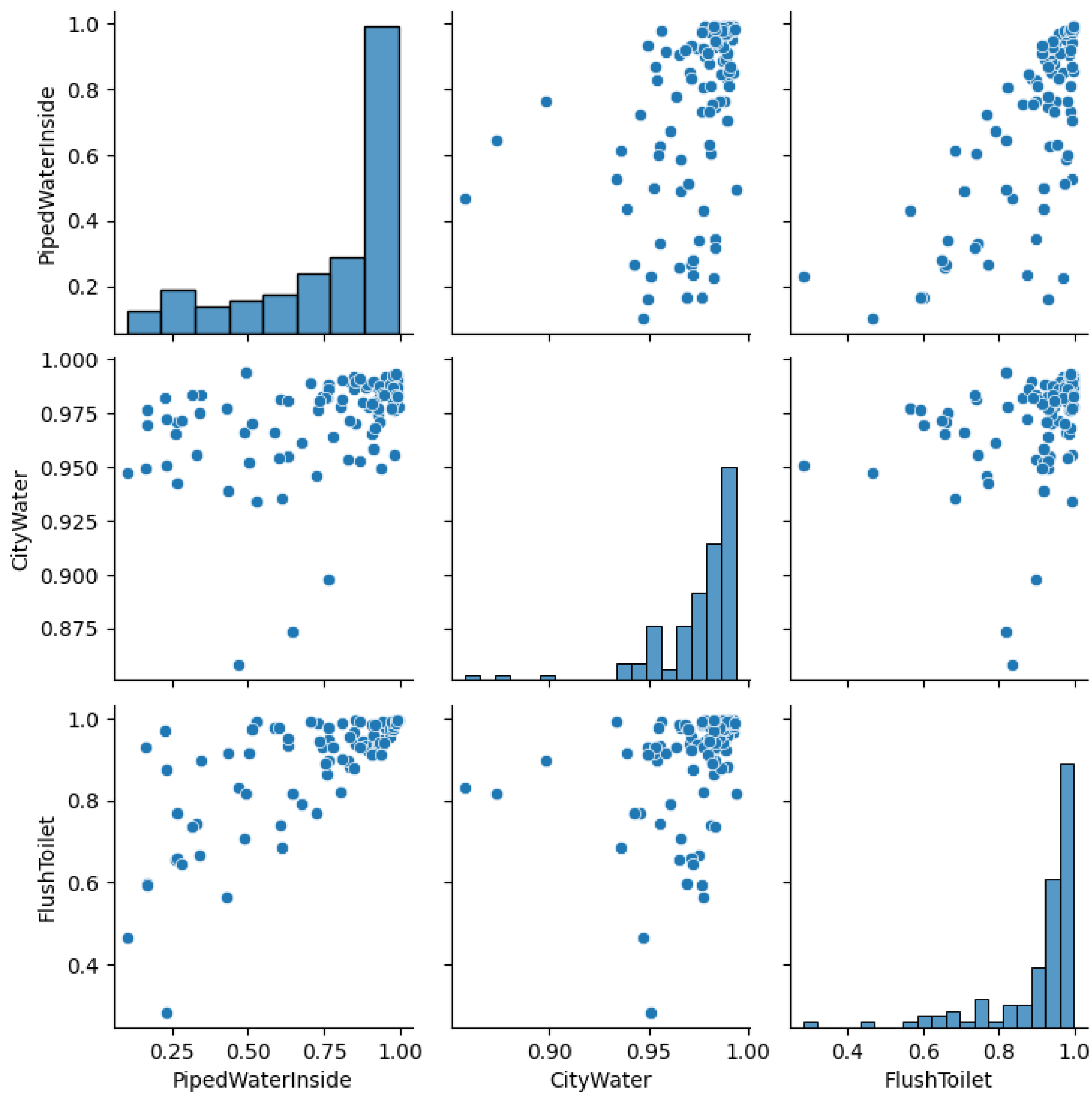


Figure 4.1: Correlation between the different indicators used to determine the water quality ES demand factor

Using these indicators, the demand factors for each ES was determined for all wards. In figure 4.2 the demand factors for two ES, social interaction (labelled simply "social") and water, are shown. From these maps, the difference in distribution of demand factors become clear: some ES, such as social interaction, are much more widely demanded than other ES such as water. To see all ES demand factors mapped, see figure 4.3b.

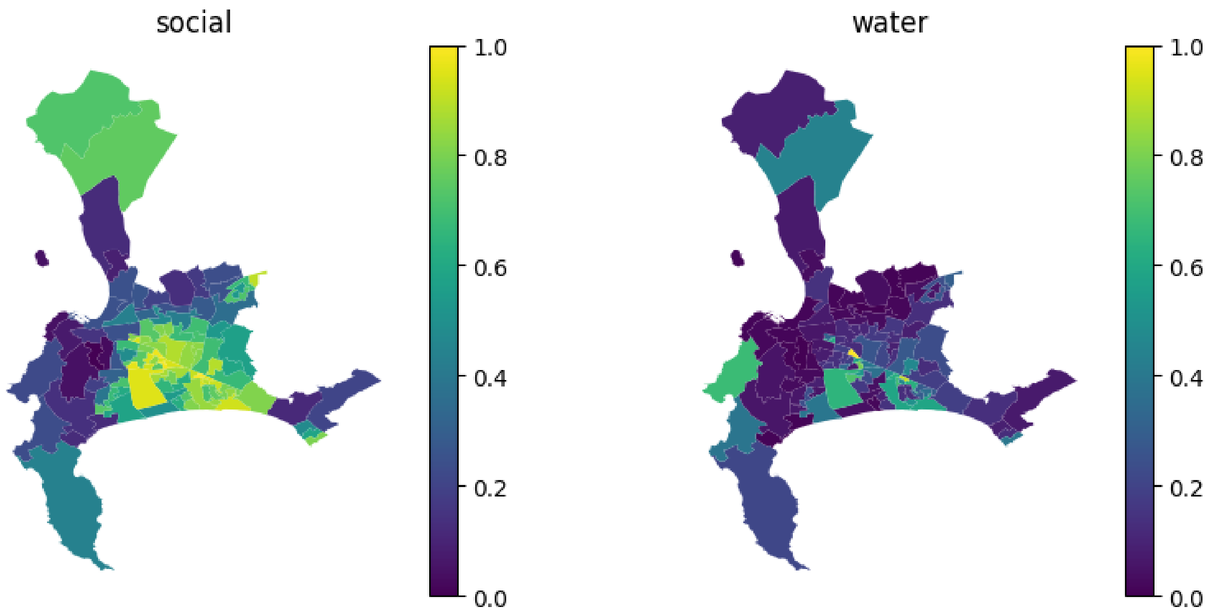
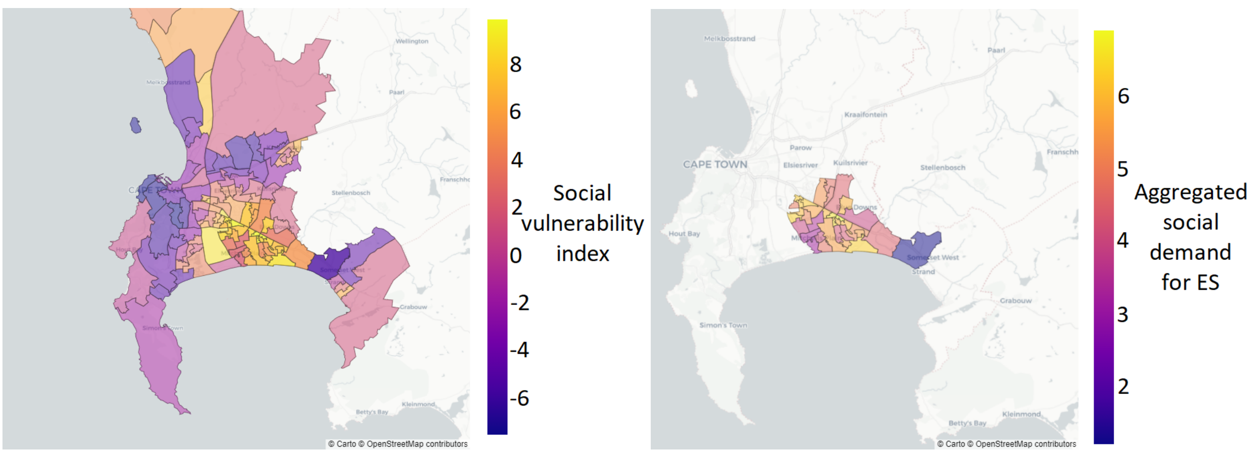


Figure 4.2: Demand factors for social interaction and water ES

The overall SoVI was also calculated using Apotsos (2019)'s methodology, which was then, among other factors, used to select a limited number of wards for further processing (shown in figure 4.3a). A notoriously vulnerable area in the city of Cape Town is known as the Cape Flats to where many people were forcefully located to during the Apartheid government regime, far from the urban core of the city (where most jobs are located) and often without proper infrastructure or services.

The selected wards, plotted in figure 4.3b, do not make up the entirety of the Cape Flats, due to the following reasons:

- Some Cape Flats wards were excluded due to differing city features (for example, the Philippi farmlands that consist of rural homesteads and small farms, or the Cape Town International Airport),
- Some wards outside the Cape Flats, in the region of Firgrove, were included to capture the natural floodplains and dunes in the area. Additionally, the socio-economical differences between the area allow for insightful context-giving to the range of inequalities within the city.



(a) PCA-calculated social vulnerability index in Cape Town (Apotsos 2019)

(b) Aggregated social demand for ES in analysed Cape Town wards

Figure 4.3: Social vulnerability in Cape Town and the analysed area

This historical inequality is reflected in the calculated SoVi, shown for all wards in Cape Town in figure 4.3a. The SoVi shown in this figure, ranges from -8 to 8 and indicates a unit-less magnitude of social vulnerability, useful only in comparison with other wards. The first and second components, respectively, covered 46 % and 18 % of all variance in the input components – typically considered as still being useful for SoVI calculation (Vincent 2004). From this, the aggregated social demand for ES were calculated for the selected wards by aggregating the social demand for each ES (including social interaction and water shown in figure 4.2), which is shown in figure 4.3. It is visually evident that there is a strong similarity between the literature-based SoVI and the aggregated social demand for ES. The social demand for each ES per ward is shown in figure 4.3b. PCA variance explanations, which provides more information on the calculation of each ES demand factor with PCA, can be found in appendix A table A.2.

4.2 Land-use and land features

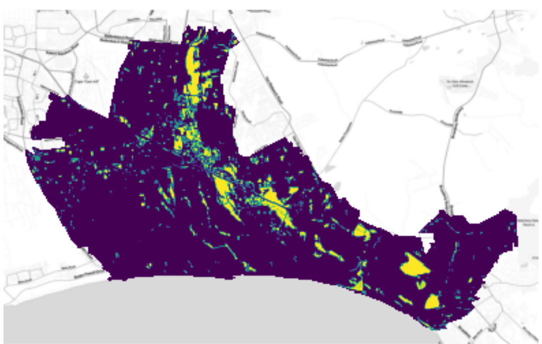
While social vulnerability to climate change involves many socio-economic factors, physical and geographical features, such as flood risk, are also important. Furthermore, to establish more practical recommendations for NbS placement and selection, zoning and land-use are also important.

4.2.1 Land-use

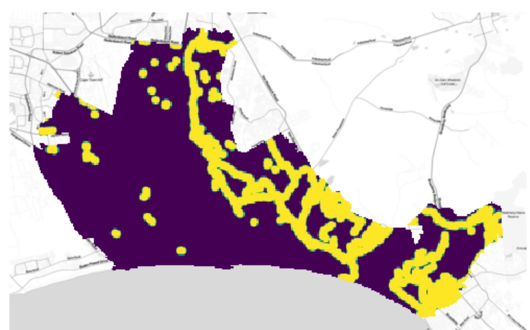
Land-use and zoning play a particularly important role in the city of Cape Town with regards to urban planning and development. Particularly, new developments need to be placed in the appropriate zone, and requests for changes to zoning are known to be a time-intensive process, as mentioned during some expert interviews. With publicly available zoning maps from the Cape Town Open Data Portal (City Council of Cape Town 2020b), zones were categorised based on whether the construction of certain NbS would be allowed within current land-use regulations. By consulting the City's integrated zoning scheme (City Council of Cape Town 2016), it was determined in which zones an urban agriculture solution, for example, could be implemented without additional consent, and so forth. The complete mapping of allowed NbS per zoning type can be found in the appendix A in table A.3.

4.2.2 Flood risk

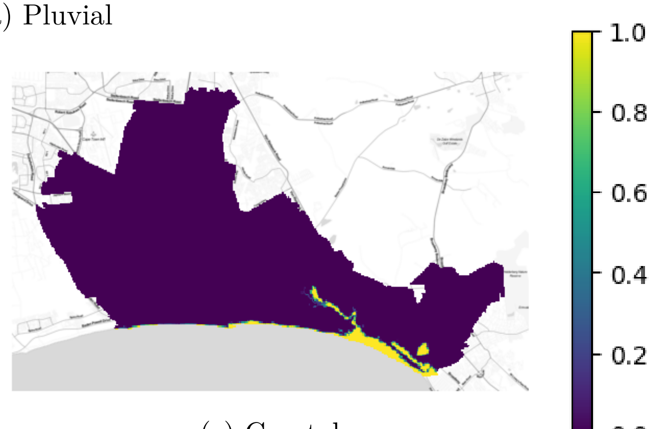
The normalised flood risk based on the flood-risk proxy layers are shown in figure 4.4. Cells that were determined to have a high flood risk (of the various different types), were assigned higher values for that flood type. For pluvial flooding, any cells that were part of the City of Cape Town's open stormwater body layer were determined as having high risk. For fluvial flooding, these were cells within a range of approximately 1.5 km of the river's center line were determined as being high risk. This represented a pessimistic view on the extent of fluvial flooding. Finally, for coastal flooding, cells that were 5m or lower below sea-level were marked as being high risk - representing an pessimistic case of sea-level rise for the short-term future, inline with Cape Town's climate risk estimations (AFD Consulting 2019). These risk values were then normalised between 0 and 1, from low or no risk to high risk. From these maps, two flood-risk hotspots become apparent: along the Kuilsriver for pluvial and fluvial flooding, and along the eastern coast side for coastal flooding.



(a) Pluvial



(b) Fluvial



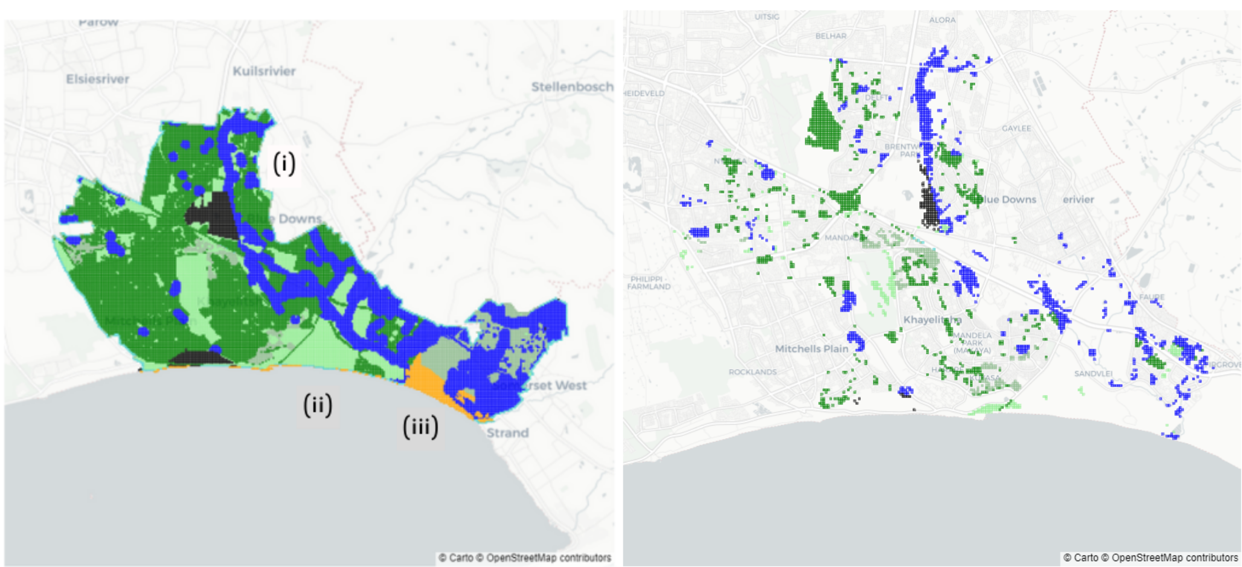
(c) Coastal

Figure 4.4: High (1) to low (0) simplified flood risk of the selected neighbourhoods

4.3 Nature-based solutions

Figure 4.5: Legend for plotted nature-based solutions

After determining ecosystem service demand, these demands could be matched to specific nature-based solutions that offered those ecosystem services, and prioritised based on the highest 10% of aggregated demand for ecosystem services. This prioritisation factor is selected as 10% based on a sensitivity analysis of the impact of prioritisation on NbS selection-error (see section 4.4.2). In figure 4.6 the results of this analysis are plotted for all cells under consideration (4.6a) and also for those cells with the highest demand, or priority, for ecosystem services (4.6b). It becomes clear that certain nature-based solutions dominate – particularly river projects for the water ways (blue), and urban green space (dark green) and urban agriculture (light green) elsewhere.



(a) Preferred nature-based solutions

(b) Prioritised nature-based solutions

Figure 4.6: PCA-calculated NbS preferences

When looking at the prioritisation of NbS in figure 4.6b, we see how the course of the Kuils river (i) is most suitable for river projects, while urban agriculture is particularly preferred over the agriculturally zoned area close to the Macassar dunes (ii). Additionally, the only place where beach and dune projects are recommended, are on the banks of the Helderberg marine protected area (iii), likely due to its low elevation above sea-level. When these NbS are prioritised for aggregated ES demand, however, we see a few pockets that have the highest demand for its respective NbS. This indicates that, while each cell has its preferred NbS, some areas have a higher ES demand for certain NbS.

4.3.1 The impact of different factor valuing

To answer sub-research question 3, it is required to understand where the demand for ecosystem services is higher from both a social and ecological perspective. To better understand that and gain an insight into the distribution of ES demand and how different perceptions of decision-makers might affect the output of this approach, different ecosystem service weighting schemes are utilised to determine the aggregated demand. These weighting schemes change the weights of certain factors in determining the demand for particular ecosystem services, illustrating how outcomes would change if certain ecosystem services were valued more than others. In interest of understanding the impacts of these weights, different weighting schemes assign a value of either 0, 0.5, or 1 to a weight to reflect the importance of each

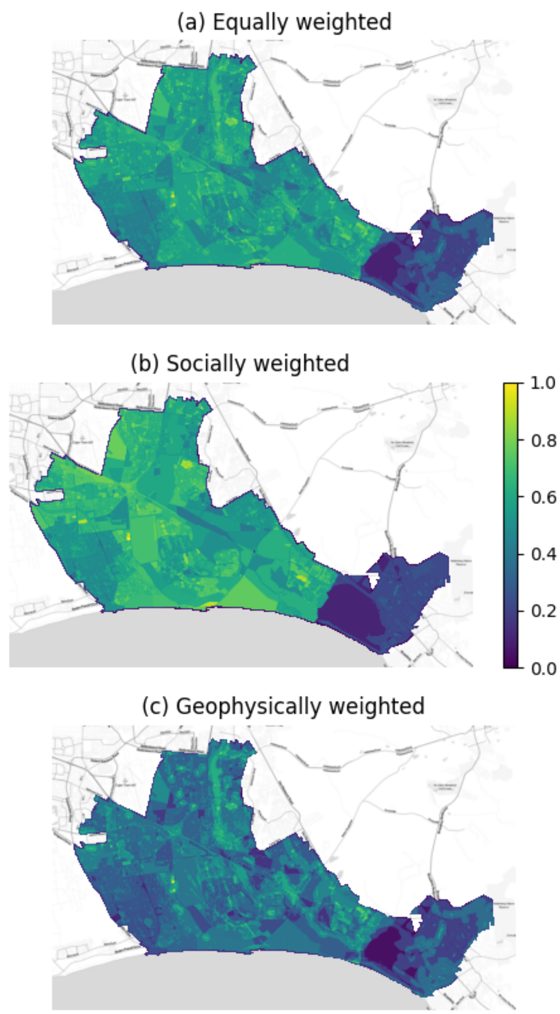


Figure 4.7: Normalised aggregated ES demand

factor in the respective weighting scheme: 0 is completely excluded, 0.5 is partially important, and 1 is important in the weighting scheme. This simplistic weightings, while not extensive, allow for greater insight while not greatly increasing computational requirements or conceptual complexity. The specific weights for each weighting scheme can be seen in table 4.1.

Comparing these different weighting schemes allow for understanding how changes in ecosystem service valuation might affect the most suitable NbS. This is also important for decision-support: investigating the impacts of these different weighting schemes helps to evaluate the impacts of decision-makers with different value-weightings. For policy-makers that value social factors more than physical ones, for example, aggregated ES demand would be adapted accordingly, and different areas would be prioritised.

In figure 4.7, the aggregated ecosystem service demand is plotted for these different weighting schemes. Here, it already becomes clear what role socio-economic and geophysical factors play individually, and how equal weighting (a) incorporates both. One example of this is the Kuils river that flows vertically from the top to the middle of the map. In both equally weighted and geophysically weighted schemes, a high ecosystem service demand is found due to the increased flood risk close to the river, while this is not directly visible in the socially weighted scheme.

Table 4.1: Ecosystem service weights for different weighting schemes

Ecosystem service	Equally weighted	Socially weighted	Geophysically weighted
Heat stress reduction	1	0.5	1
Economic	1	1	0
Resource production	1	1	0
Health	1	1	0
Culture	1	1	0
Coastal	1	0	1
Fluvial	1	0	1
Pluvial	1	0	1
Social interaction	1	1	0
Water quality	1	0.5	1
Education	1	1	0

4.3.2 What-if analysis

Table 4.2 represents the results of a *What-if analysis* – where we see the impacts on NbS coverage over the entire area of analysis, as well as the prioritised areas, when the valuation of different ecosystem services are changed based on the different weighting schemes provided in section 4.3.1. From this table, it is clear that urban agriculture and urban green space solutions appear to target social demands more, as these are selected by the socially weighted scheme. Wetlands, on the other hand, target geophysical demands (flooding, water quality and heat stress) more – indicating that it might be a less desirable solution from a social perspective.

Table 4.2: Coverage percentage of each nature-based solution

Nature-based solution	Equally weighted		Socially weighted		Geophysically weighted	
	Tot	Prio	Tot	Prio	Tot	Prio
Green building	8.22	2.99	6.44	0.45	30.42	7.74
Beach and dunes	2.20	0	2.59	0.58	1.18	0
Wetland	3.54	0.22	2.91	0.06	64.80	87.64
Urban green space	41.21	22.47	31.94	51.69	0	0
River project	25.21	65.46	2.20	0.58	0	0
Urban agriculture	16.64	4.24	50.94	42.60	0.63	0
Conservation	2.97	4.62	2.97	4.62	2.97	4.62

Additionally, it is interesting to see which NbS are not preferred in these areas at all. Urban forests, for example, were never the primary suitable solution, and was so excluded from table 4.2. This exclusion comes from the ES supply profile of urban forests that are closely aligned to that of urban green space, but falling short in terms of a few ES, namely social interaction and economical stimulation. Here, the categorising NbS in discrete groups clearly impacts the model results. In reality, some urban forest might potentially provide more social interaction than some urban green space due to contextual factors. Indeed, this is often seen as the case with the culturally and socially important Tokai forest (Ernstson 2013). This again illustrates the importance of ground-truthing and contextualising, while also calling for a more flexible model in terms of NbS categorisations. This aforementioned limitation results in urban forests being almost always outperformed by urban green space. Other solutions, such as beach and dune projects, remained at low coverages due to additional constraints on beach project placement (on the coast). Conservation (black) is shown to still be present in all scenarios, due to the fact that new NbS projects are not able to be implemented in land that is already zoned for conservation purposes. While these areas might already be providing ES to the surrounding communities, it is clear from the prioritisation analysis that those communities and areas still have a significantly high demand for ES. For the decision-maker, this means that some areas that are marked as a conservation area, are socially vulnerable. While NbS implementations are useful in other areas, here focus should be put on making the ES of the conservation area accessible to the nearby communities, without compromising the biodiversity of the area.

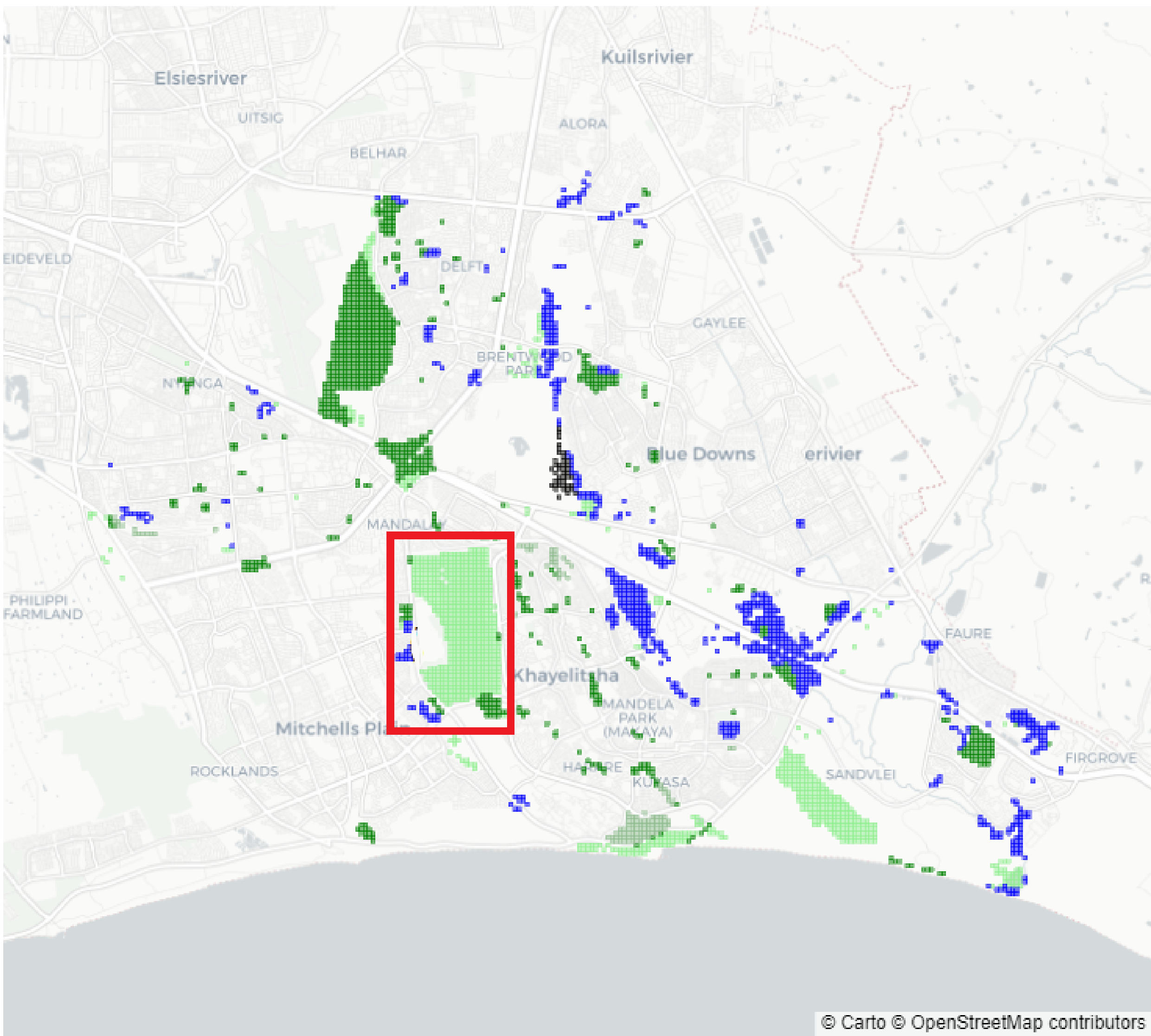
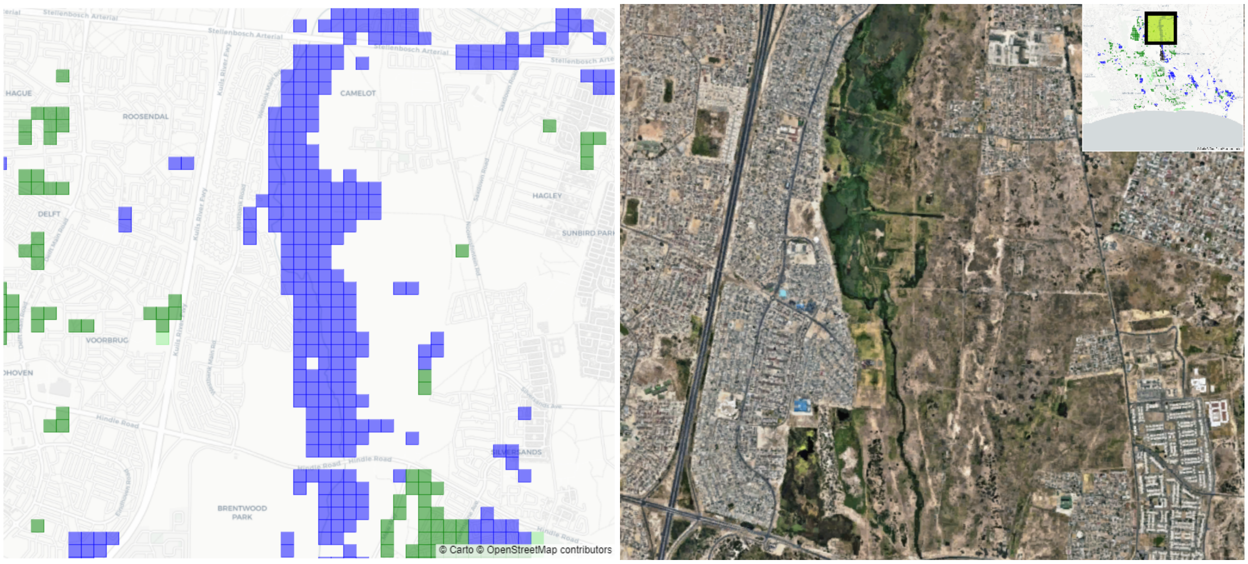


Figure 4.8: Prioritised NbS solutions for biodiversity increase

The impacts of valuing biodiversity was also evaluated, using indigenous vegetation as a proxy. This was done by comparing the base case, with no biodiversity included in ecosystem service demand, to a case where areas with pre-exisiting indigenous vegetation (equated to areas with higher biodiversity) were also given more importance. This was based on the City of Cape Town's Biodiversity Network data (City Council of Cape Town 2019) and data available from the Cape Town Open Data Portal (City Council of Cape Town 2020b). In figure 4.8, the differences in prioritised areas can clearly be seen. Some areas, such as the area surrounding the False Bay TVET College Swartklip campus (shown with the red rectangle), are prioritised. The usefulness of these insights, however, might break down upon considering the value conflicts of urban nature-based solutions that are intended to be open and accessible to the public as opposed to conserved areas that are often protected from the public. The Swartklip area, for example, might not best preserve its biodiversity through the creation of the suggested urban agriculture projects with large mono-culture planting approaches.

4.3.3 Prioritised areas

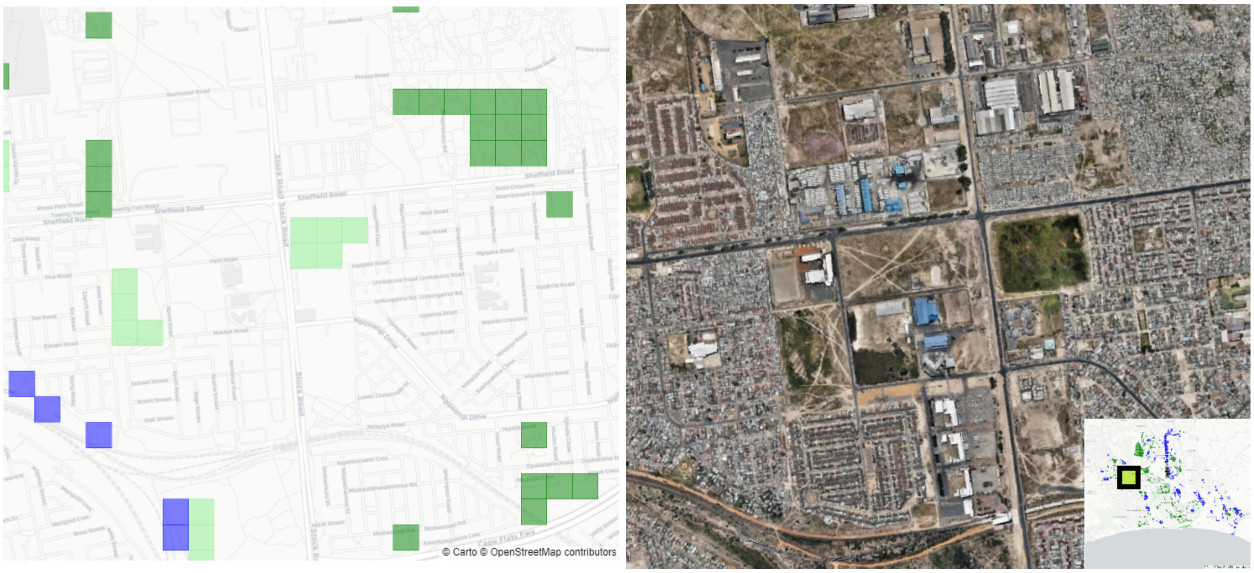
It is interesting to take a more in-depth look at some of the prioritised NbS cells. We see both larger NbS recommendations, such as a river project at the upper Kuils river (figure 4.9), as well as smaller, more specific recommendations, such as urban agriculture and urban green areas in Philippi East (figure 4.10).



(a) Preferred nature-based solutions (b) Satellite image

Figure 4.9: Large scale NbS: The upper Kuils river, Delft, Cape Town

The river project (blue) recommended for the upper Kuils river, shown in figure 4.9a, shows that surrounding areas might benefit from this larger scale NbS being implemented there. When comparing to satellite imagery of the same area, shown in figure 4.9b, we see that there are indeed big portions of open land next to the river. The model, which operates only at a local level (meaning ES demand is assumed to be met by NbS only within the same cell) here prioritises some areas that contain open space. This interesting behaviour is due to how socio-demographic data, provided from the 2011 South African census aggregated by ward, were sampled into cells. Thus, cells with open space are marked as vulnerable – when in reality no-one lives there. Since the census only has data on a ward-level, it is also practically difficult to determine the number of such "empty" cells, and is a considered limitation of such a quantitative approach as is taken in this thesis in that limitations of the data source are transferred to the approach that uses it.



(a) Preferred nature-based solutions

(b) Satellite image

Figure 4.10: Small scale NbS: Philippi East, Cape Town

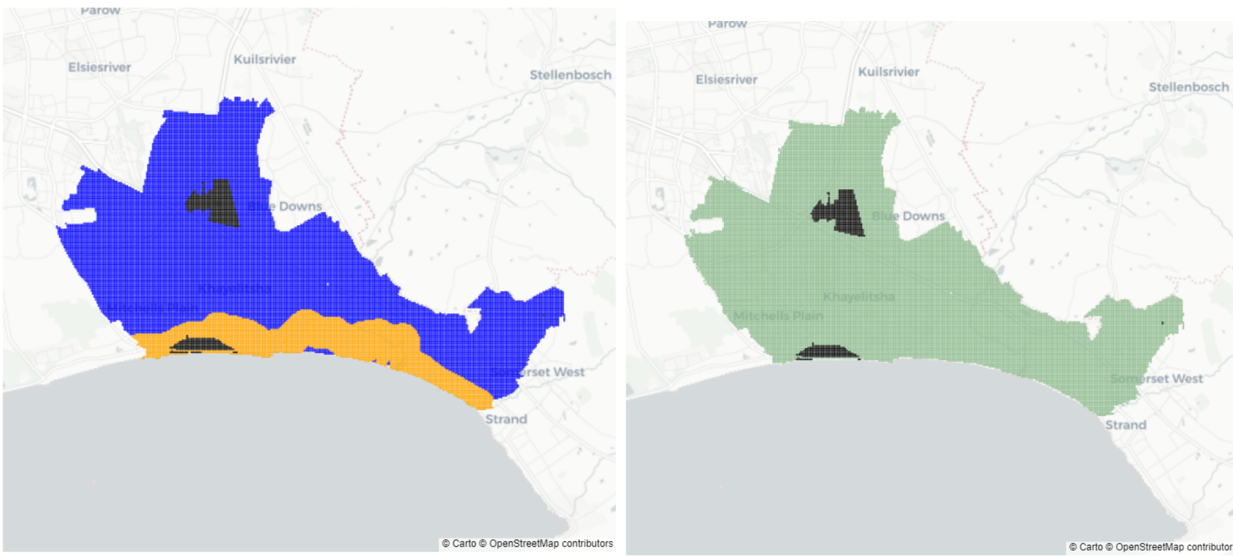
In figure 4.10a, we see some smaller scale NbS being recommended for the Philippi East area – specifically urban agriculture and urban green space. As opposed to the river project shown earlier, these projects are much more tightly integrated into the community. Indeed, when looking at the corresponding satellite imagery in figure 4.10b, we see that the preferred NbS do correspond to open, centrally located areas in the area. Notably, however, we also see that some of the recommended NbS, such as the north-eastern urban green space (dark green) are in reality covered by informal settlements. While this does not exclude this as a potential solution for the area, the scale would have to be different and take the existing structures into account – which further can increase implementation complexity and cost.

4.4 Verification and comparison

In this section, the results of the verification and comparison tests are shown. This is important for understanding the usefulness and potential risks of this approach for decision-support for urban NbS planning.

4.4.1 Verification of NbS matching algorithm

The NbS matching algorithm was verified to ensure that it functioned as designed. This was done by changing valuation of demand factors to match those of a single NbS – with the expected result that only the matched NbS would then be preferred over the entire analysis, as this NbS would be the maximum benefit option. This would be the case everywhere, except where there are strict rules for where a given NbS cannot be implemented: conservation areas, and beach projects required to be close to the coast. When these tests were run with value weighting matching the profiles of the beach project and green building respectively, the results shown in figure 4.11 were obtained with the expected behaviour.



(a) Value weighting set to beach project profile (b) Value weighting set to green building profile

Figure 4.11: NbS matching model verification

Importantly, the land-use limitations were not included in this verification test. This is due to how land-use is implemented in the model: where certain NbS are allowed in a land-use zoning (such as urban green space in a general residential zone), the aggregated ES demand for that NbS is increased, while for cases where NbS are not allowed (an urban farm in a single residential area, for example) the aggregated ES demand is unchanged. In this way, zoning does not outright block any NbS from being implemented, but rather makes some NbS appear more attractive and suitable than others due to fewer legal and zoning barriers. The reasoning is that, in cases where the ES demand for a certain NbS is particularly high in an area despite zoning differences, special consent can be obtained for its implementation.

4.4.2 Sensitivity of prioritisation

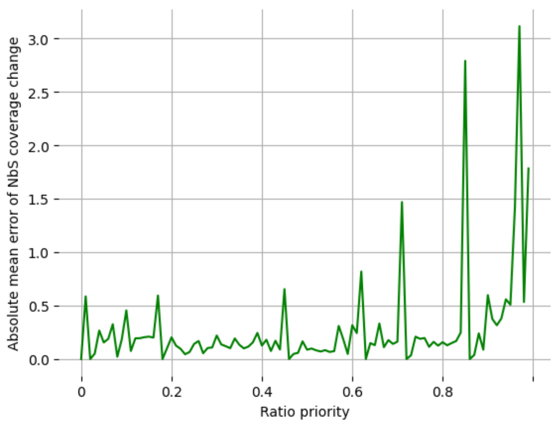


Figure 4.12: Sensitivity test for priority cell selection

In figure 4.12 the error between successive iterations of a smaller and smaller number of prioritised cells in terms of coverage, calculated with equation 3.1 in section 3.3.4, is plotted. This error shows the average change in overall coverage ratio over all NbS if the number of prioritised cells are decreased. In figure 4.12 it is clear that the prioritisation proportion becomes more sensitive as more cells are excluded. To select a prioritisation proportion in a relatively stable range of operation, while still making a meaningful exclusion of non-prioritised cells, a prioritisation proportion of 90% was selected. This means that the cells that had the top 10% of aggregated ecosystem service demand were considered as priority cells.

4.4.3 Comparison with social vulnerability calculation

As the ecosystem service demands are constructed indicators, additional comparison can provide additional insight into these methods. While this does not provide direct validation of either method, it is important to note that vulnerability is an abstract and subjective concept and, as such, is practically difficult to accurately validate. Accordingly, comparison is required to ensure that the values, calculated through PCA, realistically and representatively reflect the defined vulnerability of the real population.

The cross-correlation per ward of the PCA-determined and direct vulnerability counting (see section 3.3.6) ES demand factors are shown in table 4.3, with all demand factors being strongly correlated, except for notably the social interaction and cultural ES demand factors, potentially due to the difficult nature of quantifying cultural value. This indicates a limitation in the model in terms of conclusions to be drawn from cultural ES demand.

Table 4.3: Cross-correlation between PCA and directly counted vulnerabilities

Ecosystem service	Cross-correlation
Social interaction	0.757932
Water quality	0.954115
Education	0.962401
Heat stress reduction	0.927271
Economic	0.940861
Resource production	0.989924
Human health	0.906119
Culture	0.096144

Additionally, the determination of aggregated ecosystem service demand is spatially consistent with PCA calculated social vulnerability indices in past studies (Apotsos 2019), and can be found in appendix A.

4.5 Expert interviews

Although the NbS matching model was created based on relevant literature and applied on data sets of Cape Town, further contextualisation is crucial for the practicality and usability of results. Furthermore, qualitatively contextualising the model and its implications allows for better understanding into the social vulnerability-informed ES demand framework. Interviews were conducted with five individuals in the fields of nature-based solutions, Cape Town governance, and social inequalities in the city. As only five experts were consulted, they were selected to cover different domains which this thesis consists of. Furthermore, no statistical conclusions were drawn from these interviews due to the limited sample size. Instead, interviews were used to explore the range of contextual factors that affect the implementation of NbS in Cape Town: barriers and considerations of implementation, prioritisation of implementations, and unique dynamics within the Cape Town arena. For detailed information on interview coding and the interview protocol, see appendix B.

4.5.1 Barriers and considerations

Participants were asked about challenges facing Cape Town in general, but also what they perceived as barriers towards the implementation of NbS in the city. Their responses were classified under three categories. The fist category related to political barriers (41 instances) – including a lack of political will, government coordination, and community involvement (as illustrated in Box 6) – due in part to a lack of evidence and bad governance. The second category, financial barriers (10 instances) explained the practical financial limitations of implementing such projects, including cooperation with the private sector. The third category involved geographical barriers (17 instances), mostly concerning the required space of NbS, how they can be scaled up, as well as the restrictions imposed by city zoning schemes. Due in part to these barriers, participants expressed the importance of prioritisation (8 instances).

Box 6: Quote from interviewee 3

About a local municipal councillor – “He said don’t teach the same citizen engagement. Communities don’t know what they want.”

Interestingly, when asked about special considerations that should be taken when implementing NbS, participants gave mostly social considerations (42 instances), such as involving the community, effective communication, job creation, and security concerns. Security is a major concern for NbS implementations, both practically and optically, as communities can see this issue as a disservice of NbS.

4.5.2 Prioritisation

As mentioned, prioritisation was mentioned as an important factor. With limited resources, the most effective areas should be selected. When asked how ES were distributed among different groups, respondents' answers were categorised in three ways. Firstly, context (8 instances) was shown to be important in how ecosystems interact with communities, as that depends on the socio-economic class and urbanisation status of the community. Secondly, some ES were mentioned to be more important to the vulnerable (40 instances), particularly in terms of community building, security, social justice and job creation. On the other hand, differing trends were mentioned that determine these interactions and reliance on ES (18 instances), such as rural-urban divides, community resilience and adaptive capacity. An interesting concept that was also mentioned, is that of *epistemic distance*. Epistemic distance can be defined as the distance between where an ES is produced and where it is consumed (Leyshon 2014). More vulnerable communities are said to have a shorter epistemic distance to ecosystem services, and so benefit from them more directly, such as through resource production in the form of food or medicine. Other, more well-off communities have a larger epistemic distance and only see indirect benefits from ecosystems, such as air filtration. This direct relation for vulnerable communities results in greater sensitivity to ecosystem disruption; vulnerable communities will feel the absence of the firewood-providing forest much faster than well-off communities will feel the absence of an air-purifying garden. As shown in Box 7, the concept of racially-based ES became apparent, which even more emphasised the need for prioritisation of NbS planning. Indeed, an important feature of some interviews was understanding who the real benefactors would be of such NbS implementation. Often, such implementations are promoted and marketed as benefiting vulnerable groups, whereas in reality, they mostly cater to populations with more power (financially or politically).

Box 7: Quote from interviewee 1

"And I guess what we must ask ourselves, you know, I talk about Cape Nature and and so forth, who benefits from the good governance of natural resources that's occurring there? You know what is nature being being governed for as a kind of area of recreation for for white people or, you know, tourists in South Africa or are we actually really saying, well, listen, how can we – how can people living in these poor areas benefit from these protected areas and and the kind of pristine environment that, that, that earmarks some part of of Cape Town. "

4.5.3 The Cape Town arena

To understand additional contextual factors that might affect the model and the ES demand framework, participants were also asked to describe the uniqueness of Cape Town. Firstly, Cape Town's geo-physical uniqueness was mentioned (24 instances), particularly in terms of its urban layout and infrastructure, as well as disproportionate benefits of nature. Secondly, Cape Town's social uniqueness (33 instances) was identified, particularly in terms of its spatial inequality as part of its Apartheid legacy (see Box 8), but also the importance of tourism in many sectors of the economy. The effects of the Apartheid government's forced expropriation of populations from their homes are still significantly impacting the fabric of the city, with some urban policies by newer administra-

Box 8: Quote from interviewee 5

"You know and and and then what has happened is people have been moved and relocated to even further away communities, perhaps on a flood plain. But even further from their jobs, their communities" tions only reinforcing inequality (albeit unintentionally). Finally, Cape Town's uniqueness in terms of governance (19 instances) was mentioned, particularly with regards to the relatively better level of governance when compared to other cities in South Africa, as well as the level of priority that conservation enjoys.

Conservation plays an interesting role in this arena. Participants indicated that conservation might either impede (9 instances) or help in promoting (7 instances) nature-based solutions, due to the complex relationships between social-ecological systems. This is indicative of a larger value-conflict in this arena - at which point should nature's utility to human populations take precedence over its conservation? Indeed, conservation in South Africa typically follows a strict preservation approach, minimising community-ecosystem interactions. This is due to, among other things, a strong conservation tradition (South Africa's protected areas are some of the oldest on the continent (O'Farrell et al. 2012)), but also significant global and national pressure to conserve nature. Access to well-governed conservation areas are often limited to wealthier areas, which impacts access to the ES, such as recreation and flood risk mitigation, that they potentially provide.

4.5.4 The NbS matching model in context

Based on the contextual factors extracted from the interviews, the NbS model was evaluated to gather insight into which dynamics were captured by the model or not in table 4.4. It is important to note, however, that this does not directly explain the models usefulness or accuracy, but rather frames the results obtained in the larger context of urban NbS planning. Additionally, table 4.4 shows possible future expansions to the model to potentially improve results.

Table 4.4: Evaluation of contextual concepts in the NbS matching model

Contextual concept	Implemented in model	Corresponding model component
Political barriers	No	NA
Financial barriers	No	NA
Geographical barriers	Yes	Land-use, geographical maps
Prioritisation	Yes	Prioritisation based on aggregated ES demand
Epistemic distance	No	NA
Spatial inequality	Yes	Social vulnerability to climate change
Conservation	Partially	Incorporation of conservation as a land-use, but not capturing its ES supply

Interview participants were also asked about the role, and potential risks, of a data-informed tool such as is presented here could carry when used for decision-making. While participants cited the importance of risk management (4 instances), they also expressed the severe need of data-informed decision-making for policy makers in Cape Town (6 instances) and welcomed such a tool and its potential insights to decision-support for policy-makers.

5. Discussion

From this study, several insights are provided for both practitioners and researchers in the field of NbS planning. These insights are discussed in this section.

5.1 Framework and model

In creating a social vulnerability framework to determine the demand for ecosystem services, easily accessible quantitative data sets can be used to determine the magnitude, and nature, of ecosystem service demand in urban areas. Mapping the many, often abstract ecosystem services that NbS provide to existing vulnerability frameworks, also allows for an improved understanding of the relationships between urban NbS and social vulnerability. This framing of ecosystem services through social vulnerability carries the following benefits:

1. An implicit focus on climate justice is placed by the prioritisation of socially vulnerable persons,
2. Social demand for ES can be approximated without using qualitative, and often difficult to gather, primary data sources, and
3. A clearer conceptualisation is created of the relationships between NbS and social vulnerability to climate change.

Through this focus on climate justice, the framework explicitly introduces concepts of representational and distributional justice. Representational justice is incorporated through how the specific ES demands of vulnerable communities are taken into account - reflecting their needs directly in the preferred and prioritised NbS. Distributional justice is incorporated through the prioritisation mechanic; NbS are selected and placed wherer their benefits can be distributed to those who need them the most.

It was also found, however, that some concepts remain difficult to capture quanitatively, such as ecosystem services like cultural value and social interaction. More research is required into better defining these parameters, while remaining cognisant of the importance of local context when making these valuations.

With the creation of the NbS matching model, the aforementioned NbS-vulnerability relationships were visualised on a case study of Cape Town, South Africa. Using different ES value weighting schemes illustrated how some NbS are more tightly coupled with social factors such as economic opportunity and health (such as urban agriculture), while others have more influence over geographic factors such as flood risk (such as wetlands). The issue of prioritisation was found to be important in the urban planning sphere. This was incorporated by the matching model through two prioritisation decisions:

1. Which NbS is the most suitable for a given area, and
2. Which areas in the urban sphere should be prioritised.

With the incorporation of various land-use and land feature maps, other important factors such as zoning regulation, technical NbS requirements, and existing conserved areas could be taken into account. While some of these maps, such as flood risk maps, were simplified proxies of actual flood risk, the modular nature of this NbS model allows for easily improving these dependent models at a later time. This all results in a tool that can aid policy-makers in selecting areas for urban NbS intervention, so that their limited funds can create maximum impact. While these insights can be obtained from the model, it is important that the results be contextualised, and not used as definitive fact. In the case of urban agriculture, for example, community farms and vegetable patches have often been implemented in vulnerable communities with limited or no success (as was also mentioned in expert interviews). These results should thus only serve as an indicator of where these NbS are most demanded, but if this demand is adequately met by an actual NbS depends on the implementation trajectory itself.

5.2 Expert interviews

During the expert interviews, the social vulnerability framework and NbS matching model were contextualised further to the case study of Cape Town, in an effort to partly evaluate dynamics that the model might not have captured, but also to provide a more realistic set of considerations and limitations for policy makers to accompany the results of the NbS matching model. This contextualisation step is shown to be important based on both literature (see section 2.2) and expert interviews. Particularly, several contextual concepts such as political barriers (political support, community engagement and poor governance), financial barriers (cooperation with the private sector and funding for projects) and epistemic distance (the degree to which ES are used directly or indirectly) were not included explicitly in the model. Accordingly, the model results should be used with these limitations in mind. This contextualisation step provides useful insight to this decision-support approach's use by policy makers, as they can better understand the reach and scope of the approach.

Experts also emphasised the need for coordinated planning of NbS, prioritisation of project locations and community engagement to increase chances of NbS project success. This need for larger-scale coordination can be achieved by aligning urban NbS planning with other, larger scale interventions such as integrated climate action programs or conservation management.

5.3 Policy considerations

While policy makers in Cape Town have shown interest and commitment in using NbS as climate mitigation tool (City Council of Cape Town 2020a; City of Cape Town 2018), the lack of consideration of selection and prioritisation of different NbS, particularly based on the social demands and vulnerability of the local population, shows the potential benefit of the presented approach to aid in strategic decision-making and implementation. Additionally, policy-makers lack decision-support for creating such policies and supporting NbS implementations. This approach, through its prioritisation and visualisation, provides that decision-support. For example, knowing which areas in a particular neighbourhood are most suitable for certain types of NbS, allows decision-makers not only to more effectively use limited resources for larger impact, but also for basing these decisions on more transparent, data-informed frameworks. The presented approach also provides grounds for communicating potential policies and NbS implementations with relevant stakeholders, which allows for greater community involvement and public buy-in. The opportunities of this approach to allow for coordinated approaches for NbS implementations also mitigates often encountered limitations and shortcomings encountered during the implementation phase of NbS in urban areas.

Additionally, actual implementation of NbS projects, while well-studied, still proves to be a significant barrier in the success of these projects. NbS projects often need additional support or considerations for successful and just implementation. In analysing purported barriers and considerations of NbS implementations, as well as the insights derived from the social vulnerability framework, several different policy pathways and considerations have been identified for increasing the implementation of climate just NbS in Cape Town (figure 5.1):

- NbS as supporting component to conservation,

- NbS as a tool for climate mitigation and adaptation,
- NbS as a climate justice tool for community development.

These policy considerations involve aligning urban NbS planning to other, established initiatives to address the coordination and community involvement challenges that are so often experienced by NbS implementations. Aligning with conservation provides access to more resources and institutions - partly due to South Africa's well-evolved conservation sector (Holmes et al. 2012; O'Farrell et al. 2012). Protecting biodiversity through this way also results in increased NbS resilience. More research is needed however, into the interaction of NbS with conservation, as the provisioning of certain ES might be affected by the conservation status of a given NbS (such as resource production in protected forests, for example).

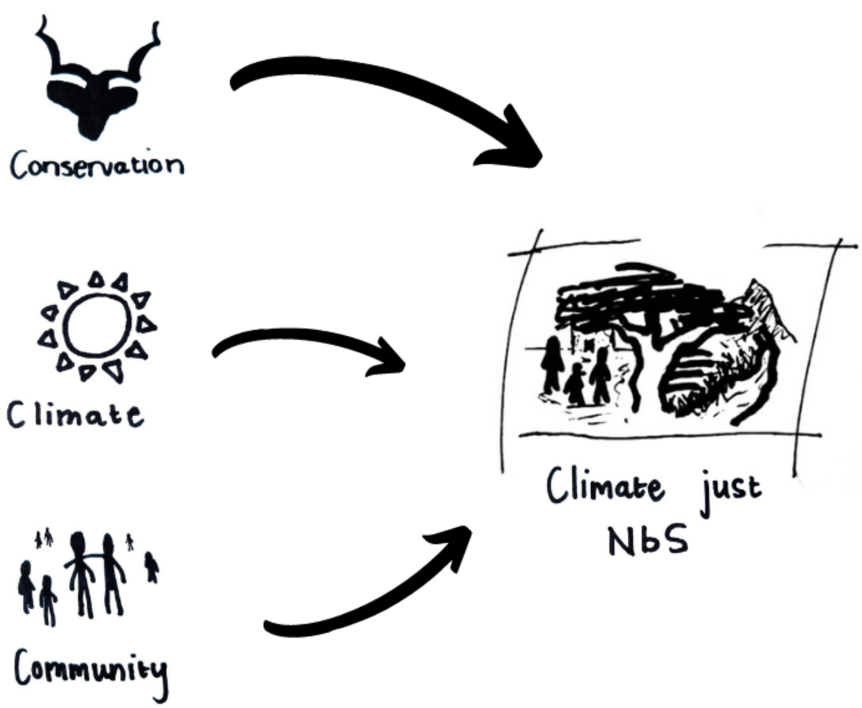


Figure 5.1: 3 C's – Policy considerations towards climate just NbS

The second consideration, involves using NbS as a climate mitigation tool to obtain greater political will and stimulate public buy-in. Focusing and prioritising more climate vulnerable communities allows for more effective results. The decision-support approach provided in this thesis contributes significantly towards this policy pathway. Finally, community involvement should be a main consideration towards the implementation of climate just NbS. The importance of contextualisation in urban NbS planning, here incorporated through expert interviews, should be addressed through community involvement and ground-truthing. There exists many perceived barriers towards community involvement by policy-makers (see section 4.5), but remains a necessary and important step in the planning and contextualising process, and helps in ensuring that envisaged NbS are not only fit-for-purpose, but also sustainable in the long-term.

5.4 Limitations

While the study carries value through the creation and application of the social vulnerability framework for ES demand, its limitations are arguably just as important to consider.

5.4.1 Conceptual limitations

A core limitation of this approach rests at a fundamental level of how NbS are classified and considered. In this thesis, NbS were categorised into discrete groups based on certain shared characteristics. While this discretisation is often done in literature to facilitate study and planning (World Bank 2021), as well as comparison among and within cities, it does not necessarily accurately reflect the broad range of various characteristics that specific NbS implementations might have. This is also applicable to the scale at which NbS are considered for this thesis; for this approach NbS are considered as isolated entities that function independent of each other, when in reality many multi-scale dynamics and interactions also influence their performance (Bridges et al. 2021; Slinger 2021).

5.4.2 Methodological limitations

There is much debate over the value and risks associated with the calculation of social vulnerability and related indices (Bucherie et al. 2022; Katic 2017; Vincent 2004). The framework that this study uses is no different – which is made more clear for some ES, such as culture, that are typically difficult to define and measure. How ES demand was framed in terms of social vulnerability to climate change is also important; different framings might also be realistic but produce different results.

In terms of the model, there are important limitations to take into account. The model only considered the spatial dimension of ES demand and NbS supply, and thus neglected the temporal dimension, which is particularly important for NbS and ES that change over time (Kabisch et al. 2016; Langemeyer and Connolly 2020; Slinger 2021). Geographic aggregation, such as populating different model cells with ward-level data, could also have led to some edge-effects that were not explicitly determined. Furthermore, some geo-physical concepts, such as flood risk and biodiversity, were implemented relatively simply – potentially limiting the results of the model to the usefulness of these simple mappings themselves.

The expert interviews that were conducted, while useful for contextualisation, still favoured generally privileged voices. This risks minimising the voices and opinions of those that would directly experience the impacts of the results of such a model when used for decision-making. Furthermore, the small sample size (N=5) of interviewees, necessitated by lack of resources and time, is too small to gather more statistically valid results. This was mitigated by only using the interviews as part of a contextual lens. It remains important, however, that the results of this study be further validated through additional analysis of expert opinion, as well as community insights.

5.4.3 Implementation limitations

As the results of the most recent South African census have not been published at the time of writing this study, data from the 2011 census had to be used – potentially giving recommendations that are no longer applicable. This is, however, easily addressed as soon as newer census result become available.

Additionally, carbon sequestration was not considered in this approach due to the relatively local scale of the analysis. Further study could explore the potential air quality benefits from NbS as an additional ES demand. It is also important to note that, while the model seems complex and comprehensive, that this should not create false confidence in the model. Instead, confidence should come from the systematic verification and validation tests done here, but also ground-truthing and results comparisons that were excluded from this study.

The largest ecosystem in the Cape Town area, the surrounding ocean, was not considered in this study. Many ES are derived from this ecosystem, such resource production, recreation and cultural and social value, but was excluded from the scope of this approach. NbS have been applied in aquatic contexts in Cape Town (City Council of Cape Town 2020a) and might impact results of this study through additional benefits that are enjoyed by communities within close proximity to the ocean. This also holds for other existing NbS that were not incorporated into the model.

Finally, the importance of community engagement and ground-truthing cannot be overstated. This decision-support approach should be used only as an informative planning tool, not as a definitive and complete solution of the NbS implementation process. Like each community and neighbourhood, each NbS implementation is unique and different, and must be treated as such. Involving the community allows for understanding how these NbS implementations might be different, and how the process should be adapted to meet the community's needs.

5.5 Relevance and implications

The decision-support approach presented in this thesis is relevant to both the spheres of NbS planning and social vulnerability to climate change analysis. By providing decision-makers with visual prioritisations and selections of NbS for an urban area, they can better make decisions of where to locate which type of NbS implementations from a climate justice perspective. Current decision-making approaches do not incorporate such social vulnerability concerns explicitly (City Council of Cape Town 2020a; City of Cape Town 2018).

The novel approach for quantitatively determining ES demand provides for new avenues of research towards better understanding the complex interactions between social vulnerability and ecosystems. As socio-ecological systems are studied more and more, the social vulnerability framework for ES demand provides another bridge between two often too separated worlds.

This study also holds implications for the field of NbS for climate adaptation. Through vulnerability index calculation methods, quantitative data can be leveraged to incorporate social vulnerability in planning with a city-level lens of NbS prioritisation and selection. The presented framework also allows for repeatability in other cities or case studies due to its modular structure – particularly where only quantitative data sets are available.

6. Conclusion

In the field of NbS planning, climate justice is often not explicitly considered. In cases where it is indeed included in analyses, these often rely on qualitative data sources to establish justice considerations, which increases the barrier of study, while excluding cases, such as many cities in the Global South, where only secondary data sources are readily available. Compounding these factors, is the lack of decision-support for policy-makers regarding NbS planning.

In this thesis, these issues are addressed through a decision-approach: first, a social vulnerability framework for estimating ecosystem service demand was created, then used for matching and selecting appropriate nature-based solutions for the City of Cape Town. This methodology allows for prioritisation of NbS at a city scale from a quantitative climate justice perspective. Through contextualisation with expert interviews, constraints and considerations in applying the framework and model were identified, while verification and comparison tests identified limitations of the social vulnerability framework.

6.1 Answering the research question

The main research question of this thesis is shown in Box 9:

Box 9: Main research question

How can climate justice be incorporated in the urban planning and policy of nature-based solutions in the city of Cape Town, South Africa?

Four different subquestions were created to answer this question, illustrating also how this approach was seqentially conducted:

SQ1: What are the current socio-spatial inequalities in Cape Town?

As there exist many ways in which socio-spatial inequalities can be determined and measured, this was operationalised through the concept of social vulnerability to climate change. Making use of existing methods to determine social vulnerability indices quantitatively, social vulnerability indicators were selected based on literature and available data. Leveraging data from the 2011 South African census allowed for collecting indicators for processing. This was then used through principal component analysis (PCA) analysis to answer subquestion 1, showing where the most vulnerable live in Cape Town. This was found to be predominantly in the region known as the Cape Flats. Using different dimensions of social vulnerability, and framing it in terms of ecosystem service (ES) demand, allowed also to gain a multi-dimensional view into the vulnerability of the region. This led also to the study being refined to a region in the Cape Flats for further analysis.

SQ2: What are the impacts of nature-based solutions in terms of climate justice, and how can they be assessed?

Using ES proved to still be a useful way of evaluating the impacts of NbS. While in literature ES have mostly been used for NbS usefulness, here its use was expanded through the incorporation of climate justice by making use of the concept of social demand for ES. Framing ES demand in terms of social vulnerability to climate change allowed for connecting vulnerabilities to the impacts of NbS. This connection was created by evaluating climate justice in terms of the ES that are demanded by communities on the one hand, and the ES that are provided by NbS on the other. In this way it became apparent that some NbS are more preferred for different types of vulnerable communities, with river projects and urban green space being particularly preferable. The climate justice impacts of NbS was assessed by evaluating the mismatch between ES supply and ES demand. These complex impacts were also further contextualised through expert interviews – with interviewees emphasising that ES are used in different ways by more and less vulnerable communities. Through this differing ES use, the importance of prioritisation of NbS location and type was made clear.

SQ3: Which locations are the most ecologically and socially suitable for nature-based solutions in Cape Town?

The NbS matching model identified the most ecologically and socially suitable locations for NbS in Cape Town, as well as prioritisations of these locations. Applying different weighting schemes for how ES demand is weighted in the NbS matching model, allowed for understanding ecological and social suitability, while also giving insight into how policy-makers with different value weightings could potentially impact decision-making. It was found that social and ecological suitability do not always align, resulting in added complexity and trade-off decisions for planners. By prioritising all NbS based on aggregated demand for ES, the most suitable locations, both socially and ecologically, were identified. These consisted of both larger scale areas, such as the Kuilsriver area, and also many smaller scale areas across the area of study.

SQ4: What are the implications of introducing climate justice into urban planning for nature-based solutions?

Using expert interviews, the model and overall decision-support approach was contextualised. This revealed the boundaries of operation within which this approach can be used. These boundaries included the incorporation of geographical barriers to NbS implementation, prioritisation of NbS implementations, inclusion of spatial inequality, and the partial consideration of conservation efforts. Other barriers to NbS planning, such as political and financial barriers, as well as more intricate dynamics of NbS with conservation, were excluded. This framework allows for transparent, data-informed planning of NbS based on distributive and representational justice - supporting decision-makers in prioritising limited resources to help Cape Town's most vulnerable populations through NbS. In this way this decision-support approach, including the presented framework, was used to determine how climate justice can be incorporated into Cape Town's urban planning.

6.2 Policy recommendations

The following insights are of importance for policy-makers regarding planning of urban NbS in Cape Town:

- By prioritising projects by social vulnerability, and matching NbS to different dimensions of vulnerability, climate justice can be incorporated into urban planning in Cape Town, especially by leveraging already available data sets such as the national census.
- Contextualisation and community engagement remain important to project sucess, as well as capturing concepts like political and financial barriers.
- Three policy pathways (the 3 C's) can be followed to gain support for NbS implementations and are important considerations regarding the implementation of NbS: Conservation alignment, Climate adaptation and Community development.

6.3 Recommendations for future work

As mentioned in section 5.4, there are many limitations in the approach presented here. While future work can involve improving the existing approach through incorporating more accurate flood risk and biodiversity models and air quality for example, there also exists potential to build on this work. When using a catalog of all existing NbS within Cape Town, the framework can be used to assess their current impact in terms of social vulnerability, and potentially serve to shed more light on how ES benefits are distributed spatially for different groups. Furthermore, by incorporating non-local dynamics of NbS over a city scale, NbS and their geographic locations can be better valued in terms of green corridors, biodiversity connectivity and air quality improvement. These concerns can also be addressed by incorporating a system-level view of NbS – which allows for capturing multi-scale dynamics and valuations of NbS. This notably requires redefining and re-categorising different types of NbS and their respective benefits and disservices. Repeating the decision-support approach presented here with a different case study will also allow for additional insights into the generalisability of the approach, and potential inter-city comparisons. Finally, while mentioned briefly in this thesis, the complex relationship between conservation and urban NbS must be further investigated in order to better understand the co-benefits and trade-offs that arise when assessing the biodiversity-social vulnerability value conflict. Thus, using the vulnerability framework and NbS model presented in this thesis, the City of Cape Town can better incorporate climate justice into their urban NbS planning. The results from the models, contextualised by expert interviews, also provide insight into the implications of climate justice for NbS implementations.

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Appendices

A. Model description

This section provides additional information around the creation, setup and analaysis of the social-vulnerability framework for ES demand, as well the NbS matching model. To determine the ES demand, the data sources provided in table A.1 were used.

Table A.1: Data layer and sources for NbS matching model construction

Data layer	Data set	Data source
Census data	2011 South African Census	Statistics SA Open Data Portal
Ward geometries	Cape Town Ward shape files	Cape Town Open Data Portal
NbS ES provision	A Catalogue of NbS for urban resilience	The World Bank (World Bank 2021)
Land-use	Cape Town integrated zoning scheme	Cape Town Open Data Portal
Pluvial flood map	Stormwater waterbodies	Cape Town Open Data Portal
Fluvial flood map	Open watercourses	Cape Town Open Data Portal
Coastal flood map	5m Contour lines of Cape Town	Cape Town Open Data Portal
Biodiversity map	Indigenous vegetation- current extent	Cape Town Open Data Portal
Coastal region	Coastal urban edge	Cape Town Open Data Portal

It is clear from algorithm 1 that the matching model follows a relatively simple approach to match ES supply to demand. This is possible because of the simplification of the ES supply of NbS: as ES supply varies greatly between different implementations of even the same NbS, a generalised approach is taken here to understand the potential ES that a NbS *can* potentially supply

Algorithm 1 NbS matching and selection algorithm

```
for cell in cells do
    for nbs in nature-based solutions do
        for es in ecosystem services do
            nbsES_sum ← cell[es] × nbs[es] × weights[es]
            distance[nbs] ← distance[nbs] + nbsES_sum
        end for
        for land in land-use restrictions do
            nbsLU_sum ← cell[land] × nbs[land]
            distance[nbs] ← distance[nbs] + nbsLU_sum
        end for
    end for
        cell[highest_demand] ← max(distance)
        cell[best_nbs] ← index(max(distance))
    if cell is not coastal and cell[best_nbs] = "Beach and dunes" then
            cell[highest_demand] ← secondmax(distance)
            cell[best_nbs] ← index(secondmax(distance))
    end if
    if cell is conservation then
            cell[best_nbs] ← "Conservation"
    end if
end for
```

A correlation of 0.986183204878824 was determined between the aggregated ES demand and SoVI. This, shown in figure A.1, shows how aggregated ES demand can be used to represent social vulnerability, at least in how it is defined by Apotsos (2019).

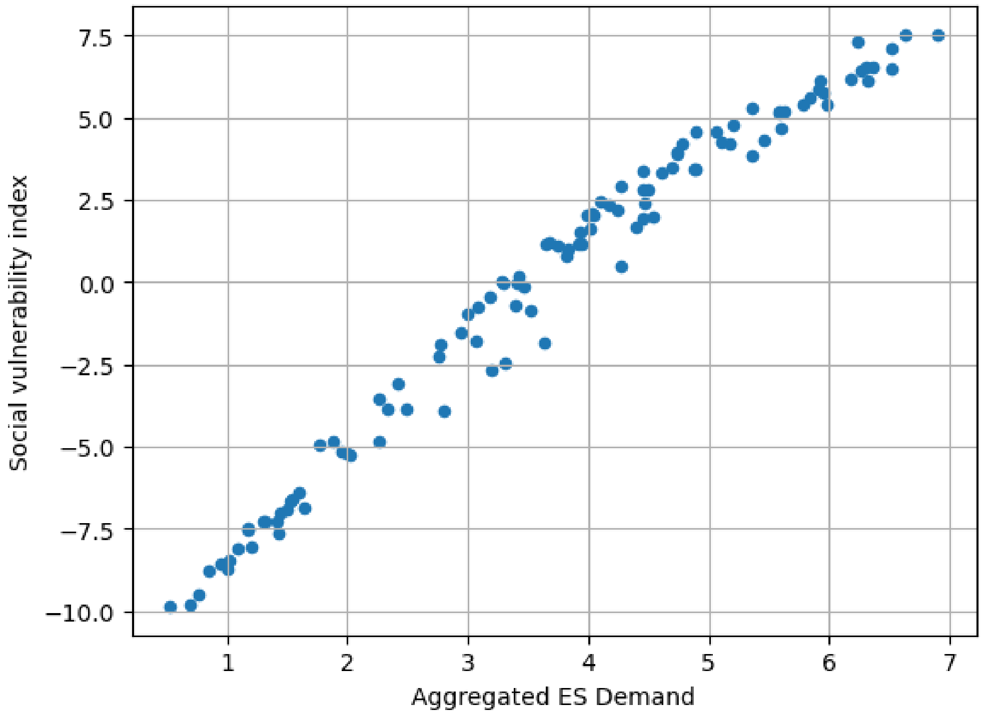

Figure A.1: Correlation between aggregated ES demand and social vulnerability index

In table A.2, the amount of variance explained by each calculated ES demand index is given. This illustrates how much of the variance between the selected original parameters is captured by this demand factor. For factors that were more related, such as those used in determining *economic* demand, a higher amount of variance could be explained by the first principal component.

Table A.2: Explained principal component variances per ES demand

ES demand index	Explained variance per principal component
social	[0.54925341]
water	[0.6757954]
education	[0.77404248]
heatstress	[0.65477772]
economic	[0.81288459]
resources	[0.76787689]
health	[0.66354579]
culture	[0.55839302]

Here now follows cross-correlation plots for the indicators for each ES demand factor, described in section 3.2.1.

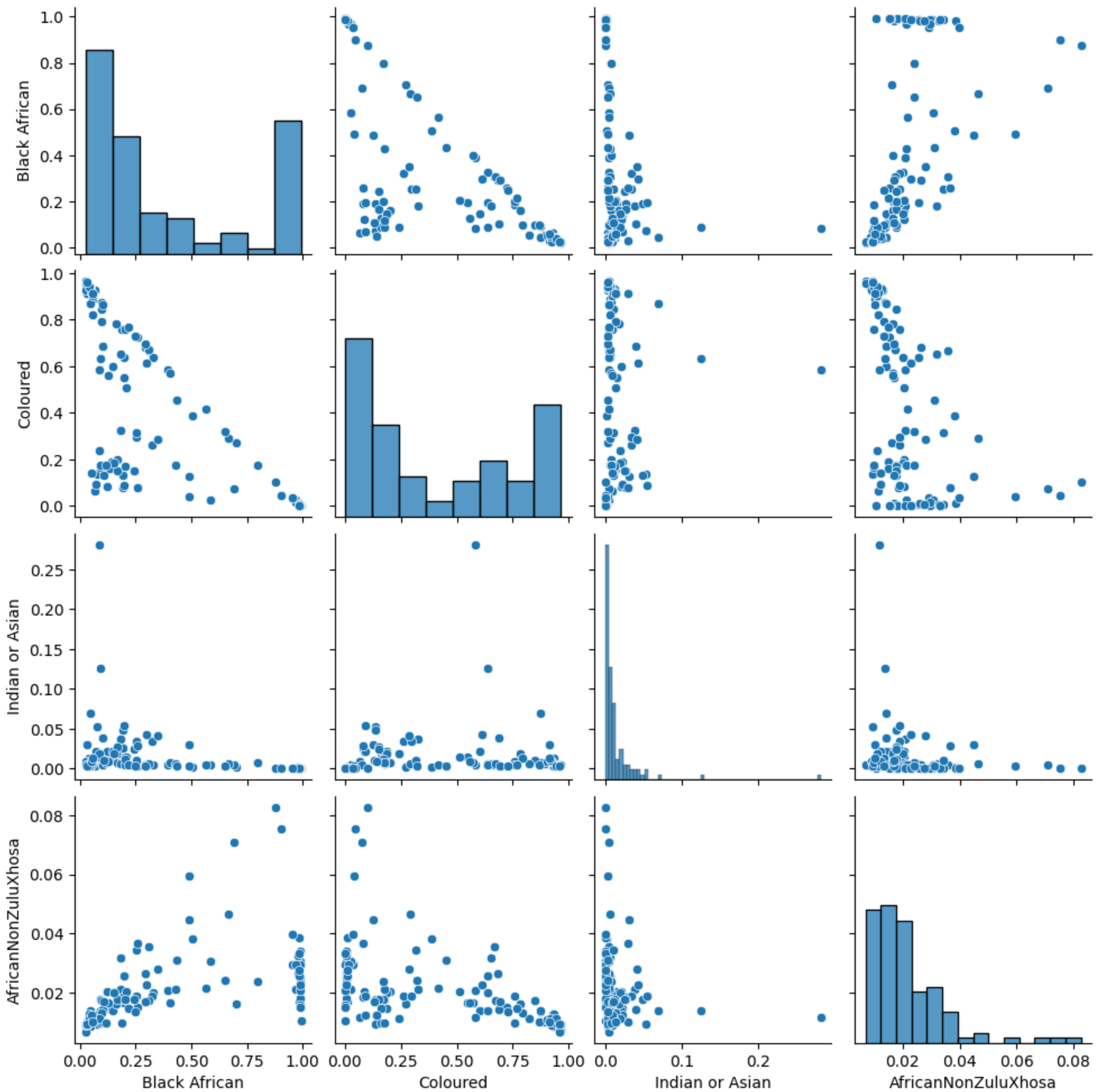

Figure A.2: Correlation between the different indicators used to determine the culture ES demand factor

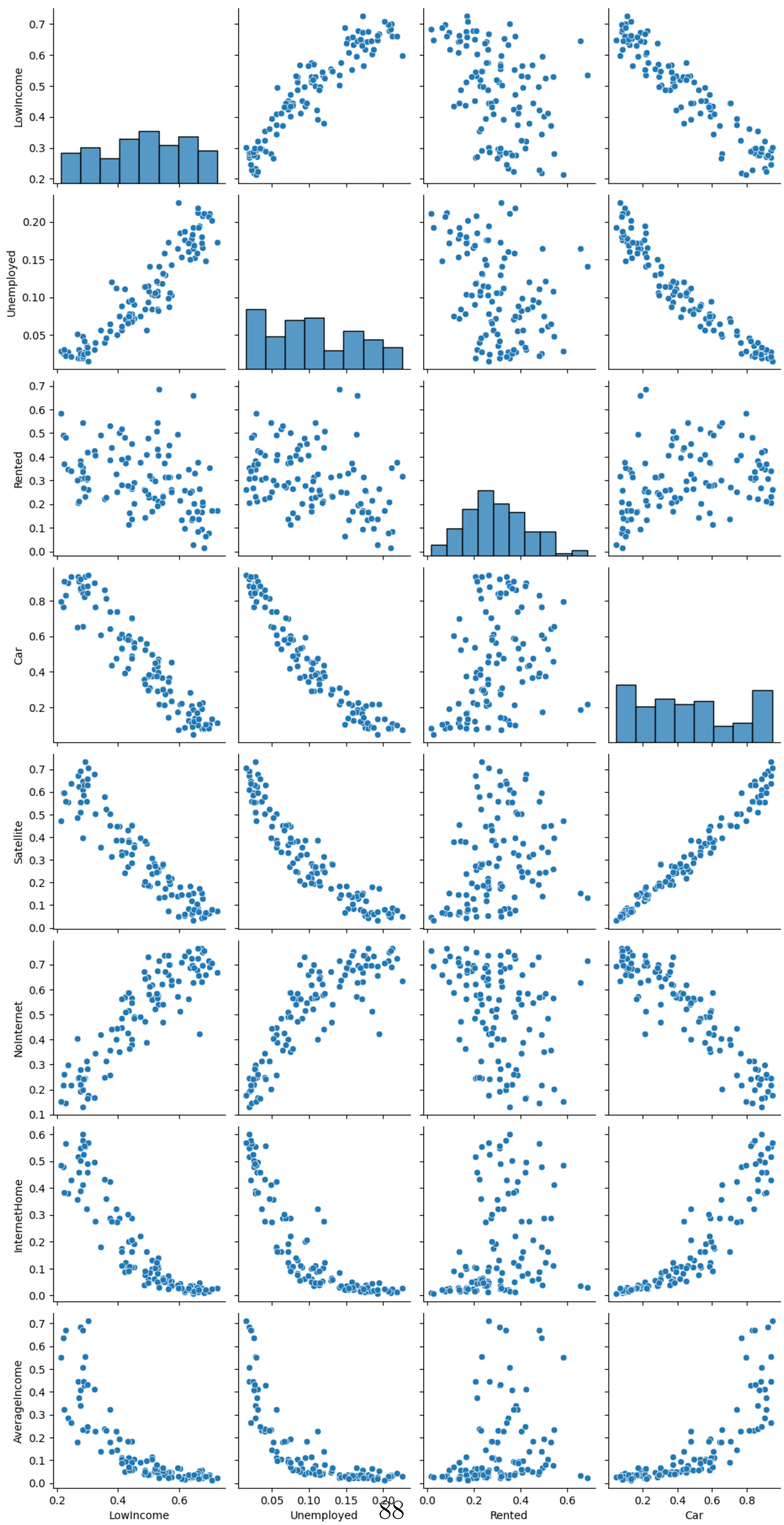

Figure A.3: Correlation between the different indicators used to determine the economic stimulation ES demand factor (1)

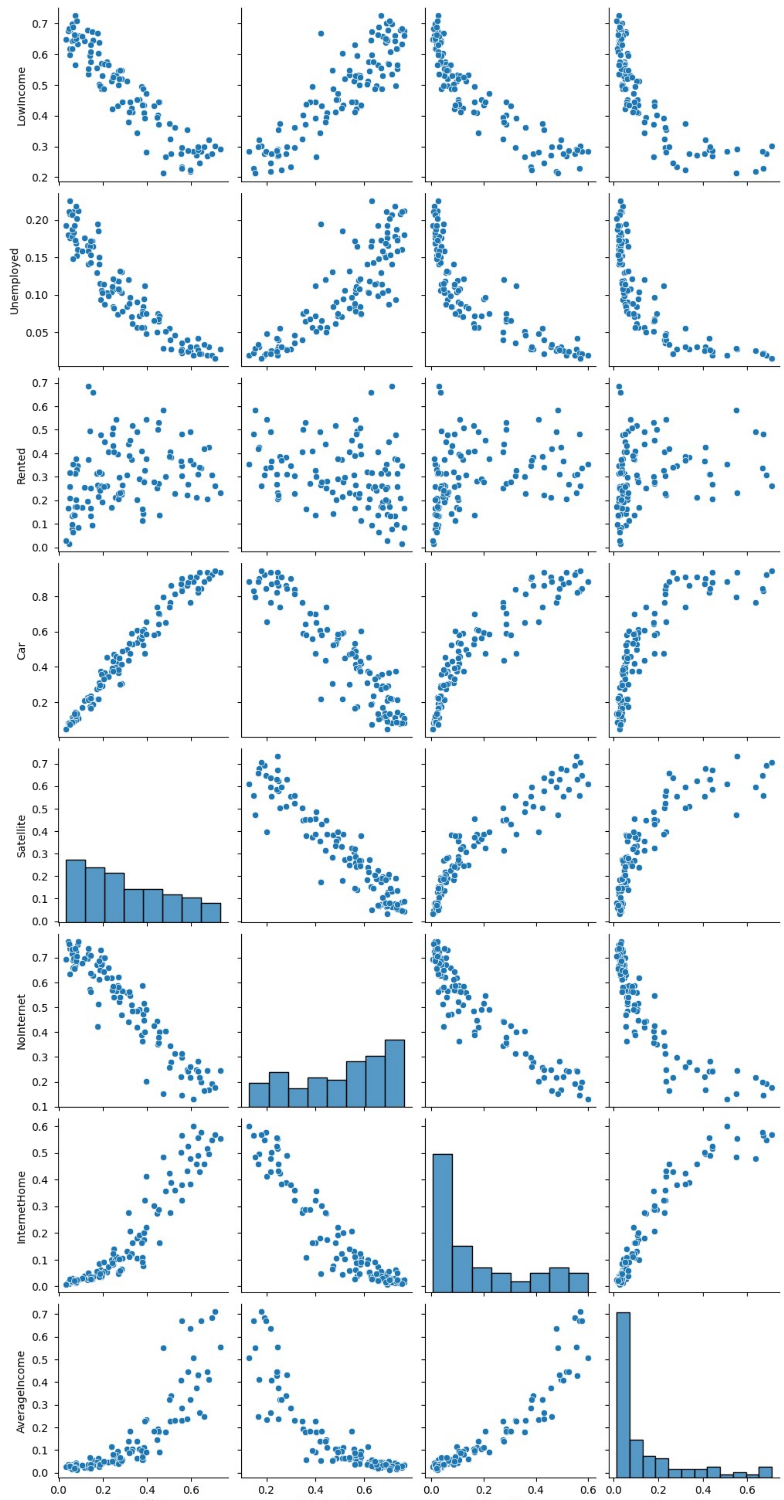

Figure A.4: Correlation between the different indicators used to determine the economic stimulation ES demand factor (2)

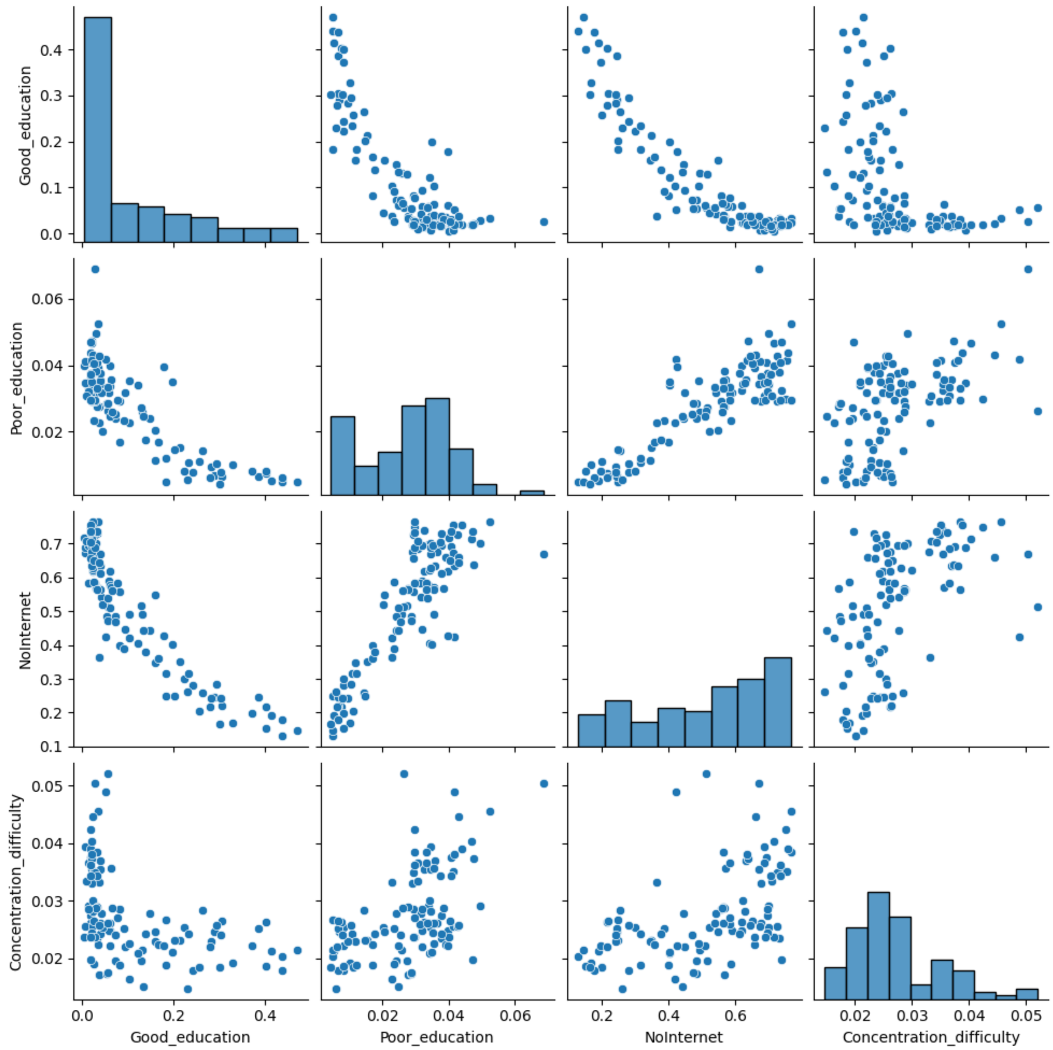

Figure A.5: Correlation between the different indicators used to determine the education ES demand factor

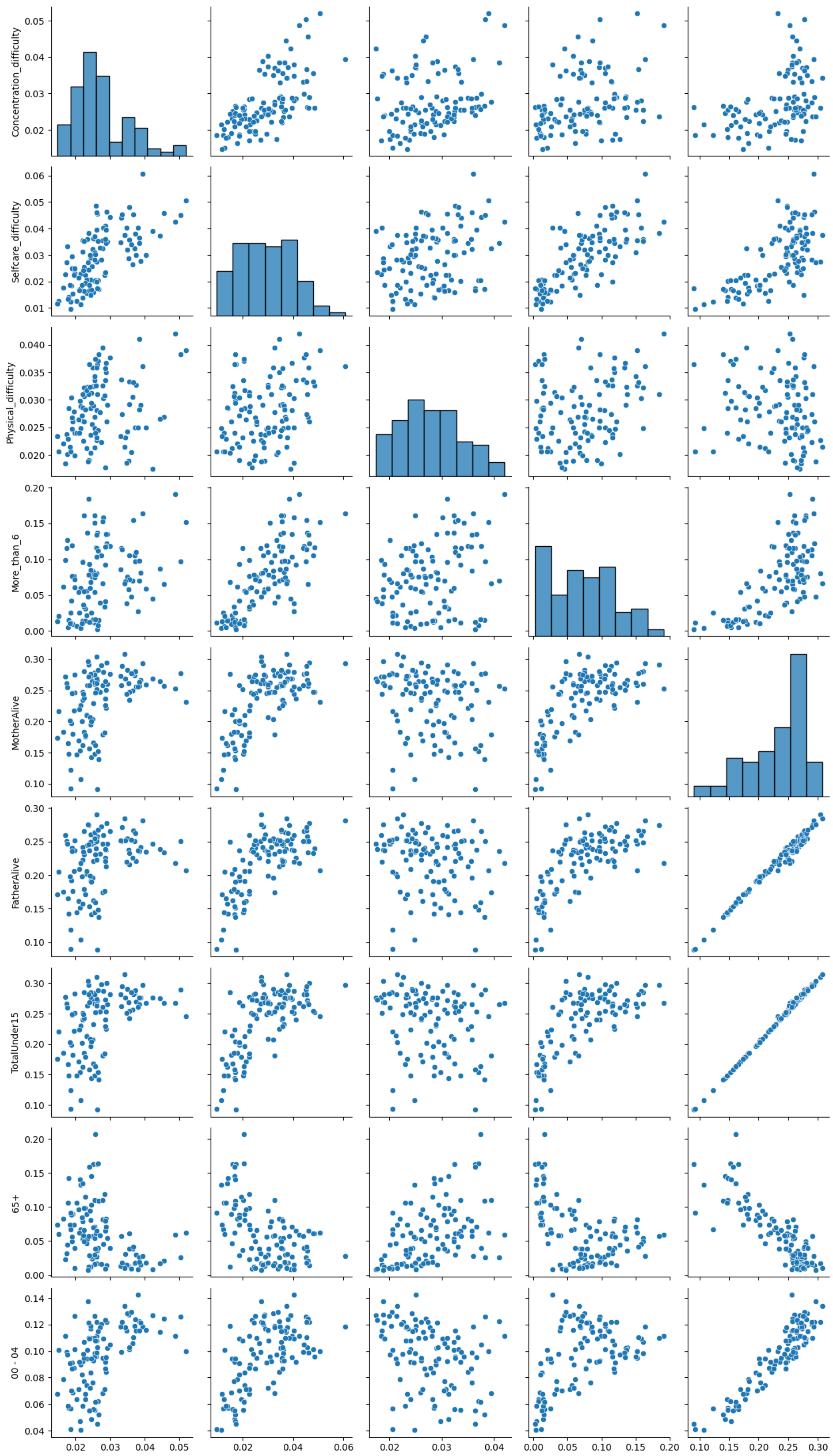

Figure A.6: Correlation between the different indicators used to determine the health ES demand factor (1)

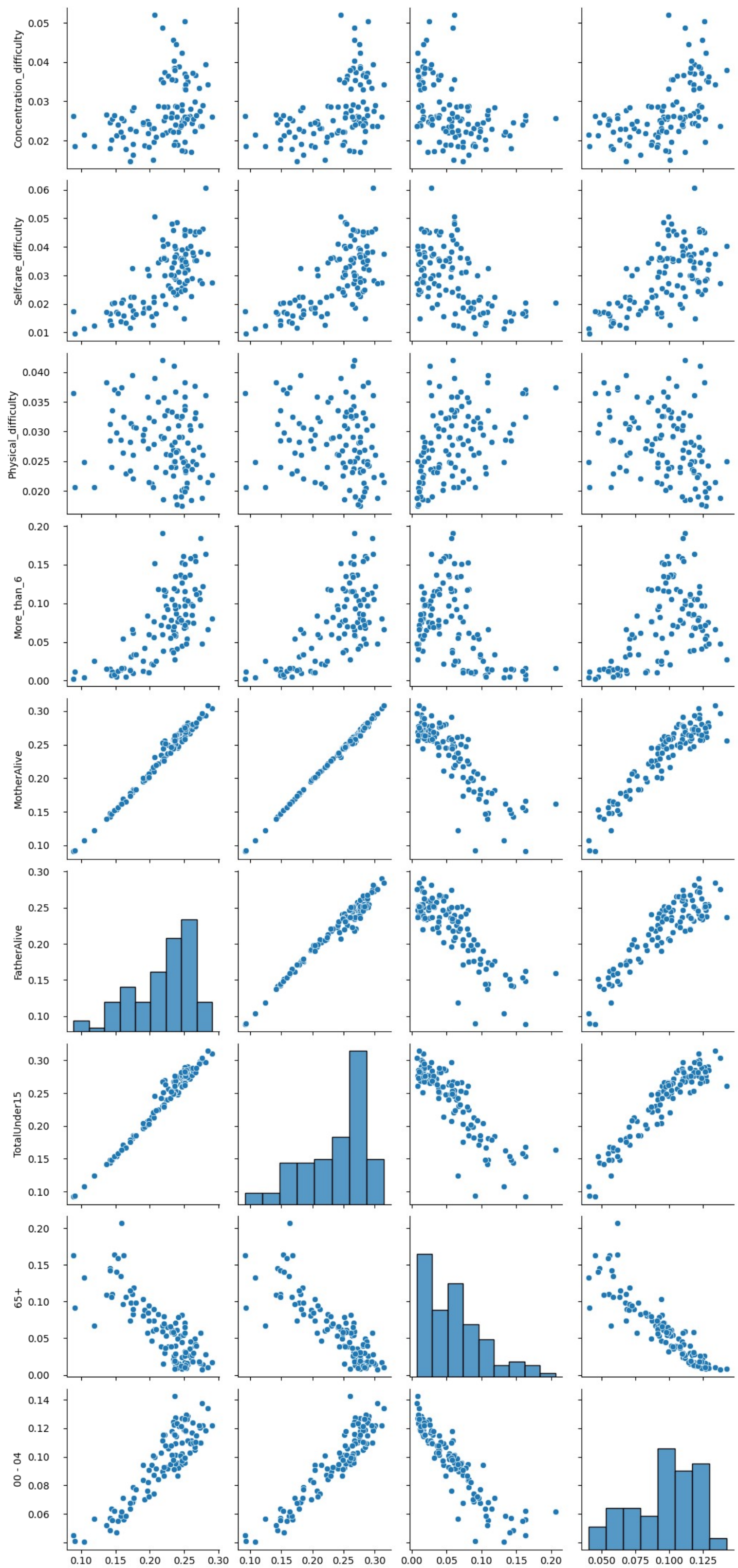

Figure A.7: Correlation between the different indicators used to determine the health ES demand factor (2)

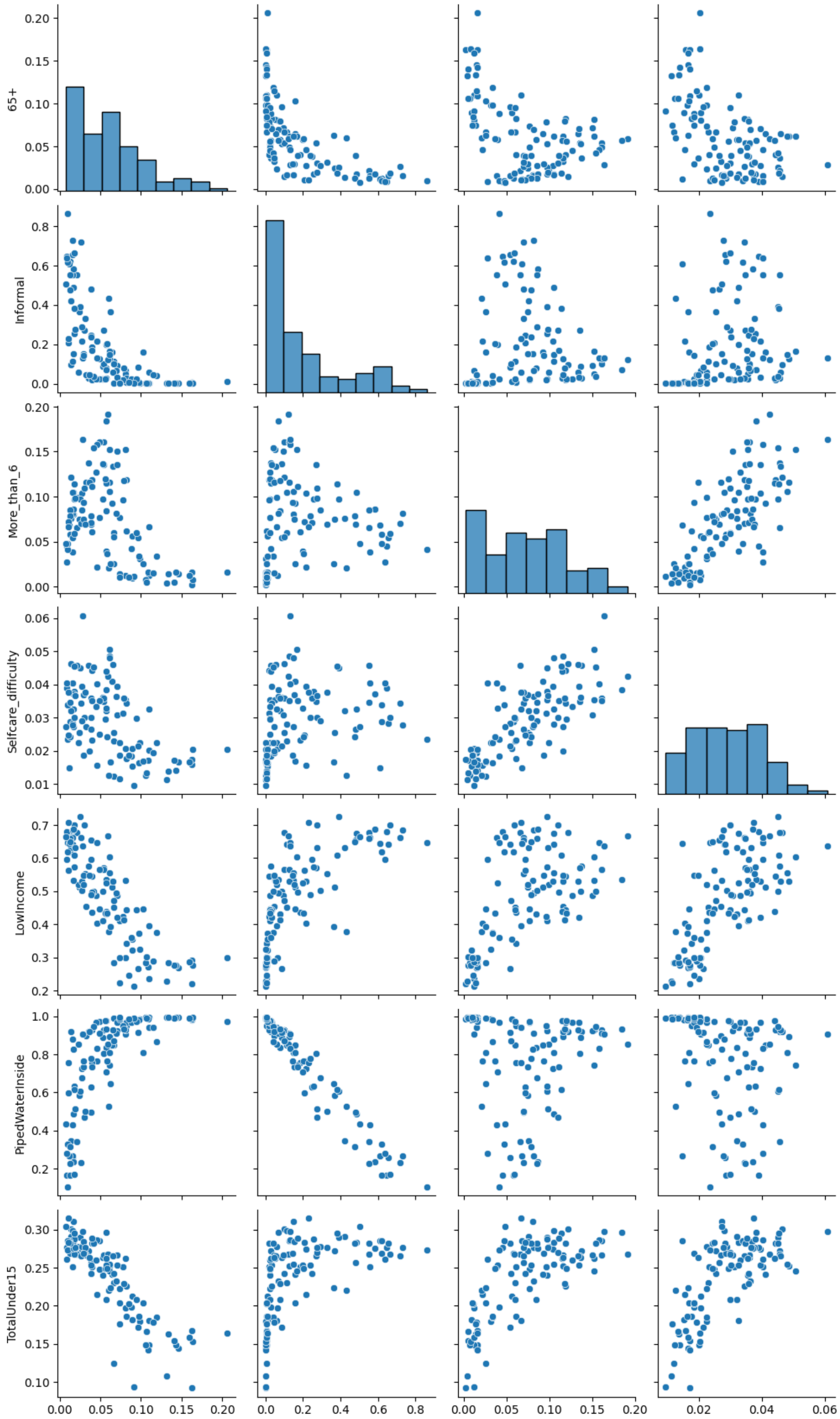

Figure A.8: Correlation between the different indicators used to determine the heat stress ES demand factor (1)

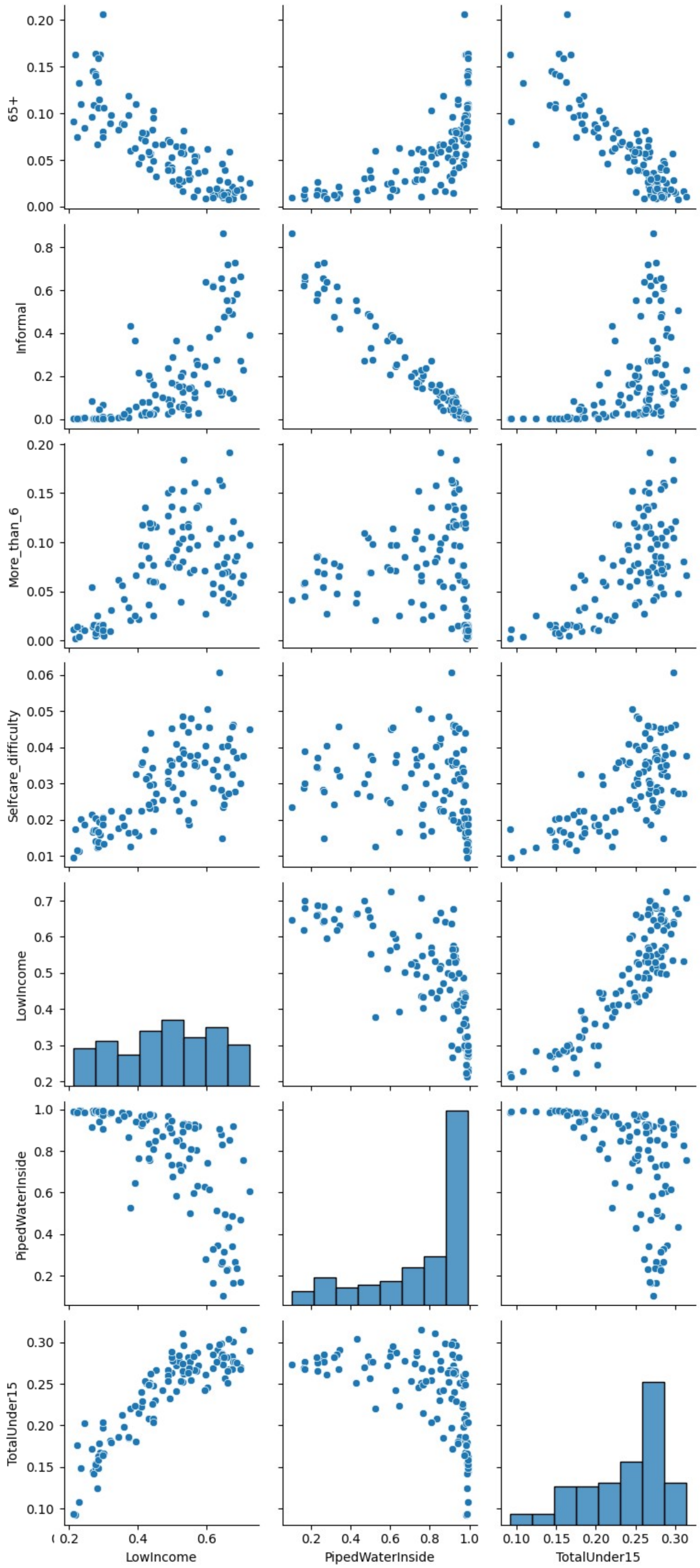

Figure A.9: Correlation between the different indicators used to determine the heat stress ES demand factor (2)

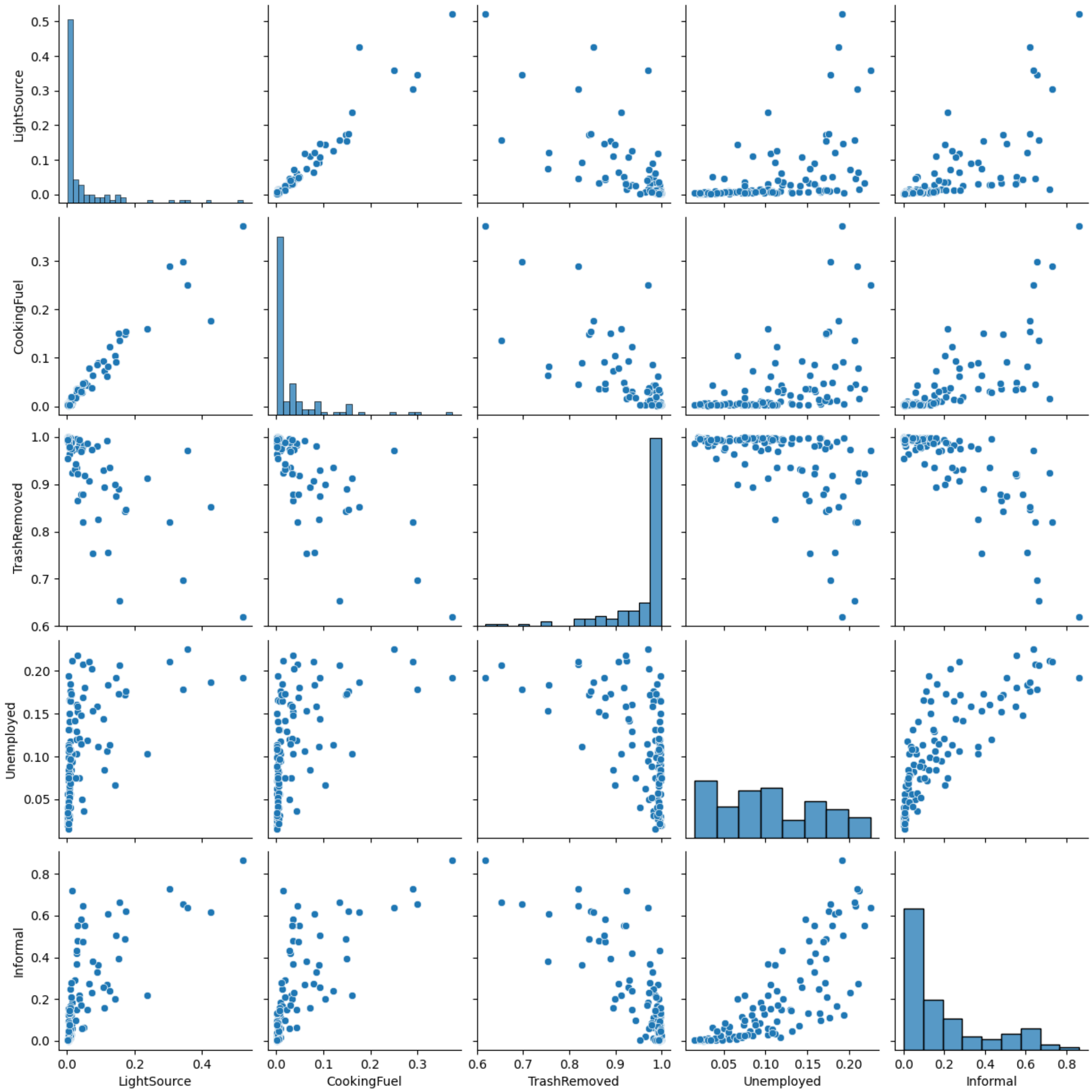

Figure A.10: Correlation between the different indicators used to determine the resource provision ES demand factor

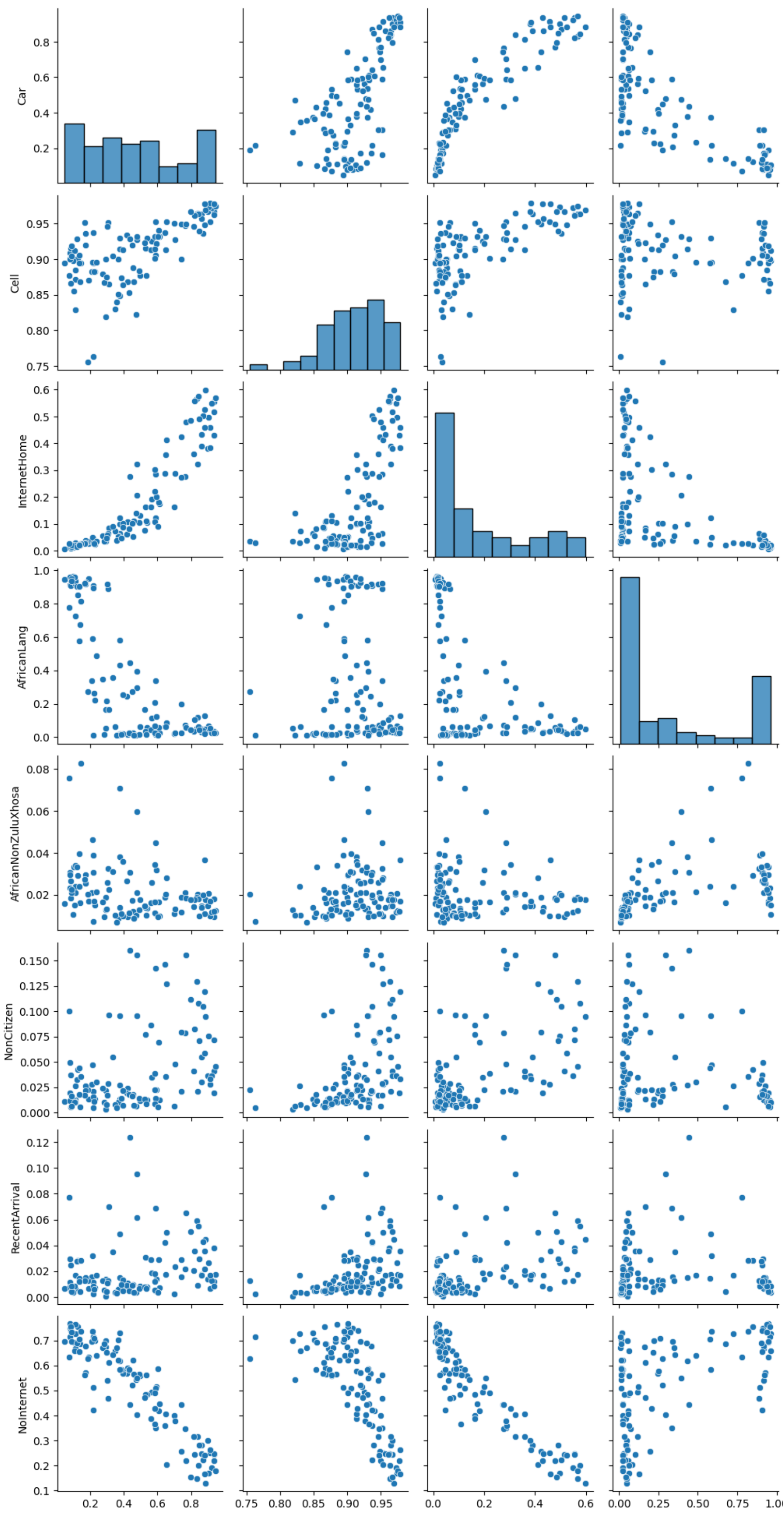

Figure A.11: Correlation between the different indicators used to determine the social interaction ES demand factor (1)

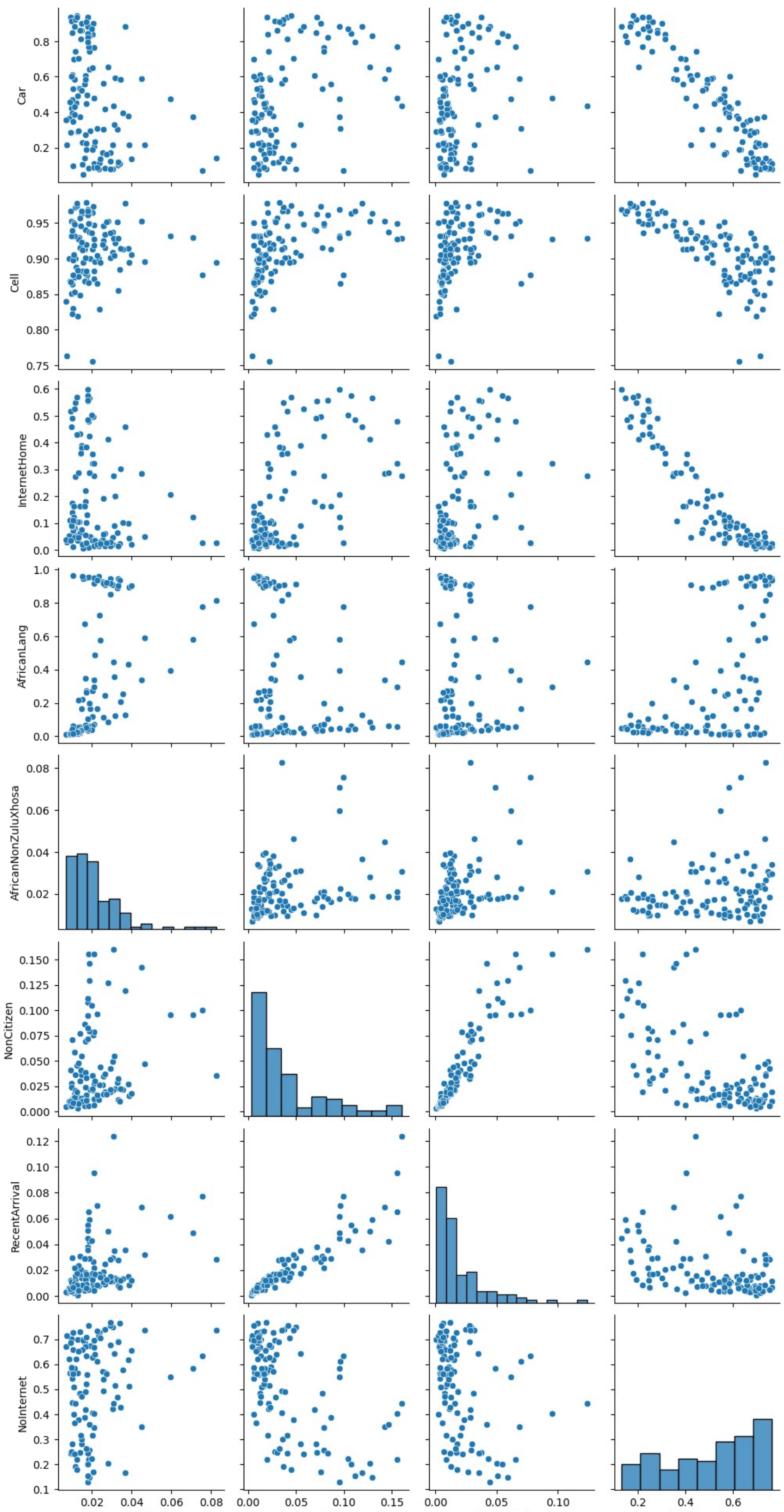

Figure A.12: Correlation between the different indicators used to determine the social interaction ES demand factor (2)

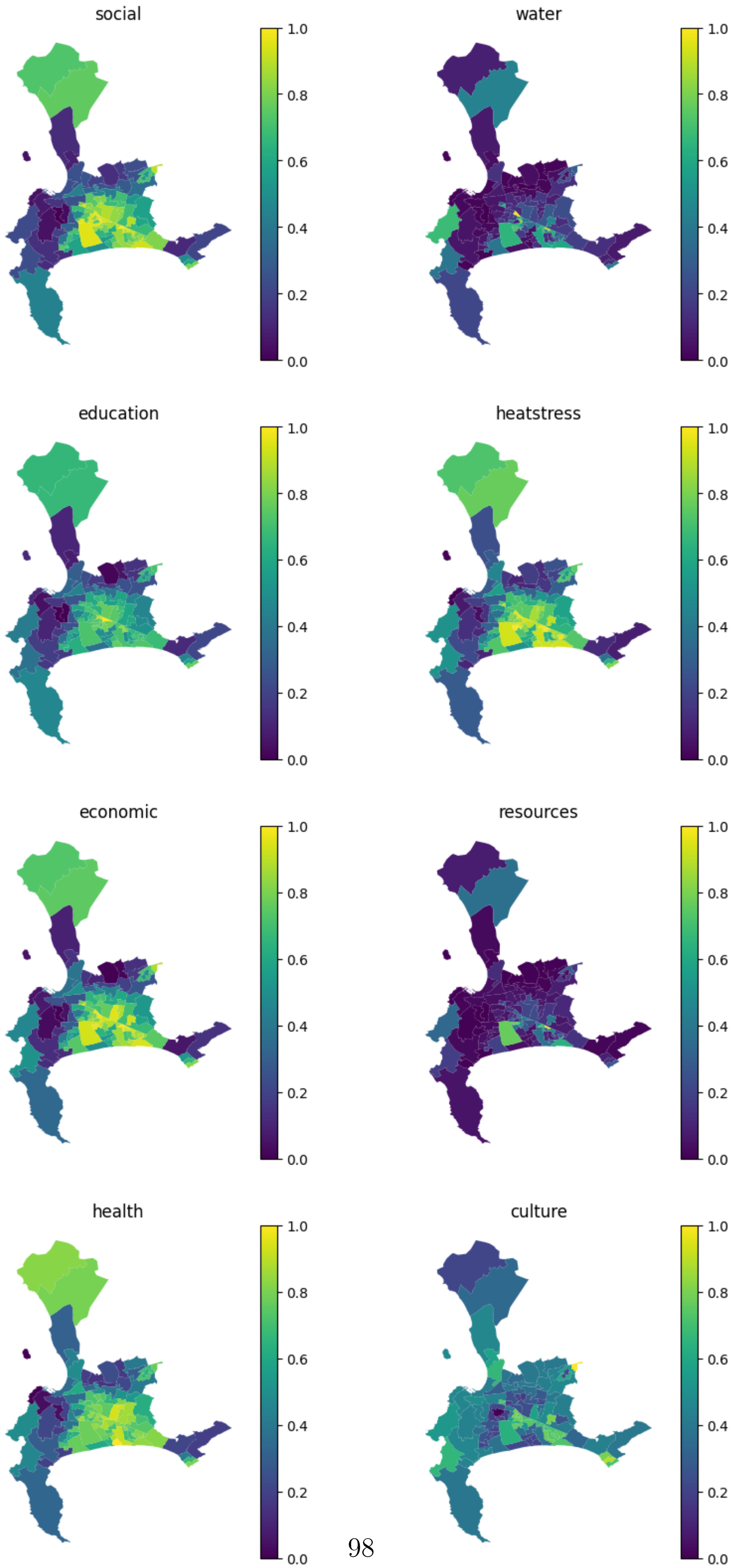

Figure A.13: Calculated social demand for different ecosystem services

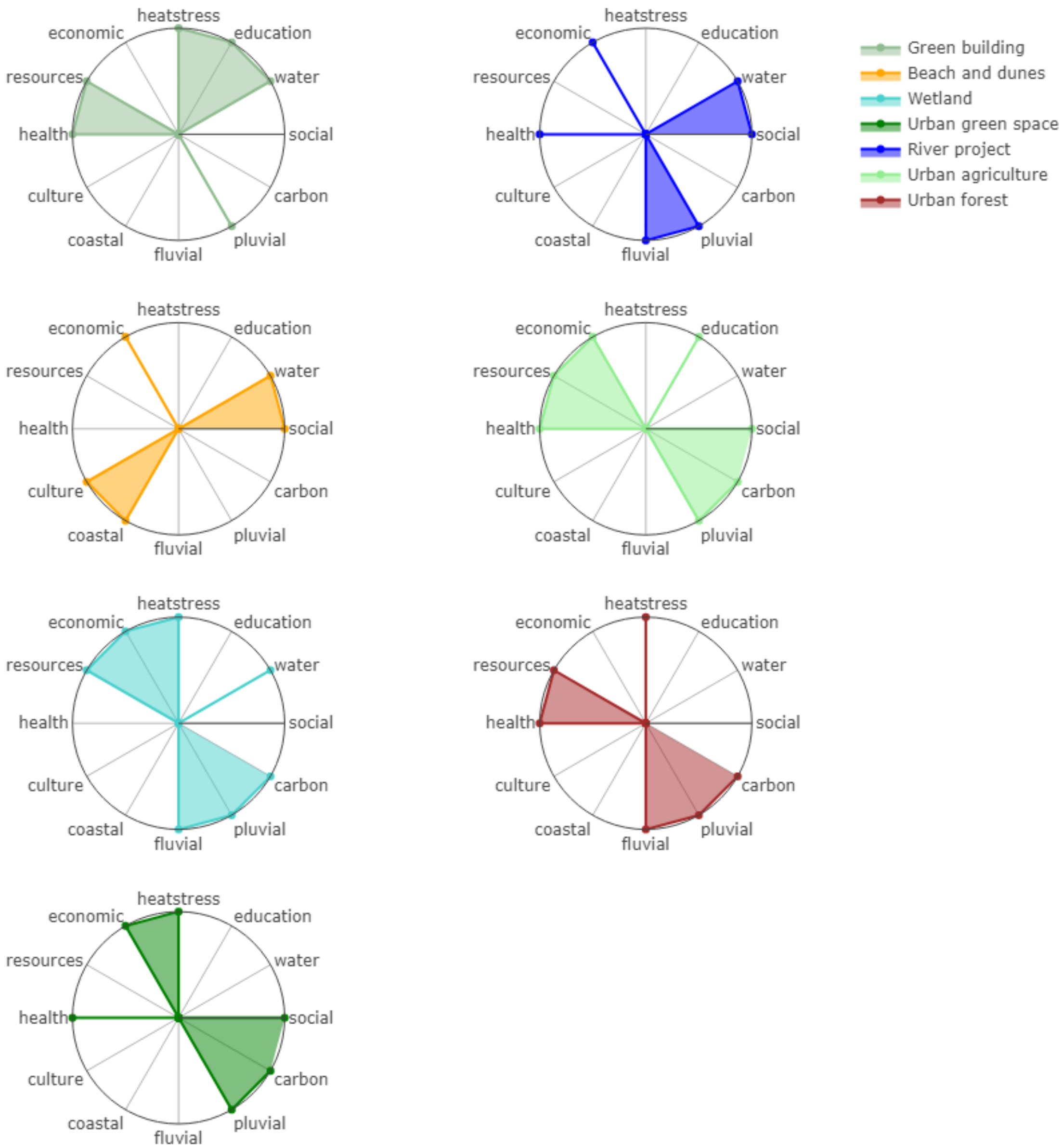

Figure A.14: Ecosystem service provision of different NbS

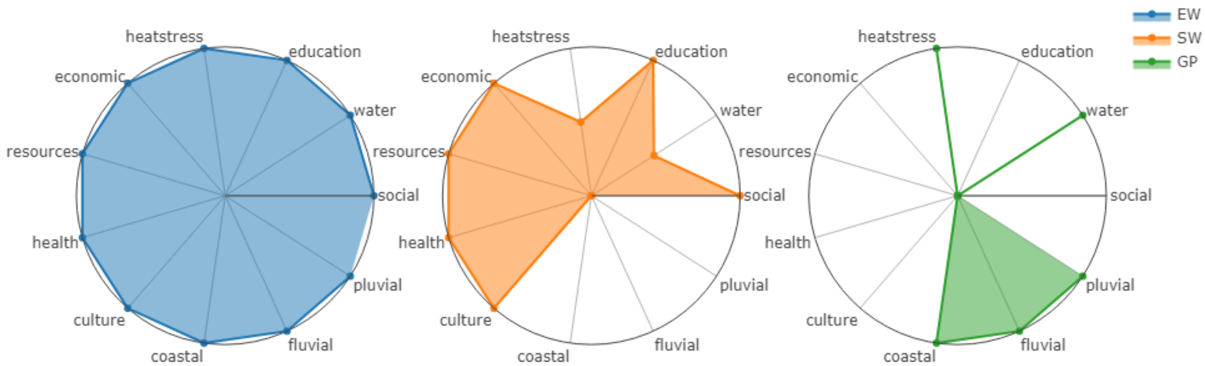

Figure A.15: Ecosystem service weighting of different weighting schemes

In figure A.15, the ES weighting profiles for the different weighting schemes are shown. For equal weighting, all ES are equally valued, while this is changed for the socially weighted and geo-physically weighted weighting schemes respectively.

The zoning limitations per NbS were derived from the Integrated Zoning Plan (City Council of Cape Town 2016) based on what is already allowed for construction in the provided zones. The zoning codes used are provided in table A.4.

Table A.3: Zoning limitations of different nature-based solutions

Nature-based solution	SR1	SR2	GR	CO	LB2	GB	MU	GI	OS1	OS2	OS3	AG	RU	TR1	TR2	UT
Green building	1	1	1	1	1	1	1	1	0	0	0	0	0	1	0	0
Beach and dunes	0	0	0	1	0	0	0	0	1	1	1	0	1	0	0	0
Wetland	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Urban green space	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
River project	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Urban agriculture	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Urban forest	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0

Table A.4: Zoning codes in the City of Cape Town (City Council of Cape Town 2016)

Zoning code	Zone
SR	Single residential
GR	General residential
CO	Community land
LB	Local business
GB	General business
MU	Multi-use land
GI	General industry
OS	Open space
AG	Agriculture
RU	Rural
TR	Transportation
UT	Utility

B. Expert interviews

Before interviews were conducted, the interview protocol was created to facilitate the flow of conversation, and information. Some questions were asked first to make interview participants feel more comfortable (Knott et al. 2022), after which more complex questions were asked. After interviews were conducted, they were transcribed. Summary notes were made during this process from which primary codes were created. This led to a process of open coding, during which each of the transcripts were coded line-by-line with the relevant codes and quotes, based on the content as well as the question to which the response was directed. Already here, specific quotes of interest were marked. As the interviews were semi-structured, the content of the responses was carefully considered to match the response codes to the correct question. Some general codes were also used across the whole transcript to indicate recurring themes in the conversation. After the open coding process was completed, the codes for each question were categorised into axial codes that were more useful for contextualising the approach and answering the research questions. Due to protection of personal and identifiable data, the direct interview transcripts, as well as more information on the participants cannot be included in this report.

Table B.1: List of interview participants

Number	Interview participant	Date	Manner of meeting
1	Project leader at international conservation NGO, social-ecological systems expert	01-05-2023	Online, recording and transcript
2	Urban inequalities researcher	02-05-2023	In-person, recording and transcript
3	Legal expert and ex-local government official	02-05-2023	Online, recording and transcript
4	Head of NbS at international consulting firm	02-05-2023	Online, recording and transcript
5	Head of urban activist group in Cape Town, city planner	03-05-2023	Online, recording and transcript

Table B.2: Open and axial coding results of expert interviews

Question	**Open coding**	**Axial coding**
I1. Tell me about yourself and your job position.	Not coded	Not coded
I2. How would you rate your experience and knowledge out of 5 in the following domains:	Not coded	Not coded
- Inequalities and climate vulnerability		
- NbS, ecology, and conservation		
Governance in Cape Town		
V1. What do you think are the key challenges facing Cape Town in terms of climate vulnerability and inequalities?	Political injustice	Governance
	Infrastructure	
	Urban planning	
	Accessibility	
	Housing	
	Informal settlements	
	Transportation	
	Lack of coordination	
	Inequality	Society
	Social Justice	
	Immigration	
	Climate Change	Climate
	Water crisis	
	Flooding	
	Biodiversity	
V2. What interventions have been applied to attempt at addressing these inequalities? Were they effective?	Affordable housing	Intervention targets
	Infrastructure	
	Water management	
	Environmental consciousness	
	Spatial inequality	
	Accessibility	
	Inequality	
	Housing	
	Lack of government intervention	Reasons for inefficiency
	Lack of coordination	
	Lack of long term planning	
	Ineffective policy	
	Environmental concerns	
	Politics	
	Corruption	

Table B.2: Open and axial coding results of expert interviews

Question	Open coding	Axial coding
	Lack of community involvement	
V4. How would you define climate vulnerability?	Climate risk	Climate vulnerability
	Resilience	
	Vulnerability	
	Adaptation	
	Subsistence farm	
	Weakness	
	Drought	
	Flooding	
	Ineffective policy	
	Inequality	
	Climate adaptation	
V5. How is Cape Town unique in the world in terms of [NbS, ecology, inequalities, climate vulnerability, governance]?	Ocean	Geo-physical
	Disproportionate benefits of nature	
	Geography	
	Urban layout	
	Transportation	
	Biodiversity	
	Inequality	Social
	Spatial inequality	
	Accessibility	
	Tourism	
	Apartheid	
	Conservation	Governance
	Skilled governance	
	Urban planning	
N1. How are the benefits (and disservices) of NbS distributed over socio-economic groups?	Reduction of safety	Low income benefits and disservices
	Community development	
	Job creation	
	Gentrification	
	Tourism	
	Air quality	
	Health benefits	High income benefits and disservices
	Land value	
	Caution	Origins
	Location dependence	
	Urban planning	
	Lack of coordination	

Table B.2: Open and axial coding results of expert interviews

Question	Open coding	Axial coding
	Disproportionate benefits of nature	Phenomena
	Inequality	
	Masking issues	
	Social Justice	
	Prioritisation of justice	
	Lack of equitable distribution	
N2. How do ecosystems and communities shape each other?	Socially economically dependent	Context
	Rural-urban	
	Inequality	
	Daily need	Short term
	Security	
	Scripted experiences	
	Reciprocity	Long term
	Community development	
	Community building	
	Social impact	
N4. Would you say that communities that are more vulnerable have a higher demand for certain ecosystem services? *ES definition optionally provided	Direct demand	Demands of the vulnerable
	Community building	
	Security	
	Social justice	
	Air quality	
	Community development	
	Prioritisation	
	Contextualisation	
	Indirect demand	Differing trends
	Epistemic distance	
	Resilience	
	Adaptive capacity	
	Rural-urban	
N5. How do these NbS interact with Cape Town's unique and rich biodiversity?	Job creation	Socio-economic
	Social justice	
	Prioritisation of justice	
	Long term planning	
	Increase biodiversity	Ecological
	Location importance	
	Caution	
	Risk management	

Table B.2: Open and axial coding results of expert interviews

Question	Open coding	Axial coding
	Biodiversity indicators	
N6. How is the community often involved in the implementation of NbS?	Community involvement	Methods
	Legal requirement	
	Cultural sensitivity	
	Social impact analysis	
	Stakeholder engagement	
	Systems mapping	
	Project failure	Failures
	Lack of community involvement	
	Rural-urban divide	
	Weak civil society	
	Barriers to implementation	
	Mistrust	
N7. What examples of urban NbS have you seen in action?	No NbS in SA	Stand-alone
	Conservation	
	Ocean	
	Open parks	
	Urban forests	
	Invasive species removal	
	Green buildings	Gray-hybrid
	Vertical gardens	
	Solar roofs	
	Climate change mitigation	
	Water management	
G1. What are the positions of local politicians and the general public surrounding these interventions?	Conservation	Supportive
	Social justice	
	Prioritisation	
	Climate change	
	Resistance to change	Opposing
	North-centric solutions	
	NIMBY	
	Lack of political support	

Table B.2: Open and axial coding results of expert interviews

Question	**Open coding**	**Axial coding**
	Security and safety	
	Lack of awareness	Neutral
	Corruption	
	Lack of understanding	
G2. What are key considerations for decision-makers/ stakeholders when considering implementing NbS?	Storytelling	Social
	Communication	
	Community involvement	
	Common identity	
	Inequality	
	Security and safety	
	Private cooperation	
	Valuation of benefits	
	Social justice	
	Contextualisation	
	Job creation	
	Resilience	Physical
	Space	
	Funding	
	Climate Justice	Climate
G4. How high a priority is the conservation of Cape Town's unique biodiversity? How would this affect NbS implementation?	Positive commitment	Priority
	Political support	
	Civil support	
	Environmentalism	
	Biodiversity	
	Trade-off	
	Socio-economic inequality	Impede NbS
	Privilege	
	Lack of coordination	
	Regulations	
	Lack of social justice	
	Ownership	Promote NbS
	Prioritisation	
	Indigenous vegetation	
	Urban development	
G5. What are the biggest barriers to implementing NbS in Cape Town?	Prioritisation	Political
	Social justice	
	Regulation	
	Community involvement	
	Political disinterest	

Table B.2: Open and axial coding results of expert interviews

Question	Open coding	Axial coding
	Resistance to change	
	Lack of evidence	
	Lack of coordination	
	Lack of long term planning	
	Financial constraints	Financial
	Private cooperation	
	Space	Geographical
	Scaling up	
	Zoning	
G6. What are the associated risks of using a data-informed decision-making tool such as what I am developing for this thesis?	Multiple methodologies	Mitigation
	Caution	
	Contextualization	
	Community involvement	
	Risk management	
	Pragmatism	
	Mapping	
	Storytelling	
	Flexibility	
	Scepticism	Risks
	Politicisation	
	Data biases	
	Inequality exacerbation	
C1. Is there anything you wanted to mention that did not come up during this interview?	Prioritization	
	Social justice	
	Urban development	
	Agriculture	
	Water	
	Action	
E3. What can be done to ensure that nature-based solutions are equitable and accessible to all communities?	Local government	
	Skilled governance	
E4. How can we ensure that nature-based solutions are culturally appropriate and respectful of indigenous knowledge?	Ethnography	Passive
	Cultural sensitivity	
	Decolonisation	
	Data analysis	
	Ethnographic mapping	Active
	Community involvement	
	Collaboration	

Table B.2: Open and axial coding results of expert interviews

Question	Open coding	Axial coding
E6. What role do you see for private industry in promoting nature-based solutions?	Regulation	
	Risk management	
	Collaboration	
E7. How can we scientifically define people's reliance on natural resources and their vulnerabilities?	Mapping	
	Remote sensing	
	Socio-economic data	
	Data analysis	

Some particularly interesting and related quotes are provided in the following tables. The quotes are categorised between the three main objectives of the interviews:

1. Understanding the uniqueness of Cape Town in this arena (table B.3),
2. Understanding how ES are typically distributed over different socio-economic groups and how that impacts prioritisation (table B.4,
3. Understanding barriers and considerations for the implementation of NbS within the Cape Town context (table B.5).

Table B.3: Interview responses on the uniqueness of Cape Town

	Interview response
Governance (19 instances)	"So obviously what the apartheid regime did was they built on communities on flood plains and of course this is one city. So our our most dancers areas currently is not in the city though it's on the periphery. It's Khayelitsha, it's all these periphery communities that are mostly located on flood planes."(5) "And I think the other thing that wasn't Cape and kept on particular has done very well is tourism that combines nature with things that people with, with development. So you'll have your infrastructure built around certain nature based solutions like the Green Park, the Green Point Park…" (3) "So there is that kind of wanna say instrumentalist reason why why the government will continue they to prioritise conservation and and nature based solutions. " (1)
Social (33 instances)	"You know the the 1% of the population becoming richer and richer and richer and middle class families and communities and you know, unemployed people struggling and struggling and struggling more… you have right next to some of the most affluent areas also some of the poorest areas or every kind of little enclaves of wealth has some Township attached to it or an area where there is a kind of a working class community living in a completely different world, so you have to these multiple worlds coexisting and they they're very little interaction with each other." (1) "You know and and and then what has happened is people have been moved and relocated to even further away communities, perhaps on a flood plain. But even further from their jobs, their communities" (5) "I think you also have a fairly vibrant civil society in the Western Cape" (1)
Geo-physical (24 instances)	"Our work is very simple that as a city we need to be proactive and and regenerative in terms of responding to our crises, from economic to inequality and also water. Day zero is coming back slightly and we know this both internally in the government. " (5) "Mountain is actually blocked the city centre, the sea and then you got a couple of key highways which get you in there, which means that where all the majority of the business and the land using like the resources are actually being blocked off by the mountain, by the ocean. And actually if you do a space syntax analysis, this becomes out as a very isolated on a global scale " (2)

Table B.4: Interview responses on prioritisation and distribution of ES

	Interview response
Demands of the vulnerable (40 instances)	"Suppose so, I suppose because they've got less means to find these services in another way. So if you talk about water, like buying water somewhere." (4) "And historically, have never had any of this stuff, so I would, I would say, you know, before you build bike lanes in, in the southern suburbs and rewild Tokai Forest you know, go figure something out for the people in Nyanga. Just you know, if you go, if you're going to be using the word justice all the time you have to ask. Why are we doing this? For whose benefit?" (1) "So you know a big, big, big political and also from an official point of view, a departure is now back yarding, so additional housing, so supporting those structures we would, I will say, advocate for nature based solutions in that space around how do we make these backyard in more regenerative, produce, food, air purification, all of that I will argue for that so so actually you can have both. " (5) "So I do think that there is room for, for nurturing more nature based solutions, especially in vulnerable communities. And when we're looking at the time that we are in now with the with the economic impact since 2009, the first economic collapse, COVID all of those things, funding from government reduced year on year, and it's going to take that route for some time to come." (3)
Differing trends (18 instances)	"And I guess what we must ask ourselves, you know, I talk about Cape Nature and and so forth, who benefits from the good governance of natural resources that's occurring there? You know what is nature being being governed for as a kind of area of recreation for for white people or, you know, tourists in South or are we actually really saying, well, listen, how can we how can people living in these poor areas benefit from these protected areas and and the kind of pristine environment that, that, that earmarks some part of of Cape Town. " (1)
Context (8 instances)	"Well, I think we have to again say like I don't think anything's universal, so I won't say it on like universal terms because like every society is different. Every city is different. People have different needs." (2)

Table B.5: Interview responses on barriers and considerations of NbS implementations

Barrier type	Interview response
Political (41 instances)	"And so community gardens has not really acquired a very positive reputation from people and and it's normally the older goggos [ladies] that run community gardens and then they have to fight off the riffraff to not ruin their they produce." (3) "the NGOs, you know, all of us are always scrambling from one five year time horizon to the next when when funding cycles stop, you know, and you can't do a climate change adaptation or a mitigation effort in in three or five years. You've gotta have, like, a 20 to 50 year time horizon." (1) "And also to to get people to support it, even if it's not occurring in their neighbourhoods and to kind of help people to understand, you know, we're prioritising this area because of these reasons and and you know you guys are next that kind of thing…" (1) "OK, there's like, all these regulations and things. And this is also why I think like, rezoning might take time because I think you have to get the Community input on it." (2) "You've gotta think of safety. You gotta think of security. And you got to think of eyes on streets." (2) "And if you want to do it in a public space, like in a mountain, you need permits from government. And sometimes these things have to be build in phases." (3) "He said don't teach the same citizen engagement. Communities don't know what they want." (3)
Financial (10 instances)	"You need money if you're going to send an army of people into an area to clear alien vegetation and and so forth." (1) "…one of the barriers and A and then finance, how do you yeah, scale up and and get sort of more private investors as well in, in, in interested and able to to invest in there usually." (4)
Geographical (14 instances)	"…I mean they take up space, so it's a I guess the that that's always a problem with it that you can't use the and that space for other, other things. " (4) "it must get the municipality's approval and the municipality will only allow you to build inside the urban edge." (3) "Space. Opportunities funding. And people with who are inspired and passionate about certain specific things" (3)