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2018

Elaboration of a “Climate Change Hazard, Vulnerability and Risk Assessment” Study to the benefit of the City of Cape Town

Inception Report

Réf. AFD/DOE/EBC/CLD | ACH-2017-026

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PROJECT BACKGROUND

This report is submitted under the French Development Agency (AFD) project: Elaboration of a "Climate Change Hazard, Vulnerability and Risk Assessment" Study to the benefit of the City of Cape Town. The project falls under the CICLIA Framework Agreement for Studies and Technical Assistance for the Cities and Climate Change Initiative in Sub-Saharan Africa, funded by the French Development Agency (AFD), EU and the Swiss State Secretariat for Economic Affairs (SECO). Specifically, this report is submitted on the outcomes of the Project Kick-off meeting held on the 6th of April 2018 and the Inception Workshop held on the 26th of April 2018, in accordance with the requirements of the Contract for Réf. AFD/DOE/EBC/CLD | ACH-2017-026. As such, this report constitutes Deliverable 1 under this contract and includes a project overview and rationale, an outline of the anticipated work schedule, an analysis of data requirements and a breakdown of the methodological approach.

ACKNOWLEDGEMENTS

We would like to thank all representatives of the City of Cape Town who participated in the Inception Workshop.

Thank you to our leading experts and OneWorld Team who delivered the objectives of this report: Belynda Petrie, Francois Engelbrecht, Martin de Wit, Jonathan Rawlins, Arthur Chapman, Anna Filipova and Theo Klein.

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Abbreviations and Acronyms

AFD	French Development Agency (Agence Française de Développement)
CCT	City of Cape Town
CoT	City of Tshwane
CSIR	Council for Scientific and Industrial Research
CSRM	Catchment Stormwater and River Management
DRM	Disaster Risk Management
GCM	Global Climate Model
GDP	Gross Domestic Product
GIS	Geographic Information Systems
FRI	Flood Risk Index
HATOY	Highest Astronomical Tide of the Year
IKM	Integrated Knowledge Management
IDP	Integrated Development Plan
MAP	Municipal Adaptation Plan
MAR	Managed Aquifer Recharge
OPP	Organizational Policy and Planning
StatsSA	Statistics South Africa
ToR	Terms of Reference
WCWSS	Western Cape Water Supply System
WMA	Water Management Area

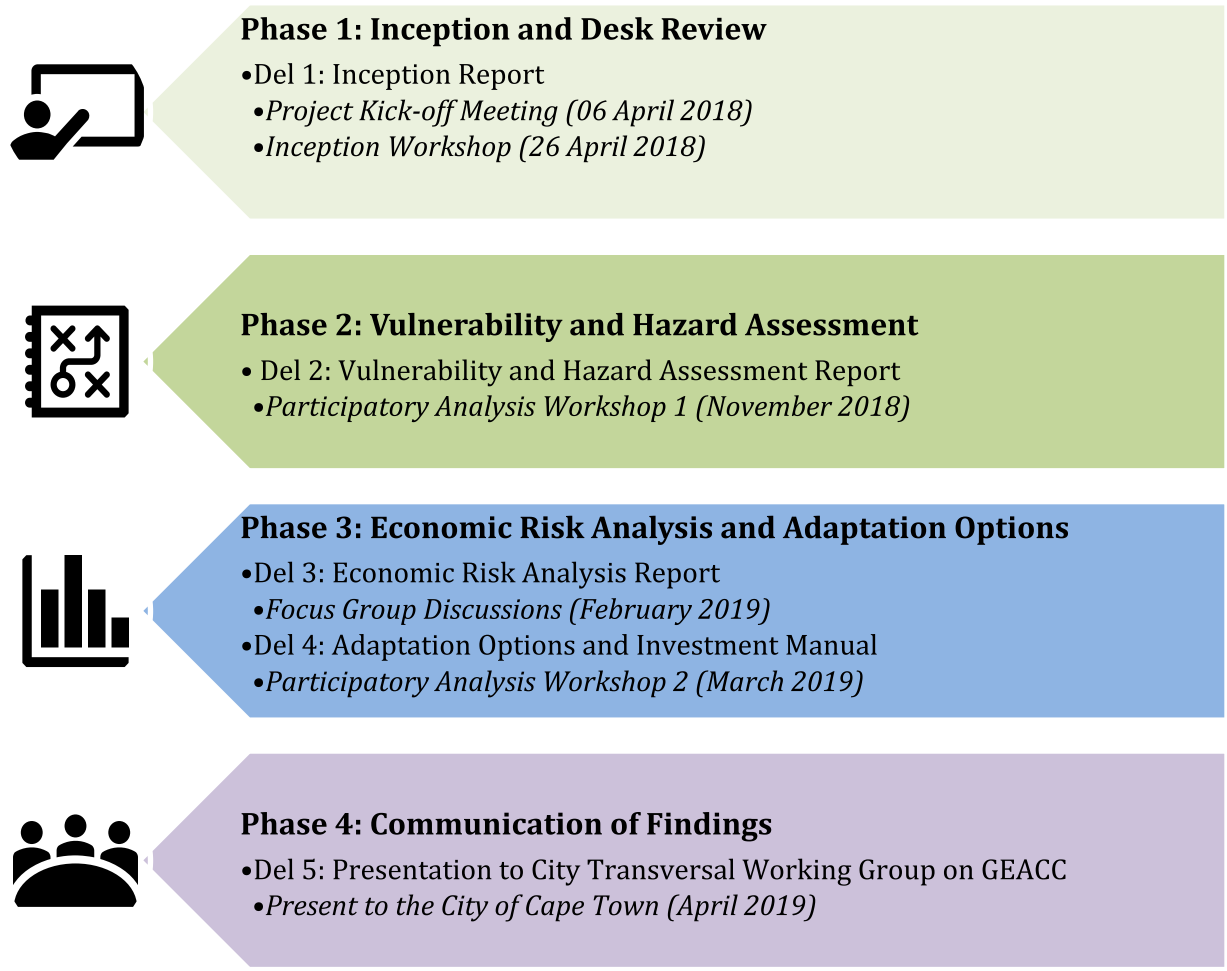
A. Introduction

This report is Deliverable 1 of the project **Elaboration of a "Climate Change Hazard, Vulnerability and Risk Assessment" Study to the benefit of the City of Cape Town**, commissioned by the French Development Agency (AFD).

Réf. AFD/DOE/EBC/CLD | ACH-2017-026.

The project is being delivered in line with a four-phased approach, with key deliverables and fieldwork activities under each phase, as illustrated in Figure 1. Building on the project kick-off meeting with the City of Cape Town (CCT) held on the 6th of April 2018 and the project Inception Workshop held on the 26th of April 2018, this report includes: i) the key outcomes of the inception phase and the anticipated work plan; ii) a critical review of existing work and an initial review of the data and gap analysis; and iii) a breakdown of the conceptual framing and an update on the methodological approach.

Figure 1: Phased Project Approach



A.1 Outcomes of the inception phase

The kick-off meeting and inception workshop were well attended with representation from most pertinent CCT departments, such as Disaster Risk Management (DRM), environment, the built environment and knowledge management and organizational research. Unfortunately, health was not represented because the invitees were unable to obtain approval to attend the workshop in time. See Appendix 1 for a list of the inception workshop attendees.

The level of engagement was excellent and the project team's workshop objectives were met. The nature and topics of the questions being raised alluded to a high-level of buy-in and technical engagement. The outcomes of the inception phase are separated into the key project parameters agreed upon, main methodological points raised and the various considerations and arrangements relating to data acquisition.

A.1.1 Key project parameters agreed

- **Project spatial boundaries:** while our proposal suggested analysing beyond the CCT municipal boundaries, it is clear that the CCT data is confined to their municipal boundaries, limiting our proposed approach to including the catchment areas that CCT feeds off and impacts on.
- **Integrated versus sectoral approach:** our analysis will take an integrated approach that ultimately will identify key vulnerabilities, and thus investments, under different thematic areas as an outcome of the analysis.
- **Economic assets:** the consideration of the impact of climate hazards on CCT economic assets refers to the broader economic assets within Cape Town (CT), as well as those owned by the CCT. The cross sectoral and stakeholder impacts of climate change on the local (and to some extent regional) economy will be considered; for example, the impact of droughts on agriculture, which in turn affects agri-processing industry in CT.
- **Key thematic areas:** it was agreed that we cover livelihoods, poverty, built environment and disaster risk as cross cutting themes.
- **Rates of change scenarios:** we will develop 3 scenarios based on the latest IPCC thinking and noting the existing CCT policy framework (which talks to a 1,5 degree future). Scenario 1: 1.5 degree future; scenario 2: 2 degree future and scenario 3: 4 degree future.
- **Timescales:** while there is confidence around many of the climate projections, timescales are a still a challenge, raising key questions such as when will the current drought conditions become the norm? Thus, timescales will be an important focus of our work, noting that the costs of adaptation investments are often incurred ahead of the change anticipated, making these investments unattractive for many.
- **Learning by doing:** the project will be framed through an iterative approach that also allows for flexibility in the adaptation options investment framework.
- **Alarmist messages:** the project team will exercise caution around messaging arising from this project's analysis. For example, the CCT is concerned about overly alarming the public on the issue of sea level rise in the absence of careful communication and information management around this climate change impact.

A.1.2 Key methodological points raised

- **Sensitivity assessment:** a key question was raised specifically around how the sensitivity layer will be developed, noting the vast range of parameters and indicators that could affect this component of the analysis. The concern is that we try to do too much and try to make this study answer too many questions, potentially diluting its quality and hence impact. While many of the examples raised are indicators that we would typically include in the adaptive capacity assessment layer, this is noted to be a valid concern. It was agreed that we will continue to refine indicator parameters in two ways: i) through weighting the input data layers according to their relevance, reliability of source, and resolution (preference for input layers of higher resolution), and; ii) through discussion with key CCT staff and during the stakeholder validation workshop. Importantly, the risk of not getting sufficient participation from the 'right' people in the CCT (e.g. in line departments such as storm water management and catchment management etc.) in the validation and verification workshops is noted.
- **Partnerships:** The CCT is mandated to build partnerships between and within departments, and we are encouraged to work within this framework. The project team is cognisant of the role of this project within the CCT's larger strategic framework, with the objective being to feed into and inform the City's future climate change adaptation planning processes. Moreover, this work

should cut across and align with other ongoing work including but not limited to the: i) Resilience Strategy under the '100 Resilient Cities Programme'; ii) Integrated Development Plan 2017-2022; iii) Social Development Strategy; iv) Economic Growth Strategy; v) Climate Change Policy; vi) Water Resilience Framework; vii) Municipal Spatial Development Framework; and viii) Environmental Management Frameworks.

- **Economic risk analysis and investment planning:** a balance between hard and soft infrastructure assets is sought using a risk-based cost-benefit approach and a social discounting approach where the rate of time preference is premised on the CCT's role as a long-term service provider versus a shorter-term investor. The risk of pooling 'soft infrastructure' risks as supporting possibilities to hard infrastructure risks as they are more difficult to quantify is noted in that the 'softer' risks may become subverted.

  The forthcoming Resilience Strategy is noted as being useful to identifying 'softer' investment options, as well as having a strong synergy with the overall project approach. Our approach recognises the need to consolidate, and add to, the City's knowledge and understanding of climate hazards, risks and vulnerabilities, as well as of the current drivers of vulnerability (existing and desirable adaptive capacities), the non-climate policies that provide important mainstreaming entry points for integrating climate responses, and existing adaptations (planned and autonomous), before determining the most appropriate course of action for responding to these challenges.

- **Social and economic assets vulnerability nexus:** on the one hand it is important to protect CCT owned assets to protect municipal revenue streams, while at the same time it is critical to build the adaptive capacities of the CCT's most vulnerable populations. The manner in which risk and vulnerability is conceptualized for hard assets vs. social assets is different and can result in incommensurate outcomes. Thus, we propose to assess each in the most appropriate manner and assess the most prominent vulnerabilities that emerge from the analyses as well as from the various stakeholder engagement processes.

  Our view is that both conceptions are important and that the cost of not building climate resilience in either is potentially significant. However, from past experience we are concerned that a specific focus on infrastructure investments to the detriment of vulnerable populations could cost the CCT in many ways in the medium to long term (politically, socially, environmentally, economically). Our caveat is that this project cannot solve these overarching dilemmas and we want to avoid the conception of climate risk and vulnerability in this project being influenced by the CCT's revenue model. It can however take a balanced, science-policy oriented perspective and this is what we aim to do.

- **Communication of findings:** a greater emphasis on the communication of the project findings to important non-city stakeholders such as politicians and business leaders was proposed. In addition, the importance of considering how data and information is presented to different investor audiences (e.g. private vs. municipal vs. international donor organisations) is noted. These recommendations have been addressed in the revised fourth phase of the project.

A.1.3 The data journey

- Having gained consensus on the importance of the underlying data to the success of the overall project, the use of CCT data will be prioritized to increase project buy-in and engagement. Otherwise Statistics South Africa (StatsSA) and Council for Scientific and Industrial Research (CSIR) will be the primary data sources, noting that the CSIR is on the scientific forefront of climate change projections for the African continent.
- Despite there being a wealth of data that is available, much of the important data for the adaptive capacity and sensitivity assessment is sensitive (e.g. informal settlement and household survey data) and might thus require extensive procurement protocols.

- The CCT will assist us in accessing pertinent information through providing critical documents and access to the relevant contacts. The corporate Geographic Information System (GIS) unit in the Integrated Knowledge Management (IKM) department and the research unit in the Organizational Policy and Planning (OPP) Department will be our primary contacts for data access in accordance with CCT protocols and rules.
- Key data related risks are largely related to time and quality. The amount of time required to comply with data access and use protocols, particularly issues around intellectual property may influence project timelines. Moreover, spatial resolution and quality control factors will be important in terms of what can and can't be used in the hazard, risk and vulnerability assessment. Nevertheless, a structured data input weighting procedure combined with participatory analysis will be used to inform the data inputs and how they influence the model. Lastly, key assumptions and omissions in the form of a gap analysis (e.g. economic data in informal settlements is sparse) will accompany the assessment to highlight what components may not have been accurately reflected in the model. Thereafter, the underrepresented aspects of the risk and vulnerability assessment will be more thoroughly investigated through qualitative means and stakeholder engagement.
- Periodic and timely collection and analysis of high-quality data is integral to the success and ownership of this project and to ensure a high level of confidence in the results. Local data is particularly critical because the adaptive capacity layer in the spatial vulnerability mapping and reports is heavily reliant on high resolution and accurate local data. It will also rely on local validation and verification processes. Therefore, it is imperative to streamline data collection and validation parameters and processes for the duration of the project during the inception phase.
- The project team is well situated to source spatial and non-spatial data of the highest quality and resolution for this project. Three key data sources are envisioned: The Council for Scientific and Industrial Research (CSIR), habitat INFO, and the City of Cape Town (CCT). The project team will be able to facilitate access to the variety of CSIR and habitat INFO datasets available, however, we expect that the project counterpart staff within the CCT will facilitate access to all local data and maps required in a timely manner. We envision that a **'data reference group'** is set up with a few select project team members and key staff from the CCT to ensure continued, iterative and effective communication and data sharing throughout the lifetime of the project. Importantly, the study will be informed by existing data and research to ensure we avoid duplication of effort and provide the most relevant analysis possible. This will require continuous data acquisition and verification between CCT and OneWorld, as well as cross-sectoral/-departmental data access. Further to this, a working Data and Literature Schedule has been set up to allow for continual updating and development of the literature base and data plan throughout the project lifecycle.
- A four-way agreement is being concluded between the CCT, the AFD, OneWorld and Suez, to facilitate the iterative data flow and access required to effectively and timeously deliver this project.

A.2 Anticipated workplan & Project Team Roles

The following workplan represents the anticipated schedule of activities and associated timeframes for delivery throughout the course of this project. As per the outcomes of the inception workshop, the phased approach has been slightly amended from the workplan presented in the original project proposal (see Appendix 2). Note that this includes reducing the total number of phases from 5 to 4, as the two components of the risk and vulnerability assessment (i.e. phases 2 and 3) have been amalgamated for easy of sequencing. Moreover, it is important to note that the overall timing of the project has been significantly delayed by the final signature of the four-way data sharing agreement by CCT, as illustrated in red in the anticipated workplan below.

For planning purposes, the light blue highlighted activities show all of the participatory processes and the vertical yellow highlighted weeks at the end of this year represent anticipated holidays.

On ***project governance arrangements***, the CCT will convene a project Reference Group (RG), comprising city stakeholders drawn from the Inception Meeting participants (targeted and present), and the AFD. The RG will meet at critical points to review project outcomes, such as the VRA results and thereafter, the draft adaptation options matrix. The project team and the CCT team will discuss and determine intervals and dates for these meetings and will endeavour to arrange them at times that suit as many RG members as possible.

	Activities	Month																																																	
		Apr-18				May-18				Jun-18				Jul-18				Aug-18				Sep-18				Oct-18				Nov-18				Dec-18				Jan-19				Feb-19				Mar-19				Apr-19			
Phase 1: Inception and Desk Review																																																					
1,1	Contracting	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x																												
1,2	Kick-off meeting	**x**																																																			
1,3	Literature review and data collection; gap analysis		x	x	x	x																																															
1,4	Sector analysis and selection			x	x																																																
1,5	Finalise work programme, reporting etc.				x																																																
1,6	Draft Inception Report				x																																																
1,7	Inception Workshop				**x**																																																
1,8	Revise Inception Report					x																																															
D-1 DEL	**Inception Report**					.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	•																											
Phase 2: Vulnerability and Hazard Assessment																																																					
2,1	Model and consolidate data																			x	x	x	x	x	x	x	x	x	x	x	x																						
2,2	Conduct spatial risk and vulnerability mapping																									x	x	x	x	x	x																						
2,3	Conduct spatial thematic assessment																													x	x	x																					
2,4	Assess cumulative impacts of drivers of vulnerability																														x	x	x																				
2,5	Participatory analysis workshop 1																																**x**																				
2,6	Draft Consolidated Vulnerability and Hazard Assessment Report																																x	x	x																		
D-2 DEL	**Vulnerability and Hazard Assessment Report**																																			•																	
Phase 3: Economic Risk Assessment and Adaptation Options																																																					
3,1	Typology of risks																																		x	x			x														
3,2	Conduct hazard risk analysis																																			x			x	x	x	x											
3,3	Social capital assessment																																								x	x	x	x									
3,4	Focus group discussions																																											**x**									
3,5	Identify investments for economic resilience																																								x	x	x	x	x								
D-3 DEL	**Economic Risk Analysis Report**																																												•								

	Activities	Month																																																			
		Apr-18				May-18				Jun-18				Jul-18				Aug-18				Sep-18				Oct-18				Nov-18				Dec-18				Jan-19				Feb-19				Mar-19				Apr-19			
3,6	Determine and rank adaptation options																																												x	x	x						
3,7	Develop manual of solutions and approaches																																												x	x	x	x					
3,8	Estimate costs of each adaptation option																																													x	x	x	x				
3,9	Participatory analysis workshop 2																																																**x**				
3,10	Finalise Adaptation Options and Investment Manual																																																x	x	x		
D-4 DEL	**Adaptation Options and Investment Manual**																																																		•		
Phase 4: Communication of Findings																																																					
4,1	Prepare communication strategy																																																			x	x
4,2	Present to the City of Cape Town																																																				**x**
D-5 DEL	**Presentation to City Transversal WG**																																																				•

The table below provides an indicative outline of team roles and responsibilities per group of activities and days allocated for each. This is high level and indicative, subject to refinement as the data access and earlier project findings highlight priorities in terms of expertise required to deliver the tasks at hand.

Table 1: Project Team Allocation

Project Component	Experts	Indicative days allocated
Inception & Desk Review		
	Belynda Petrie	8
	Jonathan Rawlins	13
	Arthur Chapman	1
	Martin de Wit	1
	Francois Engelbrecht	1
Sub total		**24**
Sectoral Hazards, Vulnerability & Risks		
	Francois Engelbrecht	26
	Rob Davies	10
	Belynda Petrie	6
	Jonathan Rawlins	15
	Pool of Experts	15
Sub total		**72**
Consolidated Hazard, Vulnerability & Risk Assessment		
	Francois Engelbrecht	7
	Rob Davies	16
	Belynda Petrie	8
	Jonathan Rawlins	22
	Pool of Experts	15
Sub total		**68**
Economic Risk Analysis & Adaptation Options		
	Martin de Wit	18
	Belynda Petrie	8
	Anna Filipova	26
	Pool of Experts	25
Sub total		**77**
Communication of findings		
	Belynda Petrie	4
	Francois Engelbrecht	1
	Martin de Wit	1
	Anna Filipova	4
Sub total		**10**
TOTAL		**251**

B. Critical Review of Existing Work

The project Terms of Reference (ToR) and the OneWorld proposal refer. This section intends to provide a succinct overview of what the literature says about climate risk and vulnerability in the CCT, as relevant to key aspects of this project, building off the ToR and proposal. As such, it provides a brief overview of the economic structure of Cape Town, climate change adaptation in Cape Town, and an overview of the impacts of climate change on key sectors, such as water.

In particular, a systematic review of all available previous work on hazard, vulnerability and risk in and around the CCT has been conducted. The project team has consulted with CCT officials, sector experts and academics to ascertain as much information on the topic as possible. The purpose of this review is twofold: i) to ensure the work conducted during this study is not duplicating any prior efforts; and ii) to identify the most important gaps in existing work, so these can be addressed through the methodological design.

The exhaustive nature of the literature schedule necessitated a general screening assessment of the available information to be undertaken to inform the gap analysis and determine the most relevant reports that require further investigation. Noting the rapidly changing climatic, socio-economic and environmental conditions within and around the CCT, more recent work was prioritized in this review. Moreover, this review situates the CCT context within the broader climate change debate.

B.1 Climate change and the City of Cape Town

B.1.1 Overview

Climate change is expected to cause severe biophysical, social, environmental and economic impacts on cities worldwide, both directly and indirectly (Tadross and Johnson, 2012). Although cities typically have the resources to adapt to these threats, the rate and extent of global climate change impacts are greater than previously projected (IPCC, 2014), and significant uncertainties in climate projections increase risk. Hence, understanding current risks and vulnerabilities related to climate change and variability is becoming a key planning process for cities around the world and South Africa (see Box 1).

Box 1. Climate Risk and Vulnerability in The City of Tshwane

Climate change projections for temperature and rainfall were established for the City of Tshwane (CoT) (City of Tshwane, 2014) using a variety of climate models and downscaled climate models. The results indicated increases in temperature of between 4 and 6.5°C by 2100, with increases of between 2-3°C expected by the mid-term (2040 –2060). Projections for rainfall suggested less rain over the CoT region in future with more hot days predicted. The occurrence of extreme weather-related events such as droughts, floods, hailstorms and heat waves are expected to increase in frequency and intensity affecting especially the vulnerable population groups, as well as essential infrastructure and economic development

This study identified impacts of changes in weather variables on different sectors, adaptation options, stakeholder roles and responsibilities, the adaptive capacities of communities within the CoT and barriers to effective to adaptation. A categorisation of vulnerability was established based on key sectoral vulnerabilities including human health, human settlements that are at risk of flooding, agro-ecosystems that provide food security, water security, high energy demand for domestic and industrial use and ecosystem goods and services. The various regions of the CoT were ranked according to their social, health and environmental vulnerability with a ranking of low, medium or high. Region 1 is ranked highly vulnerable due to the informal settlements and high population density and its location within important flood lines. Regions 2, 3, 4, 5 and 6 have medium to high vulnerability and Region 7 has a low to medium vulnerability. Adaptation options by sectors were presented for possible adoption in line with the Framework for a Green Economy Transition to be critical for climate change adaptation and building resilience of the City. Adaptation options range from the development of early-warning systems to legislative changes and water restrictions.

Global climate modelling suggests that there will be significant climate change impacts in South Africa, and specifically in the Western Cape Province (Hewitson, 2005; Engelbrecht et al.,2009; Louw et al., 2012; Engelbrecht et al., 2015; Engelbrecht and Engelbrecht, 2016). Recent climate change risk and hazard research (Brundrit, 2016; Fairhurst, 2008; Cartwright, 2008; Jack et al., 2016) indicates that the CCT is currently facing four key climate change impacts:

1. A decrease in annual average rainfall and a change in the seasonality of rainfall;
2. An increase in mean annual temperature: higher maximum temperatures, more hot days, and more frequent and intense heat waves;
3. An increase in average wind strength; and
4. An increase in both the intensity and frequency of storms: short, high intensity rainfall events and increased size and duration of coastal storms.

It is expected that these changes, already observed to some or other extent, will continue to occur in addition to sea level rise (see Box 2) and that climate change induced sea level rise will further exacerbate the severity of storm surges and therefore their impact (Brundrit, 2009). As with other extreme events, the recovery period between storm events is expected to shorten, leaving economies and livelihoods more vulnerable than they perhaps already are. Moreover, these risks are further intensified by the burgeoning population of the city, estimated to reach 4.23 million by 2023 (Western Cape Government, 2016).

Box 2. The Risk of Sea-level in the City of Cape Town

Sea level rise is one of the most prominent effects of climate change affecting cities. Sea level rise refers to the overall increase in volume of water in the World's oceans, which increase mean sea levels. Attribution of sea level rise to climate change is through the process of thermal expansion of ocean water and melting of ice sheets and glaciers on land. Sea level rise at different locations may vary from the global mean as a result of local factors such as storms, tides, land subsidence, currents etc. Moreover, the impacts of rising seas are primarily a function of spatial development patterns. Even small increases in sea level can have devastating effects on coastal habitats and infrastructure.

The CCT is a developed coastal city with varied topography ranging from low lying sandy coastal plains to Table Mountain standing over 1000m above sea level. The CCT has been identified as being highly vulnerable to sea level rise in the short to long term. This is important because the CCT has 300km of coastline under its jurisdiction (Brundrit, 2008a) with important dunes, or soft infrastructure, protecting low lying lands beyond them. Storms can destroy sand dunes and their reconstruction, or rehabilitation, takes time (Fairhurst, 2008). Human-induced risks must be coupled with this climatic risk; according to Fairhurst (2008) some of Cape town's dune systems have been cut off from their natural replenishment opportunities and are not therefore able to offer the protection that they otherwise would. The same report outlines Cape Town's various coastal zones, indicating where the impacts of sea level rise are likely to be, or are already being, felt. Among these are industrial areas, suburbs and human settlements, that are already vulnerable because of low adaptive capacities. For example, human settlements characterised by low levels of income, or high levels of poverty, unemployment and inequality, typically have low levels of adaptive capacity, such as communities in the Cape Flats, while well-established industrial areas, such as Paarden Eiland, are not protected from the impacts of storm surges through climate resilient design of roads, property and/or electrical infrastructure.

There has been extensive research into climate change impacts for the CCT, however, much of the research and associated data is disaggregated and/or entirely discrete. The risks associated with sea level rise, flooding, drought and fires have been assessed at different spatial and temporal scales for different purposes. This makes integrated development and investment planning difficult, as different risks and hazards cannot be compared and assessed on an even keel.

Climate changes can be meaningless without translation into impacts. In turn, understanding impact has much more meaning when understood in terms of vulnerability. Climate impacts are experienced differently, depending on the inherent level of vulnerability. Understanding vulnerability provides the ideal point of departure for integrated climate-smart development and investment planning. Moreover, vulnerability is differentiated by development factors, such as poverty, education, access to safe water, along with other indicators that make up our understanding of adaptive capacities in a geography or system. It is also a function of exposure and sensitivity to climate risks as evidenced in the sea level rise example. Thus, understanding existing work on prominent climate hazards and associated vulnerabilities and risks is a key point of departure to assess the relevant knowledge and information gaps.

B.1.2 Prominent climate hazards, vulnerabilities and risks

A disaster-risk, vulnerability and manageability assessment for the CCT was undertaken in 2009/2010 (Aurecon, 2010) to establish a priority rating of hazards and disasters and offer a prioritization tool for the municipality. The assessment included a quantification of relevant hazards and disasters based on the probability of occurrence and estimation of severity of impacts. Societal, environmental, infrastructural and economic vulnerabilities were then quantified, followed by potential coping-capacities using simple multi-criteria assessment and rankings. Relative disaster risk priority scores were determined using the following formula:

$$Relative\ Disaster\ Risk\ Priority\ Score = Hazard\ Score\ \times Vulnerability\ Score \div Manageability\ Score$$

This assessment incorporated a multitude of hazards and disasters, many of which are related to climate variability and change. Water-table flooding, storm-water overflow flooding, severe storms, sea-level rise and structural fires in informal settlements were identified as having a 'very high' overall disaster risk score. Notably, drought was not considered as a hazard under this assessment.

Building on this assessment and following an extensive assessment of the available literature, relevant climate hazards have been categorised as follows: heavy rainfall, floods (inland floods inclusive of storm-water overflow, water-table flooding and river/flash flooding), droughts, fires, sea-level rise (including coastal flooding, coastal erosion and storm surges), heat waves (high temperatures) and strong winds. Table 1 outlines and briefly describes the related existing works relevant to these hazard categories relevant to the CCT.

Table 2: Existing Work on Climate Hazards Facing the City of Cape Town

Climate Hazard	Existing Work	Description
Heavy Rainfall	De Waal et al. (2017)	A generalised Pareto distribution and a peaks-over-threshold sampling approach was applied to 76 rainfall stations across the Western Cape to test the assumption of stationarity, which holds that natural systems vary within an envelope of variability that does not change with time, by examining the changes in extreme 1-day rainfall high percentile. Findings: While there is no clear spatial coherency to the results, the general trend indicates an increase in frequency of intense rainfalls in the latter half of the 20th and early 21st centuries.
	Jack et al. (2016)	Climate change trends (temperatures and rainfall) for the Cape Town region based on historical climate data. Dataset analyses based on surrogate datasets (satellite-derived rainfall estimates) and global data compilations. Findings: overall increase in rainfall in the north of the Cape Town region (West Coast) and a decline in the southern part.

		Increase in rainfall during June for the 2046-2065 period but a decrease for other months and the 2081-2100 period.
	Mukheibir and Ziervogel (2007)	This paper presents and discusses an overarching framework that would facilitate the development of a Municipal Adaptation Plan (MAP). The example of the CCT illustrates some of the sector-level assessments and potential climate threats, such as urban water management, stormwater, fires and coastal areas, as well as resource mobilization issues that need to be addressed during the development and implementation of a MAP. Stormwater: the intensity of rainfall in the Western Cape can be expected to change due to climate variability. An increase in the number of extreme events will have the effect of substantially increasing the losses to the public and private sectors, as well as increasing personal hardship for the people directly affected. Adaptation options: ongoing monitoring and warning, reducing the impacts of these natural hazards through infrastructural means, increasing the flood event return period, maintenance of stormwater drains, development of resilient infrastructure.
	Tadross and Johnston (2012)	Climate change (rainfall, temperature, evaporation and extreme events) projections were established based on downscaled Global Climate Models (GCMs) and sectoral impacts and vulnerabilities were assessed (water and sanitation, transport, health, energy, livelihoods). Findings: decreases in rainfall are suggested all year round with the greatest changes during the main rainfall season in June, July and August. During the December-February median changes are small, with consistent model simulations tending towards the western regions over the ocean.
Floods (inland floods inclusive of storm-water overflow, water-table flooding and river/flash flooding)	Bangira (2013)	The aim of the study was to evaluate flash flood potential areas in the western part of South Africa by using remote sensing and in situ data to map flash flood potential areas in selected catchments by integrating precipitation, topographic and soil wetness products. High rainfall intensity of short duration on saturated soils as well as on steep slopes favours flash flood potential. Areas with greatest potential for flash flooding were found to be those that have received high rainfall when the antecedent soil moisture was high and have steep slopes that increase the flow of run off to low contributing areas.
	Bouchard et al. (2007)	A flood risk index (FRI) pilot study in the Cape Flats to improve disaster planning. Aim of the project is to create guidelines for community-level structural improvements and effective communication methods for the CCT to improve current flood risk management strategies. Use of population data, rainfall data and flood incident reported to the Catchment Stormwater and River Management (CSRM) management unit. Findings on hazards: current incident

		reporting system is underutilised in informal areas, no systematic data collection, current topographical data is insufficient for use in FRI.
	DiMP (2006a, 2006b and 2006c)	Assessment of risk and vulnerability of Phola Park and Khayelitsha informal settlements. Outcomes: flood and fires are the main risks perceived by the community. Everyone is at risk, specifically those living close to Potsdam Road and those living close to the river at the far end of the settlement. Children are more at risks of illness. Poor building materials and lack of flooring, poor infrastructure in terms of water pipes and standpipes.
	Mauck (2017)	Assessment of the feasibility of implementing Managed Aquifer Recharge (MAR) as a strategy for flood prevention and supplementing urban water supply. Information on the Cape Flats Aquifer (from DWAF, 2008) and MIKE SHE model (integrated hydrological modelling system for building and simulating surface water flow and groundwater flow) use at a regional and local scale. Findings: flood mitigation on the Cape Flats was possible and was likely to be most feasible at the Graveyard Pond site. The flood mitigation scenarios indicate a potential risk to local groundwater dependent ecosystems, particularly at the Sweet Home site. Yet, it was shown that a reduction in local groundwater levels may have ecological benefits as many of the naturally occurring wetlands on the Cape Flats are seasonal, where distinct saturated and unsaturated conditions are required. Furthermore, MAR was shown to improve the yield of wellfields at Philippi and Mitchells Plain through the artificial recharge of stormwater while also reducing the risk of seawater intrusion.
	Musungu et al. (2012)	Collection and development of community-based GIS information in a flood-prone informal settlement to inform the disparities in levels of vulnerability to flood risk as well as suggest potential solutions to mitigate flood vulnerability. Findings: 3 types of flooding were mapped: flooding from underground water, flooding from leaking roofs, and flooding by run-off water. The spatial location of these flooding events was also collected. During heavy rainfall, water channelled along the roads and built surfaces of the neighbouring formal developments flows into the settlement, first flooding the shacks on the periphery and then flowing along the trenches into the centre of the settlement. Since the centre of the settlement lies at a lower altitude than the periphery, the run-off water collects in the valley, hence the rising underground water. In the valley, responses include the use of sandbags and covering the floors using blankets and concrete, as well as raising shacks on wood and stones. Waterborne diseases were correlated with winter flooding events.

	Rowswell and Fairhurst (2011)	Climate change projections (rainfall, temperature, evaporation and extreme events) were established and vulnerabilities assessed: floods will be more likely as extreme events such as storms would be more frequent. Then sectoral impacts associated with increased temperatures are discussed in relation to their impacts on livelihoods (water and sanitation, transport, health, energy). Floods have consequences on health and water. Flooding can lead to immediate loss of human life but would also place a burden on population health especially the most vulnerable. Flooding also stresses sewage and storm-water systems leading to water pollution associated with excessive levels of micro-organisms and the subsequent increase in waterborne diseases that manifests as diarrhoea and dehydration.
	Tadross and Johnston (2012)	Climate change (rainfall, temperature, evaporation and extreme events) projections were established based on downscaled GCMs and sectoral impacts and vulnerabilities were assessed (water and sanitation, transport, health, energy, livelihoods). A reduced rainfall scenario may lead to a reduction of flooding, early studies show that rainfall intensity has been increasing, thus increasing the vulnerability of dense housing, especially that constituted by informal structures.
	Ziervogel et al. (2016)	Assessment of how flood risk is governed and identification of barriers to collaborative governance to help to build a more holistic flood management approach. Using a nodal governance framework, the authors assessed the mentalities, technologies, resources and institutional structures of four different local government departments in the CCT and the extent to which they collaborate on flood risk management. Findings: Constraints to collaborative urban flood risk management are the following: technocratic approaches, lack of capacity, challenges to sharing risk between departments and with residents, political contestation and short-termism. The study suggests that collaborative flood governance that includes key CCT nodes and key external nodes (such as civil society organizations in flood-prone areas) is essential for addressing flood risk in a proactive and holistic way. Collaborative governance requires bridging the competing mentalities and technologies of different nodes and developing new hybrid technologies.
Droughts	Dennis and Dennis (2012)	Aquifer vulnerability assessed using the DART methodology (analysis of the depth to water level change, aquifer type, recharge and transmissivity) to identify areas that could experience possible changes in their groundwater resources as a result of climate change. Areas subject to average degradation of their current DART index are mainly situated

		in the Western Cape and are characterised mainly by a high slope percentage and low transmissivity values.
	Pengelly et al. (2017)	Understanding of the economic impacts of water access is limited, and there is a lack of tools available to address the trade-offs that may be required when allocating water in a water scarce system. This is needed in particular in "constrained catchments" where all readily available water is already allocated, such as the case of the Berg Water Management Area (WMA). In such catchments, future development requires additional water resources, either through the development of new resources or the reallocation from other users in the WMA. The analysis aimed to understand how decision support tools such as the IDP could add value to existing legislated processes by filling knowledge gaps or by providing a collaboration mechanism. A regional hydro-economic GIS tool has been developed to understand how water scarcity may constrain development in local economies within the Berg WMA. Findings: the absence of a regional water utility for the Berg WMA is hampering the development of water resources, particularly at a local level. Coordinated planning for future water resource interventions for those Water Service Authorities supplied by the Western Cape Water Supply System (WCWSS) must be strengthened. All spheres of government need to be more cognisant of the local capabilities and water resource availability.
	Rowswell and Fairhurst (2011)	Climate change projections (rainfall, temperature, evaporation and extreme events) were established and vulnerabilities assessed: increased water stress in the city will worsen socio-economic drought. Then sectoral impacts associated with increased temperatures are discussed in relation with their impacts on livelihoods (water and sanitation, transport, health, energy). An increase in demand for potable water, with the increase in the CCT human population will lead to further water stress.
	Tadross and Johnston (2012)	Decreased rainfall accompanied with increased temperatures could lead to severe water shortages in a region which is already prone to frequent droughts. Since 1985, there have been nine winters with total rainfall below 70% of average (an average of more than one in every three years). The region also experiences a very low rainfall to runoff conversion (3.1%).
Fires	DiMP (2006, 2006b and 2006c)	Assessment of risk and vulnerability of Phola Park and Khayelitsha informal settlement. Outcomes: flood and fires are the main risks perceived by the community. Who is at risk? Everyone. Specifically, the elderly and the children because they are less capable of escaping, and densely populated areas. What increases the risk? Increase in the population numbers and density of the area; loss of a sense

		of community resulting in social problems due to the rapid influx of people to the area; alcohol use/abuse; lack of legal electricity and refuse removal means. When is the risk higher? August is the month that has had the most fires because of the cold and damp conditions associated with living in an informal dwelling in a flood prone area – the result is that people make fires inside their dwellings for cooking, heating and drying.
	Mukheibir and Ziervogel (2007)	Vulnerability: based on model outputs, the frequency and intensity of wildfires is expected to increase substantially due to lower rainfall (reducing the moisture content of fuels), lower relative humidity, longer droughts and higher wind speeds Adaptation options: increased training in ecological fire management, increased fire-fighting capabilities, removal of plantations, control of alien invading plants, appropriate fire breaks, erosion protection.
	Rosenberg (2013)	This research focussed on Community Based Disaster Risk Management for Fires in an informal Cape Town community. The need for increased community involvement in the planning and Disaster Management processes is the premise upon which this research is based, contrasted with the typical top-down approaches commonly used in Disaster Risk Reduction. Findings: • On average 1,244.39 informal settlement fires occur per year which equates to nearly 3.5 callouts per day • More fires occur, on average, in the summer months than the rest of the year. • 4,866 informal settlement structures are affected on average each year with a similar monthly distribution to fire occurrence • 104 people are killed on average each year by all fires in Cape Town. Causes of fires in informal settlements: inappropriate use of energy, negligence and alcohol consumption, electricity connections, multi and arson fire, mountain and other external fires, unsupervised children. Factors affecting the spread: Access Issues (Narrow/Blocked Roads, low wires, complex routes etc), Informal Housing, Lack of knowledge of phone numbers, high living densities, steep slope, slow fire department reaction, lack of community fire training and strong winds. Existing coping mechanisms: moving out, support from community, formal housing built, use of community centres, return to status quo, moving out of the settlement, receive aid from City/NGO. Recommendations: increased education programmes, training of community

		members, formal firefighting equipment, formal housing and infrastructure, improved access and formal enforcement.
	Rowswell and Fairhurst (2011)	Climate change projections (rainfall, temperature, evaporation and extreme events) were established and vulnerabilities assessed: pressure on the grid system to meet electricity demand and energy-related problems. Sectoral impacts associated with increased temperatures are discussed in relation to their impacts on livelihoods (water and sanitation, transport, health, energy). Increased temperatures and heat waves could lead to changes in fire intensity and frequency, which may also trigger the destruction or migration of sensitive plant and animal species. A higher fire risk would also pose health consequences.
Sea-level rise (including coastal flooding, coastal erosion and storm surge)	Brundrit (2008a)	Sea level rise was assessed in terms of inundation based on predicted sea-level rise from Highest Astronomical Tide of the Year (HATOY) and weather effects (deviations of sea level from the predicted tide) from historical data set. Sea level rise and coastal erosion assessed. Sea level rise and coastal erosion assessed according to 3 scenarios 1. Present Day Very Worst-Case Scenario: the GIS reconstruction identifies the sections of the Cape Town coast that are most at risk 2. Scenario at the End of the Next Decade: impacts and vulnerabilities of Scenario One can then be used to illustrate what might be expected as the norm for big spring and autumn storms at the end of the next decade 3. Polar Ice Sheet Melt Scenario: the important information that came from the GIS inundation model is the order in which different land areas are overwhelmed in the inexorable rise in sea level. CCT faces significant threats from sea-level rise in the long-term with a fair likelihood of medium-term impacts related to increased intensity of storm-surge events.
	Brundrit (2008b)	Technical oceanographic analysis of Cape Town's coastline vulnerability. Exposure, and the associated risk of sea-level rise, is location specific. In this study exposure is disaggregated according to specific location's exposure to wave set-up, wave run-up, the natural predisposition of a location as a function of the coastal geology and the value or strategic nature of the development in that area. 20 locations that are known to be on the CCT's list of potentially exposed locations in terms of these four criteria.

		Table Bay: The coast is eroding in the south and is particularly vulnerable where it is backed by the lagoon of the Diep River. Atlantic Coast: Deep water is found close to the shore, permitting big waves to crash onto the coast so that protection is needed for any infrastructure at sea level. False Bay Coast: Western coast is steep but well sheltered from big waves from the southwest.
	Cartwright (2008)	Sea level rise was assessed in terms of potential economic damages to infrastructure based on modelled sea-level rise scenarios and three proxy variables (i) the sum of private property loss, (ii) the loss of tourism revenue and (iii) the loss of public infrastructure. Findings: the value of the property, tourism sector and infrastructure at risk in Scenario 1 is R5.2 billion and the risk of this Scenario occurring is valued at R 4.9 billion. The value of the property, tourism sector and infrastructure at risk in Scenario 2 is R23.7 billion and the risk of this Scenario occurring is valued at R20.2 billion. The value of the property, tourism sector and infrastructure at risk in Scenario 3 is R54.8 billion and the risk of this scenario occurring is valued at R11.0 billion.
	Cartwright et al. (2008)	Establishment of sea level rise adaptation options with no regrets solutions, physical and institutional solutions and assessment of cost and benefits of those solutions. In the context of sea-level rise, no regrets options (1) available to the CCT were established, as well as additional options such as physical (2), biological (3) and institutional (4) solutions. To prioritize those options a cost and benefits assessment was conducted and solutions were categorized from first to last resort: • First resort solutions: 1.1. Do not reclaim further land, 1.2. Do not further degrade wetland and estuaries; 1.3. Do not further degrade dune cordons; 1.4. Maintain drains and stormwater systems; 1.5. Integrate sea-level rise scenarios into future planning decisions; 1.6. Incorporate sea-level rise risks in disaster management strategies; 1.7. Decentralisation of strategic infrastructure; • Second resort solutions: 4.4. apply a coastal buffer zone; 4.6. early warning systems; 4.7. insurance market correction; 4.1. vulnerability mapping; 4.2. risk communication; 4.3. apply legislation; 4.5. prevent sand-mining; 4.6. research and monitoring • Third resort solutions: 3.1. dune cordons; 3.2. estuary and wetland rehabilitation, 3.3. kelp beds • Last resort solutions: 2.8. beach nourishment; 2.1.sea walls; 2.3. barrages and barriers; 2.4. raising infrastructure; 2.5. revetments, rock armour, dolosse and gabions; 2.7. off-shore reefs; 2.10. beach drainage
	Fairhurst (2008)	Sea level rise was assessed in terms of economic damages to infrastructure based on predicted sea-level rise from

		Highest Astronomical Tide of the Year (HATOY) obtained from SA Navy Tidal Network stations at Simon's Town and Cape Town - and the weather effects (deviations of sea level from the predicted tide) from historical data set. Specific section on storm surge and case study on the Woodbridge island in table bay. Findings: if the worst-case scenario of a storm surge and wave set-up were to occur producing an elevation in sea level up to 6.5m elevation above LLD, Woodbridge Island and those parts of Milnerton adjacent to the shoreline would be completely flooded and seriously damaged as a result of erosion.
	Hughes et al. (1993)	This paper presents the likely geomorphological changes to accompany a 1-m rise in sea level in Milnerton, linked to the Diep River system. Under normal meteorological conditions the shoreline will recede between 60m and 90m in Woodridge Island. To the north of the Island the transgression will be between 50m and 80m and, to the south, the shoreline will recede approximately 135m.
	Mukheibir and Ziervogel (2007)	This paper presents and discusses an overarching framework that would facilitate the development of a Municipal Adaptation Plan (MAP). The example of the CCT illustrates some of the sector-level assessments and potential climate threats, such as urban water management, storm water, fires and coastal areas, as well as resource mobilization issues that need to be addressed during the development and implementation of a MAP. Vulnerability: most significant impacts of sea-level rise are expected in those areas where problems are already being experienced (areas where development has taken place too close to the high-water line or at too low an elevation above mean sea level). High economic loss risk. Adaptation options: the development of a coastal vulnerability map using GIS, development of a shoreline management plan, review of the existing regulations and by-laws for developments, monitoring programme for coastal infrastructure.

	Rowswell and Fairhurst (2011)	Climate change projections (rainfall, temperature, evaporation and extreme events) were established and vulnerabilities assessed: rise in sea-level is expected to cause storm surge and erosion, increasing the vulnerability of beaches, shorelines and coastal developments and infrastructure. Sectoral impacts associated with increased sea-level rise are discussed in relation to their impacts on livelihoods (water and sanitation, transport, health, energy). Increase in frequency and intensity of storms is likely to impact transport and storage system, specifically around Cape Town harbour and low-lying area such as main road in Fish Hoek. In 25 years there 85% probability of a 61km^2 area (2% of the metro area) being covered by sea for a short period, which real estate loss was estimated at R20 billion. Any blockages in the transport network due to damage by rising sea-levels, floods, heat or sea storm surges will lead to livelihood losses, both at the time and after as cascade effects are felt throughout the economy of Cape Town. Storm and sea level rise would also have impacts on the water and sewage system as the aquifer sits on a saline wedge from the sea and sea level rise will push it inland, and thus push the water table up. Moreover, sewerage intrusions in the event of storm water drainage failure and flooding would decrease the quality and availability of water.
	Western Cape Government (2013)	This assessment describes the current state of the coastal zone in the Western Cape and interpret the environmental changes that are evident along the coastline. Indicators of the pressure on the Western Cape ocean and coastal environment, such as coastal water quality, estuary health, conservation areas, threats to marine ecosystems, as well as transformation of threatened ecosystems along the coastline are studied to assess the impacts of those on the coastal environment (pollutants from marine and land based sources, estuarine environments characterised by poor health and low levels of protection, critically endangered and endangered marine ecosystems, increased coastal environmental risks which manifest in impacts such as mobile sand dunes, increased intensity, frequency and duration of extreme events as well as decreased ecosystem resilience and alteration of natural coastal dynamics). Responses to these impacts are also listed in this chapter (coastal set-back lines, estuary management plans, focus areas for future protection, policy, tools and legislation)
Heat Waves (high temperatures)	Tadross and Johnston (2012)	Findings: Temperature rise is projected both in the long-term and mid-term. Maximum temperatures increase during all months with median changes for the 2081-2100 period as high as 3.4°C and changes for the 2046-2065 period peaking at 1.9°C during May. One can expect the frequency of days exceeding the different thresholds (30, 32 and 35°C) to more than double by 2055.

	Rowswell and Fairhurst (2011)	Climate change projections (rainfall, temperature, evaporation and extreme events) were established and vulnerabilities assessed: heat waves would be more frequent, stronger and longer. Sectoral impacts associated with increased temperatures are discussed in relation to their impacts on livelihoods (water and sanitation, transport, health, energy). Heat waves can cause deaths and many indirect health issues such as dehydration, particularly amongst the old, infirm and children. In the CCT, people living with HIV may be further compromised as their immune systems may not be strong enough to tolerate the heat. The climate projections of a reduced number of rainy days and increased number of days with temperature inversion will increase the frequency of brown haze days resulting in more risk of respiratory illness and health risks due to air pollution. Heat waves could also have damaging consequences on the transport system: rail tracks can buckle and bitumen road surfaces can melt. Increased temperature can, after flooding events, cause subsidence of roads, which leads to greater maintenance costs and reduced efficiency in the transport network. Moreover, as temperatures rise, the need for cooling will rise leading to increased demands on the energy supply network, which the electricity grid is not prepared for.
Strong Winds	Tadross and Johnston (2012)	Climate change (rainfall, temperature, evaporation and extreme events) projections were established based on downscaled GCMs and sectoral impacts and vulnerabilities were assessed (water and sanitation, transport, health, energy, livelihoods). Findings: Wind vectors tend to come more from the south east during all seasons, which increases the wind speeds during all seasons, except during winter when the dominant flow is normally from the west and reflects the northward position of the winter storm tracks.

B.2 City of Cape Town strategies and policies

A variety of CCT policies and strategies are relevant to the scope of this study. However, the degree of relevance and alignment varies according to the nature of the individual policies and strategies. The most relevant CCT policies and strategies to the scope of this study include:

- City Development Strategy (CDS, 2012)
- Cape Town Municipal Spatial Development Framework 2017-2022 (MSDF, 2012)
- Social Development Strategy (SDS, 2013)
- Economic Growth Strategy (EGS, 2013)
- Municipal Disaster Risk Management plan (MDRM, 2015)
- State of Cape Town Report (2015)
- Integrated Development Plan 2017-2022 (IDP, 2017)
- Energy and Climate Change Strategy (2005)
- Framework for Adaptation to Climate Change in the City of Cape Town (FAC4T) (2006)
- Cape Town's Action Plan for Energy and Climate Change (2011)
- Climate Change Policy (2017)

- Environmental Strategy for the City of Cape Town (2017)
- Critical Water Shortages Disaster Plan (2017)
- Water shortages disaster plan (2017)
- Resilient Cape Town: Preliminary Resilience Assessment (2018)

It is apparent that these overarching strategies largely view climate change as a challenge for infrastructure development (CDS, 2012; MSDF, 2012), social development (SDS, 2013), environmental sustainability and economic growth (EGS, 2013). The IDP refers explicitly to the need for the climate change risks and vulnerabilities experienced by the CCT to be thoroughly analysed in order to inform the required adaptation interventions across sectors.

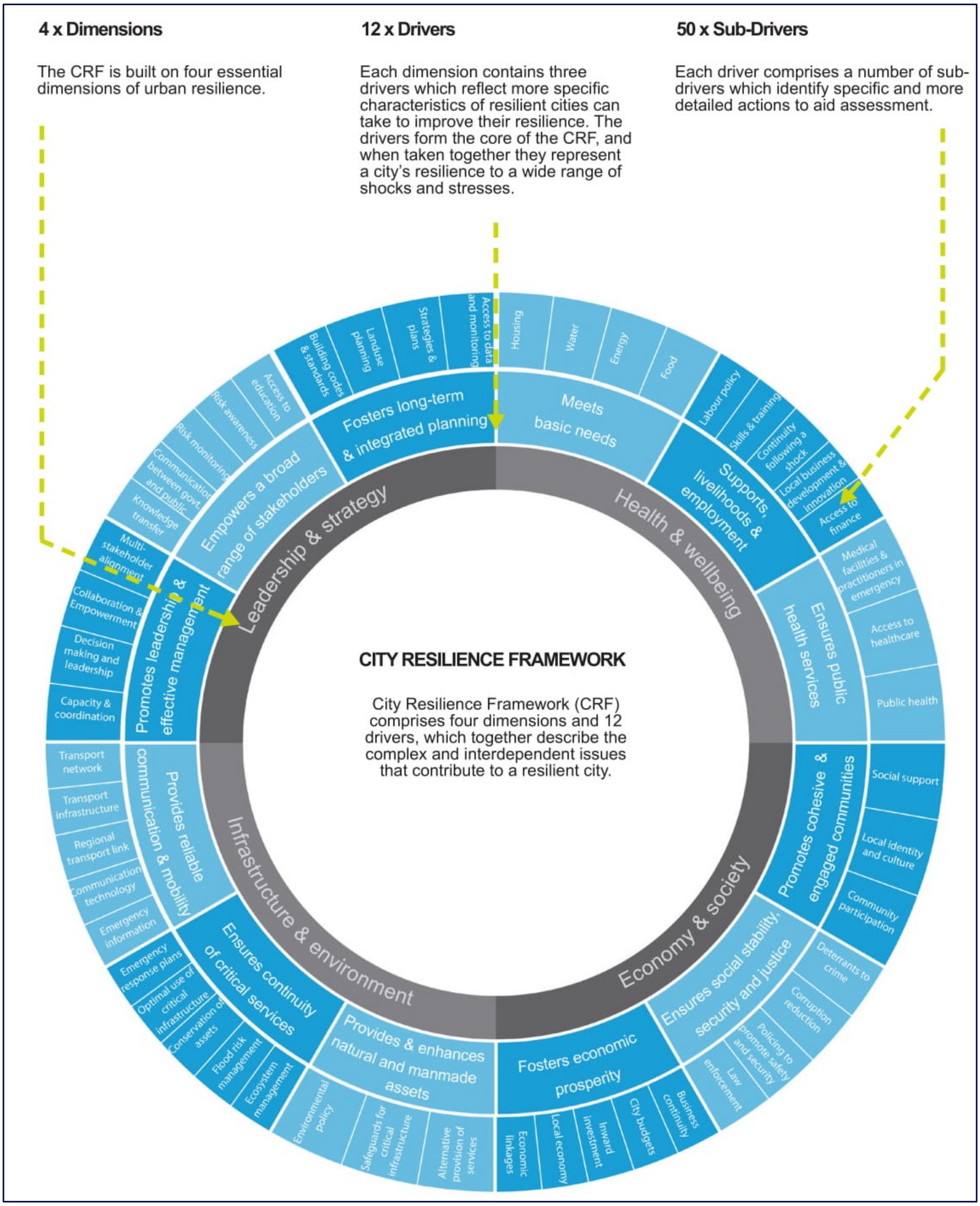
Since the development of the Energy and Climate Change Strategy of 2005, key areas of vulnerability for the CCT such as natural resource use, urban water development, industrial activities, population size and human health have been acknowledged in relation to the climate projections available at the time. The Framework for Adaptation to Climate Change in the City of Cape Town (FAC4T, 2006) as well as the Climate Adaptation Plan(s) of action (CAPA, 2011) were derived from this first strategic document. The framework provided a clear vision and direction for the city as a whole in response to the potential short- to medium-term impacts of climate change in the Cape metropolitan area. Importantly, these strategies envisioned a continually evolving climate change landscape and consequently the Climate Change policy and the Environmental Strategy for the CCT were adopted in 2017.

Environmental Management Frameworks (part of the District Plans) are the medium-term plans, that will guide spatial development processes for the next 10 years or so, in line with the municipal policy frameworks described above. For the 8 districts of the Cape Town metropolitan area, an environmental management framework has been developed to guide and inform planning and decision-making regarding activities and zones in each district.

The recently published 'Resilient Cape Town: Preliminary Resilience Assessment' (CCT, 2018), presents a resilience framework for CCT that highlights four essential dimensions of urban resilience: infrastructure and environment; leadership and strategy; health and wellbeing; and economy and society (Figure 2). Stakeholder perceptions are reviewed alongside qualitative and quantitative measures that make up the City Resilience Index. This assessment highlights key socio-economic components such as 'diverse livelihoods and employment' as the weakest dimension of resilience, further emphasising the role of unemployment, poverty and inequality in understanding risk and vulnerability. This framework provides a standardised context for understanding components of the resilience in CCT, which includes climate risks and hazards as part of a broader resilience framework. Moreover, it provides an opportune entry point to conceptually harmonise this approach with CCT's approach towards resilience.

The adaptation and investment options developed as the primary output of this study will be co-created in line with the evolving strategic direction of the CCT, primarily informed by the IDP and Climate Change Policy, with the aim of informing future adaptation planning that can be easily mainstreamed into existing policies and strategies. The CCT's social accounting matrix tool will be applied in evaluating and prioritising the adaptation and investment options under consideration.

Figure 2: City of Cape Town Resilience Framework (CCT, 2018)



B.3 Gap analysis

Building off of the critical literature review and overview of the CCT strategies and policies, it is evident that understanding complex risks and vulnerabilities is an evolving process that requires continued development. There is a clear need to update current conceptions and understandings of risk and vulnerability at the city scale. This involves addressing several key gaps in the existing knowledge base.

Generally, there is an absence of spatially integrated assessments of climate risk and vulnerability as most research to date focuses on particular areas of interest. This is compounded by the highly sector and/or single-hazard focused approaches that negate the potential synergistic and/or antagonistic impacts of cumulative hazards and vulnerabilities. There is a clear separation between risks to infrastructure and social/human vulnerabilities. Moreover, no approaches to date attempt to marry these two conceptions of risk and vulnerability in the context of a highly urbanised environment, thus there is no meaningful way to compare these types of risks.

There is a lack of a detailed assessment of inland flooding for the whole of the CCT, the focus of flooding has been primarily related to sea-level rise and coastal flooding, as well as specific areas within the city and/or institutional aspects of flood risk management. Although water shortages are largely predicted to become more frequent over time, there is little understanding of the magnitude of different driving forces. Specifically, poor correlation between ensemble projections of future rainfall and an absence of research into the potential future frequency of multi-year meteorological droughts further increases policy and planning uncertainty.

In terms of the risks of fires, there has been a strong focus on informal settlements as these are the areas where the most structural fires occur, and people are perceived to be the most vulnerable. A holistic fire risk assessment that incorporates economic risk to infrastructure and social vulnerabilities (in terms of wild and structural fires) is lacking. Moreover, there is little evidence on the risks and vulnerabilities associated with strong wind events as independent hazards rather than aggravating factors (i.e. to fires). Heat waves are also under-researched in terms of their potential frequency, magnitude and impact.

The methodological approach outlined in the next section attempts to address as many of these gaps as possible within the scope of this study.

C. Breakdown of Methodological Approach

The inception phase of this study has revealed important insights into our methodological approach, primarily from a theoretical and conceptual framing perspective. These framing questions are discussed in terms of how the methodological approach for this study has been designed, thereafter the specific activities to be undertaken are described in brief. This breakdown does not incorporate in-depth descriptions of the technical aspects of our methodology, as these have been developed in-length in the original project proposal (see Appendix 2). The breakdown of the approach presented below illustrates key changes to timeframes and phases, as well as minor technical alterations that have emerged as outcomes of the inception phase (as discussed in Section 2).

C.1 Theoretical and conceptual framing

Building on the literature review and the stakeholder engagement conducted during the inception phase, the methodological approach developed for this study has three primary and interrelated framing concepts: i) learning by doing, or an adaptive management approach; ii) the nexus between social and asset risks and vulnerabilities; and iii) the conceptualisation of what is known as the 'Post-Apartheid City'.

Adaptive management in the context of climate change uncertainty and variability has proven difficult to align with risk-based adaptation and policy-making approaches (Kuklicke and Demeritt, 2016). General adaptive management or 'learning by doing' approaches are a structured and iterative process of robust decision making in response to uncertainty, with an aim to reducing uncertainty over time through systemic monitoring. Whereas risk-based optimisation of climate policy is aimed at minimising future risks and vulnerabilities through the attribution of probability and consequence, which includes a rationalisation of how far it is 'reasonable' to go in seeking to prevent potential adverse outcomes (Amoore, 2013; Oels, 2013). In contrast, adaptive management approaches advocate for management processes to remain open to inherent uncertainty in future developments, by highlighting the conditionality and highly disputed nature of current scientific knowledge (Gardener, 2013; Holling, 1978). Thus, when seeking to marry adaptive management and risk-based adaptation policy optimisation, it is important to highlight how institutional dynamics are often as important (if not more) for the effectiveness of adaptation as the quality of the underlying science (Kuklicke and Demeritt, 2016).

The social and asset risk and vulnerability nexus, discussed as part of the key methodological points raised during the inception workshop, presents a complicated assessment framework for this study. The merits of both approaches, whether focusing on risk to vulnerable populations or vulnerable economic assets, are acknowledged and understood. These divergent conceptions of risk and vulnerability point to the intricacies and complexities of socio-political, environmental, physical and economic systems within cities. These peculiarities are of particular importance in the context of South African cities and what is envisioned as the 'Post-Apartheid City'. A legacy of the Apartheid era, the CCT remains segregated along the lines of ethnicity and economic opportunity. Continuity of urban-governance in South Africa has been the norm since the end of Apartheid, further entrenched by existing predilections and established discourses of the business-politics world in the absence of more dynamic and structured public intervention (Freund, 2010). Therefore, when assessing potential public-sector investment options, the question of how the future of the CCT is envisioned in terms of the 'Post-Apartheid City' will play an important role in how risk is conceptualised and ultimately addressed through investment planning and urban-governance systems.

In alignment with the adaptive management approach adopted in this study, we propose to assess these different economic risks based on the outcomes of the spatial hazard and vulnerability assessment. In this way, the most prominent vulnerabilities will emerge from the analysis and associated stakeholder engagement to inform the economic risk analyses. These analyses will be conducted separately for social vulnerabilities and asset vulnerabilities (i.e. hard and soft infrastructure), thereafter these assessments will be integrated to provide a holistic risk profile comparing different individual risks, which will ultimately inform the assessment of adaptation investment options. This integrated risk assessment will be conducted through the lens of the 'Post-Apartheid City'.

A 2015 review of the economics of adaptation and climate resilient development (Watkiss, 2015) found important shifts in the framing of adaptation in recent years. The current focus is more practical and early implementation oriented. This has changed the economic analysis of adaptation in three key ways: i) a stronger focus on a policy-based, or adaptation assessment approach with a view to informing early interventions, denoting a significant departure from the earlier, science-first, impact assessment studies; ii) a greater emphasis on mainstreaming climate responses into development planning and current policy as opposed to positioning climate change responses as a stand-alone activity; and iii) the separation of current variability from future climate change as a result of the increasing recognition of uncertainty. This in turn has led to a stronger emphasis on the phasing of climate adaptation responses into short and longer-term interventions, accompanied by iterative climate risk management and decision making (Watkiss, 2015). One of the key characteristics of adaptation is the profile of costs and benefits over time (DFID, 2014). Many climate changes, although incremental (e.g. temperature increases each year), are likely to be felt in the future and so the benefits of adapting to these changes can accumulate over long time horizons, although the costs are often incurred earlier. Because of uncertainty, short term interventions are typically selected for their 'no or low regret' status, meaning that these are interventions likely to have positive impacts even without climate change.

Our understanding of the project requirements is that a blended science-informed and adaptation-oriented approach and methodology is required. The studies referred to, conducted for the CCT, show that time is not on the side of vulnerable populations, and their supporting ecosystems. Current climate variability requires immediate, or short-term interventions, while the CCT would benefit from learning from these experiences in a way that can re-inform, or validate, longer term investments.

In light of this, we propose that the risk and vulnerability assessment follow the broad conceptual framing presented in CCT's resilience framework (figure 2). The four essential dimensions of urban resilience and associated drivers and sub-drivers present a logical entry point and point of departure to synergise efforts with the city to build resilience. In this way, the assessment of key climate hazards, risks and vulnerabilities will analysed within this broader resilience framework and presented in such a way that is congruent with CCT's broader resilience strategy.

A policy first approach requires an understanding of the current drivers, non-climate policy and existing adaptations. It is also important to recognise that climate adaptation is not about one technical response, but rather, involves implementing multiple responses over varying time scales. This necessitates building a spectrum of options that break down activities associated with the intervention into early activities that address current vulnerability while strengthening or building adaptive capacity, followed by longer term activities that are associated with mainstreaming climate risks and preparing for longer term challenges (Watkiss, 2015). This can lead to adaptation pathways that allow for iterative, or learning by doing decision making, building necessary flexibility into adaptation investment planning.

C.2 Phase 1: Inception and Desk Review

C.2.1 Contracting and Kick-off meeting

Facilitate meetings with key stakeholders at the CCT to gain consensus on key methodological outcomes and agree upon general terms for the work plan, deliverables, reporting requirements and associated timeframes.

C.2.2 Literature review and data collection; information and data gap analysis

Review existing hazard, vulnerability and risk assessments. Identify key research required based upon identified information and data gaps. Develop data collection processes and protocols in continuous engagement with all relevant CCT stakeholders.

C.2.3 Sector analysis and selection

In collaboration with the relevant CCT officials, identify sectors/themes to be included in the hazard, vulnerability and risk assessment. Identify key thematic/sectoral experts. Finalise scope of analysis.

C.2.4 Finalise work programme, reporting etc.

Detail final work programme in line with relevant deliverables and work schedules of all contributing experts.

C.2.5 Draft Inception Report

Draft Inception Report with full methodology and final work programme is developed.

C.2.6 Inception Workshop

Conduct inception workshop with key stakeholders identified at the kick-off meeting. Present contents of the draft inception report, with particular emphasis on data availability/collection and framing of methodology within CCT's greater strategic framework.

C.2.7 Revise Inception Report

Consolidate comments and findings from inception workshop into final inception report. Finalise critical review of existing works.

DEL 1 Final Inception Report

C.3 Phase 2: Vulnerability and Hazard Assessment

C.3.1 Model and consolidate data

Consolidate and classify all relevant datasets for exposure, sensitivity and adaptive capacity. This includes outputs of relevant climate projections and models, as well as all of the available data determined in Phase 1. Importantly, this data will include all relevant hazard risk variables and indications of sectoral assets.

C.3.2 Conduct spatial risk and vulnerability mapping

Create composite exposure, sensitivity, adaptive capacity layers and aggregate into potential impact and vulnerability layers. Perform structured and rigorous weighting assessment for data inputs. See Section D2.1.2. in Appendix 2 for a more detailed description of the technical aspects of our risk and vulnerability mapping methodology.

C.3.3 Conduct spatial thematic assessment

Overlay of relevant thematic spatial data (i.e. water infrastructure/ecological infrastructure) with vulnerability mapping. Analysis by sectoral/thematic experts to identify, type and potential magnitude of climate impacts. Identify the top 5 thematic/sectoral drivers of vulnerability, including which hazards are most likely to impact each sector or thematic area. Conduct 1st - to - 4th Order Impact Assessment for areas of relatively high vulnerability. See Section D2.1.3. in Appendix 2 for a more detailed description of the process of analysing cumulative impacts of hazards and vulnerabilities.

C.3.4 Assess cumulative impacts of drivers of vulnerability

Analyse impact of stacked, cumulative or overlapping effects of multiple hazards and vulnerabilities based on the assessment top 5 drivers of vulnerability in each thematic area. Cross-correlate key drivers of vulnerability between different thematic areas against a preliminary set of ranking criteria, to determine the most important drivers of vulnerability across all themes.

C.3.5 Participatory analysis workshop 1

Conduct first participatory analysis workshop with all relevant CCT officials (and other key stakeholders) to: i) validate the outcomes of the vulnerability assessments through informing the weighting of different indicators and potential for alternative options; and ii) validate and verify the outcomes of both the thematic and cumulative vulnerability assessments with local knowledge.

C.3.6 Draft Consolidated Vulnerability and Hazard Assessment Report

Integrate outcomes from Participatory Analysis Workshop 1. Analyse magnitude, extent and types of risks in each sector. Spatially delineate areas of exceptional risk which are expected to be affected by multiple extreme events. Finalise Vulnerability and Hazard Assessment Report for review and feedback.

DEL 2 Vulnerability and Hazard Assessment Report

C.4 Phase 3: Economic Risk and Adaptation Options

C.4.1 Typology of risks

Identify categories and criteria for classification of risks, based on international best practice and the outcomes of Phase 2.

C.4.2 Conduct hazard risk analysis

Analyse potential likelihood, magnitude and the extent of the risks for key climate hazards. Conduct scenario impact evaluation for each of the identified themes/sectors. Contrasting of risks, using 1st to 4th Order Impact Assessment Framework. See Section D2.2.1. in Appendix 2 for a more detailed description of the technical aspects of our economic risk analysis approach, noting that this will be largely determined by the availability of data and the outcomes of the risk and vulnerability mapping.

C.4.3 Social capital assessment

Conduct demographic analysis of the most vulnerable population groups to the impacts on economic sectors to understand population differentiated impacts, based on the key drivers of vulnerability identified in Phase 2. Conduct scenario impact evaluation for each of the identified themes/sectors. Contrasting of risks, using 1st to 4th Order Impact Assessment Framework.

C.4.4 Focus group discussions

Facilitate focus group discussions with targeted key experts to provide input into the economic risk assessment of hazards and social capital / human vulnerability.

C.4.5 Identify investments for economic resilience

Conduct investment analysis. Informed by economic risk assessment of hazards and social capital, to identify those most likely to make the greatest contributions to GDP and employment.

DEL 3 Economic Risk Analysis Report

C.4.6 Determine and rank adaptation options

Analyse cumulative vulnerability assessment data to identify key adaptation options and subsequently rank these options against pre-determined criteria. Develop investment action matrix of adaptation options.

C.4.7 Develop manual of solutions, technological and methodological approaches/means of implementation

Develop adaptation options and investment manual describing solution options and relevant approaches to develop increased adaptive capacity and leverage economic opportunities to climate risks. An integrated and participatory approach towards investment planning and adaptation options is detailed in Section D2.2.2. of Appendix 2.

C.4.8 Estimate costs of each adaptation option

High level economic costing analysis of adaptation options conducted.

C.4.9 Participatory analysis workshop 2

Workshop convened with relevant officials to validate and further prioritise (rank) options with the aim of reaching a balanced investment portfolio.

C.4.10 Finalise Adaptation Options and Investment Manual

Integrate outcomes from Workshop 2 into the Adaptation Options and Investment Manual.

DEL 4 Adaptation Options and Investment Manual

C.5 Phase 4: Communication of Findings

C.5.1 Prepare communication strategy

Develop a brief communications and outreach plan, outlining the means of communicating project findings to different audiences, including the development of a detailed stakeholder database for information dissemination.

C.5.2 Present to the City of Cape Town

Present project findings to the City of Cape Town.

DEL 5 Presentation to City Transversal Working Group on GEACC

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E. Appendix 1: Inception Workshop Attendees

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F. Appendix 2: Original Project Proposal

F.1 Understanding the context and needs of the City of Cape Town

F.1.1 D.1.1 Climate Hazards and Risks

Climate change is expected to cause severe biophysical, social, environmental and economic impacts on cities worldwide, both directly and indirectly (Tadross and Johnson, 2012). Although cities typically have the resources to adapt to these threats, the rate and extent of global climate change impacts are greater than previously projected (IPCC, 2014), and significant uncertainties in climate projections increase risk.

Global climate modelling suggests that there will be significant climate change impacts in South Africa, and specifically in the Western Cape Province (Hewitson, 2005; Engelbrecht et al.,2009; Louw et al., 2012; Engelbrecht et al., 2015; Engelbrecht and Engelbrecht, 2016). Recent climate change risk and hazard research (Brundrit, 2016; Fairhurst, 2008; Cartwright, 2008; Jack et al., 2016) indicates that the City of Cape Town (the City) is currently facing four key climate change impacts:

1. A decrease in annual average rainfall and a change in the seasonality of rainfall;
2. An increase in mean annual temperature: higher maximum temperatures, more hot days, and more frequent and intense heat waves;
3. An increase in average wind strength; and
4. An increase in both the intensity and frequency of storms: short, high intensity rainfall events and increased size and duration of coastal storms.

It is expected that these changes, already observed to some or other extent, will continue to occur in addition to sea level rise (see Box 1.) and that climate change induced sea level rise will further exacerbate the severity of storm surges and therefore their impact (Brundrit, 2009). As with other extreme events, the recovery period between storm events is expected to shorten, leaving economies and livelihoods more vulnerable than they perhaps already are. Moreover, these risks are further intensified by the burgeoning population of the city, estimated to reach 4.23 million by 2023 (Western Cape Government, 2016).

Box 2. The Risk of Sea-level in the City of Cape Town

Sea level rise is one of the most prominent effects of climate change affecting cities. Sea level rise refers to the overall increase in volume of water in the World's oceans, which increase mean sea levels. Attribution of sea level rise to climate change is through the process of thermal expansion of ocean water and melting of ice sheets and glaciers on land. Sea level rise at different locations may vary from the global mean as a result of local factors such as storms, tides, land subsidence, currents etc. Moreover, the impacts of rising seas are primarily a function of spatial development patterns. Even small increases in sea level can have devastating effects on coastal habitats and infrastructure.

The City of Cape Town is a developed coastal city with varied topography ranging from low lying sandy coastal plains to Table Mountain standing over 1000m above sea level. The city has been identified as being highly vulnerable to sea level rise in the short to long term. This is important because the City of Cape Town has 300km of coastline under its jurisdiction (Brundrit, 2008) with important dune, or soft infrastructure, protecting low lying lands beyond them. Storms can destroy sand dunes and their reconstruction, or rehabilitation, takes time (Fairhurst, 2008). Human-induced risks must be coupled with this climatic risk; according to Fairhurst (2008) some of Cape town's dune systems have been cut off from their natural replenishment opportunities and are not therefore able to offer the protection that they otherwise would. The same report outlines Cape Town's various coastal zones, indicating where the impacts of sea level rise are likely to be, or are already being, felt. Among these are industrial areas, suburbs and human settlements, that are already vulnerable because of low adaptive capacities. For example, human settlements characterised by low levels of income, or high levels of poverty, unemployment and inequality, typically have low levels of adaptive capacity, such as communities in the Cape Flats, while well-established industrial areas, such as Paarden Eiland, are not protected from the impacts of storm surges through climate resilient design of roads, property and/or electrical infrastructure.

There has been extensive research into climate change impacts for the City of Cape Town, however, much of the research and associated data is disaggregated and/or entirely discrete. The risks associated with sea level rise, flooding, drought and fires have been assessed at different scales for different purposes. This makes integrated development and investment planning difficult, as different risks and hazards cannot be compared and assessed on an even keel.

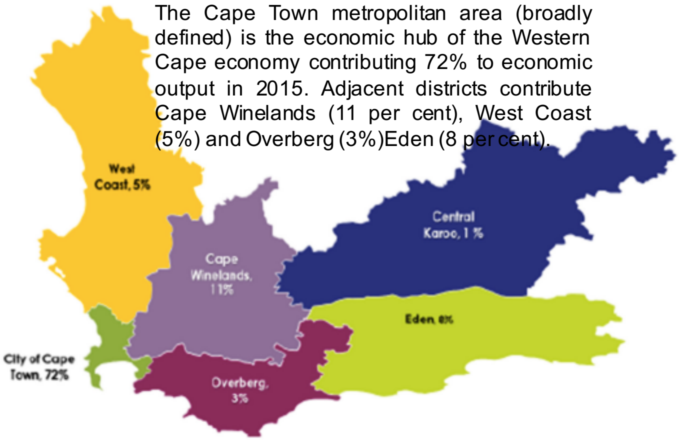
Climate changes can be meaningless without translation into impacts. In turn, understanding impact has much more meaning when understood in terms of vulnerability. Climate impacts are experienced differently, depending on the inherent level of vulnerability. Understanding vulnerability provides the ideal point of departure for integrated climate-smart development and investment planning. Moreover, vulnerability is differentiated by development factors, such as poverty, education, access to safe water, along with other indicators that make up our understanding of adaptive capacities in a geography or system. It is also a function of exposure and sensitivity to climate risks as evidenced in the sea level rise example.

The purpose of this study is to consolidate and analyse existing data and to close some of the gaps identified with a view to honing priority response options as informed by science. Most importantly, the study will bring new information through spatial delineation of the impacts of climate change and corresponding vulnerabilities, as well as through analysing the stacked impacts of different hazards analysed by existing studies. Based on this information, the study will also aim, in close collaboration with the City, to develop and prioritise adaptation options. These findings will ultimately inform the development and updating of the City's Climate Change Adaptation Action Plan. Importantly, the findings will inform the development of a manual of adaptation options as the basis for investment planning for climate resilience for the City.

F.1.2 D. 1.2 Context and Economic Structure of Cape Town

"The … city's economy has a number of characteristics that differentiate it from the rest of the country. ….. Cape Town has become a mostly service-driven economy." (City of Cape Town 2013)

Figure 1: Share of economic contribution to the Western Cape economy by district.



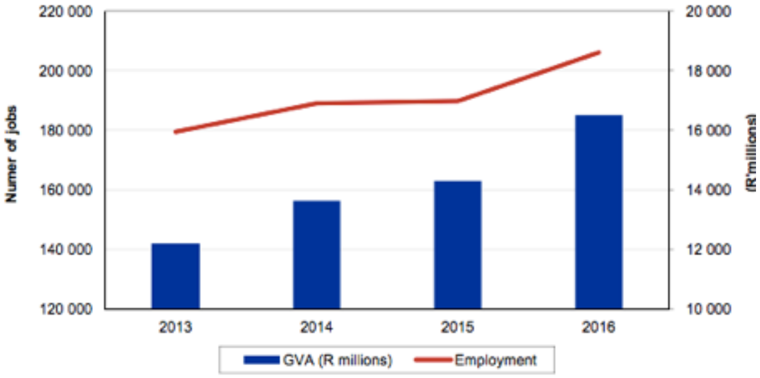
The largest contribution to economic growth (68.1 per cent) in the City comes from - finance, insurance, real estate and business services. However, this is not unique to the city. From 2005 to 2015, the finance, insurance, real estate and business services sector was also the largest average contributor to economic growth in the three largest districts by economic output, (the City of Cape Town, Cape Winelands, and Eden) as well as the Overberg District. These sectors are high knowledge intensively based economic activities, and employment is dominated by highly skilled and professional people. Cape Town also has particular strengths in R&D, knowledge intensive start-ups, and various creative industries.

This concentration of knowledge intensive economic activities is reflected in the growth of the Western Cape Business Processing Outsourcing (BPO) sector, which grew at an average annual rate of 84 per cent between 2012 – 2016, culminating in 20 500 jobs in 2016. The Western Cape BPO sector also increased its share of the South African market from 40 per cent in 2012 to 63 per cent in 2016. The sector is important because it presents a strategic opportunity to employ young people who have the required higher educational qualifications with work experience, a greater chance of longer term economic inclusion.

Tourism is also an important economic and social activity that contributes to growth and job creation in the Western Cape. It has beneficial knock on effects to many other sectors. Most of the jobs in these sectors require lower skill levels, creating opportunities for young and lower skilled unemployed people. The Western Cape's tourism sector has shown resilience in recent years and has grown significantly. Although domestic tourism is important Cape Town has become an international destination of note (from the UK, Germany and USA respectively) and forms a gateway to inland attractions. In 2016, 1.56 million international tourists travelled to the Province (a year-on-year increase of

18.5 per cent). These tourists created a foreign spend of R18.1 billion in 2016. Between 2014 – 2016 GVA for the Western Cape increased from R12.1 billion to R16.5 billion, and approximately 26 618 jobs were added to the sector (see Figure 2 below).

Figure 2: Western Cape tourism and employment 2013 -2016



Source: Western Cape Department of Economic Development and Tourism, 2017

Other sectors that are important to the Cape Town metropolitan area are commerce, manufacturing, agriculture and agro processing (grapes and apples to wine and fruit juice), fishing, and the informal economy.

In 2015 the informal economy comprised a quarter (393 525 workers) of the Metro's workforce. Its key features which also differentiate the Western Cape from the rest of South Africa are educational qualifications and earnings (Skinner 2006). More than two-thirds of informal workers had secondary schooling qualifications, substantially more had matric (21% compared to 14% in other key provinces), and conversely substantially less people with minimal education (27%) than KwaZulu-Natal (50%) and Gauteng (45%). There is a close correlation between education levels and higher incomes, and this is reflected in higher income levels prevalent in the Western Cape informal economy. For example, in 2005 only 16% reported earnings below R500 in comparison to the national figure of 47%, whilst 40% reported incomes between R1001 and R2500. To put this in perspective household subsistence level for Cape Town was calculated to be around R1900 in August 2004.

The population of the province is concentrated in Cape Town (64%), followed by Cape Winelands (14 per cent). The population concentration mirrors the regional economic nodes. In a real, physical sense, the city is growing as a consequence of urbanisation and inward migration. Approximately 50 000 people move to Cape Town every year in search of better opportunities – both employment and life style. Net in-migration is estimated at over 290 000 people between 2011 and 2016, mostly from the Eastern Cape, Gauteng and abroad. The former are mainly unskilled, whilst the latter two sources of migration represent professionals exhibiting high income, high skilled, population movements.

Cape Town presents a complex picture with respect to wealth and poverty. Although the intensity of poverty (i.e. the proportion of poor people that are below the poverty line) within the City of Cape Town is still very high, it has decreased from 42.8 per cent in 2011 to 39.3 per cent in 2016. There has also been a decrease in the number of indigent households between 2014 and 2015; numbers falling from 288,724 to 231,793.

To capture relative inequality, the annual income for households living within Cape Town is divided into three categories i.e. the proportion of people that fall within the low, middle and high-income brackets. This provides a good idea about the level of inequality, the level of poverty, and the distribution of income spatially. Table 1 below shows the relative levels of poverty and inequality across the City of Cape Town in 2016. Poor households fall under the low-income bracket, which ranges from no income to just over R50 000 annually (R4 166 per month).

Table 1: Cape Town geographic distribution of income by low, middle and high (%).

Income levels	Tygerberg	Blaauwberg	Northern	Khayelitsha Mitchells Plain	Helderberg	Cape Flats	Table Bay	Southern
Low	41.6	39.3	32.4	63.0	45.1	51.1	34.6	30.5
Middle	48.1	40.0	40.0	33.7	40.6	39.0	43,5	40.0
High	12.4	20.8	27.7	3.3	14.3	9.9	31.9	29.6

As a measure of poverty and relative income inequality, there are a disproportionately high distribution of households in the low income bracket in Khayelitsha/Mitchells Plain (63%), Cape Flats (51.1%), and Helderberg (45.1%), whilst within Khayelitsha/Mitchells Plain, 16.5 per cent have no income at all. The relationship between income characteristics of some of the suburban districts and climate change is discussed below in the section below on Climate Change Economic Risk Analysis and Hazard Adaptation and Investment Planning.

F.2 Methodology

F.2.1 Methodological Overview

A 2015 review of the economics of adaptation and climate resilient development found important shifts in the framing of adaptation in recent years. The current focus is more practical and early implementation oriented. This has changed the economic analysis of adaptation in three key ways: i) a policy based, or adaptation assessment approach with a view to informing early interventions, denoting a significant departure from the earlier, science-first, impact assessment studies; ii) a greater emphasis on mainstreaming climate responses into development planning and current policy as opposed to positioning climate change responses as a stand-alone activity, and iii); the separation of current variability from future climate change as a result of the increasing recognition of uncertainty. This in turn has led to a stronger emphasis on the phasing of climate adaptation responses into short and longer-term interventions, accompanied by iterative climate risk management and decision making (Watkiss, 2015). One of the key characteristics of adaptation is the profile of costs and benefits over time (DFID, 2014). Many climate changes, although incremental (e.g. temperature increases each year), are likely to be felt in the future and so the benefits of adapting to these changes can accumulate over long time horizons, although the costs are often inccurred earlier. Because of uncertainty short term interventions are typically selected for their 'no or low regret' status, meaning that these are interventions likely to have positive impacts even without climate change.

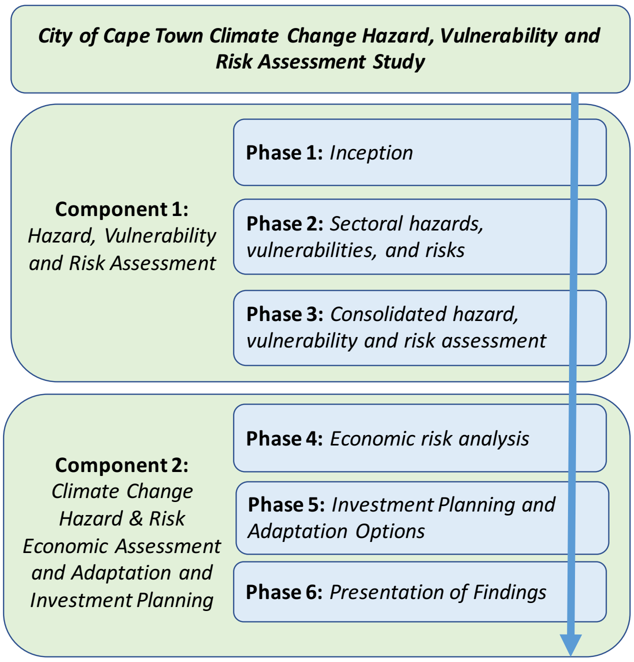
Our understanding of the project requirements is that a blended science-informed and adaptation oriented approach and methodology is required. The studies referred to conducted for the City show that time is not on the side of vulnerable populations, and their supporting eco-systems. Exacerbated, current variability requires immediate, or short-term interventions, while the City would benefit from learning from these experiences in a way that can re-inform, or validate, longer term investments.

A policy first approach requires an understanding of the current drivers, non-climate policy and existing adaptations. It is also important to recognise that climate adaptation is not about one technical response, but rather, involves implementing different types of adaptation over different time scales. This necessitates building a spectrum of options that break down activities associated with the intervention into early activities that address current vulnerability while strengthening or building adaptive capacity, followed by longer term activities that are associated with mainstreaming climate risks and preparing for longer term challenges (Watkiss, 2015). This can lead to adaptation pathways that allow for iterative, or learning by doing decision making, building necessary flexibility into adaptation investment planning.

In light of this, and based on the team's extensive experience in climate change vulnerability assessment and adaptation planning, the work under this project will be conducted under two main components, as represented in Figure 3 below.

- ***Component 1:*** *Hazard, Vulnerability and Risk Assessment*
- ***Component 2:*** *Climate Change Hazard Adaptation and Investment Planning*

Figure 3: Elaboration of a climate change hazard, risk and vulnerability assessment study



These components comprise all the phases and deliverables outlined in the project ToR and are not treated discretely. Rather, our approach recognises the need to consolidate, and add to, the City's knowledge and understanding of climate hazards, risks and vulnerabilities, as well as of the current drivers of vulnerability (existing and desirable adaptive capacities), the non-climate policies that provide important mainstreaming entry points for integrating climate responses, and existing adaptations (planned and autonomous), before determining the most appropriate course of action for responding to these challenges.

A coherent methodology, comprising several steps that align with the phases and deliverables, is designed to deliver all the required outputs in an integrated study.

The specific tasks under each of the two components are discussed in detail under sections D.2.1 and D.2.2.

F.2.2 D.2.1 Approach and Methodology – Component 1

In Component 1, the key activities, which are underpinned by the qualifications of key and supporting experts (as described in section D.3), include modelling and spatial mapping, risk and vulnerability assessment, climate science, research, socio-economic and environmental impact analysis.

Component 1 includes all activities under Phase 1, 2 & 3 of the ToR.

D.2.1.1 Phase 1 - Inception

During the inception phase, the project team will work closely with the City of Cape Town to finalise the work plan, deliverables, reporting requirements and time frames for these. This will include a discussion with the City and relevant sectoral officials to determine the sectors, which will be included in the sectoral hazards, vulnerabilities and risks assessment. The team of sectoral key experts, as illustrated in section D.3 will be finalised based on the outcomes of this discussion.

The project team will also endeavour to conduct a review of all existing hazard, vulnerability and risk assessments, in light of the latest climate science, with the aim of avoiding duplication of the work, as well as identifying gaps, which will become a key focus of the work under the current study. Data collection processes and protocols will also be discussed and agreed upon during this phase, as well as the most relevant spatial scale for analysis.

After Jack et al. (2016), the City of Cape Town does not exist in isolation from the surrounding region, but rather is dynamically related to the surrounding region with respect to water supply, food supply, tourism, and other economic activities. It will be important to agree, during the Inception Phase, the boundaries and bounds of this project. We propose than the climate data analyses are carried out for a spatial domain covering a loosely-defined Cape Town "region", which broadly covers the City of Cape Town and relevant hydrological catchments on which Cape Town draws its water resources as well as relevant agricultural areas. Considering the dynamic and multi -scalar and -sectoral influence of climate change on the City of Cape Town, it is proposed that the vulnerability, risk and hazard assessment covers a larger sphere of influence, as opposed to the limits of the municipal boundaries. Similarly, at least some of the response, or adaptation options, while located within the City of Cape Town's borders, are likely to have implications, or knock on effects, outside of the city, requiring consideration.

The resulting inception report (Deliverable, or D-1) will include the final methodology and work plan with specific timelines, as well as a final team of sectoral experts and a summary of the findings from the review and gap analysis. Importantly, this report will explicitly detail the advantages and disadvantages of the finalised methodological approach in the broader context of integrated city planning and investment.

D.2.1.2 Phase 2 - Sectoral hazards, vulnerabilities, and risks

A structured and systematic approach towards assessing hazards, vulnerabilities and risks, underpinned by OneWorld's tried-and-tested Risk and Vulnerability (R&V) mapping methodology (See Box 2.), along with a risk assessment framework, will be applied to each sector (as determined in Phase 1). This approach will result in the output of sector specific risk and vulnerability maps that illustrate 'hotspot' areas.

Box 3. OneWorld & Habitat INFO's R&V Mapping Track Record

OneWorld, in partnership with Habitat INFO, have developed the methodology for and undertaken R&V Assessments across Southern Africa. Together, they conducted GIS-based R&V mapping across the entire SADC region for the Southern African Regional Climate Change Programme (RCCP), funded by the UK's Department for International Development; the Strengthening Climate Resilience in the Kafue Sub-basin (SCRiKA), funded under Pilot Programme for Climate Resilience (PPCR); the Zambezi River Basin for a Hydropower and Climate Change Project in the Zambezi Basin, funded by CDKN; district level R&V mapping for the Limpopo region in Mozambique, funded under PPCR; the Limpopo River Basin for the Resilience in the Limpopo River Basin (RESLIM) Program, funded by USAID; and a landscape level assessment of Northern Zambia for the Transforming Landscapes for Resilience and Development in Northern and Southern Zambia (TRALARD-Zam). The results of these assessments form a composite picture of hotspots of particular risk and vulnerability.

Final reports for the SCRiKA project are available via the OneWorld website, or here:

Risk and Vulnerability Assessment Final Report:

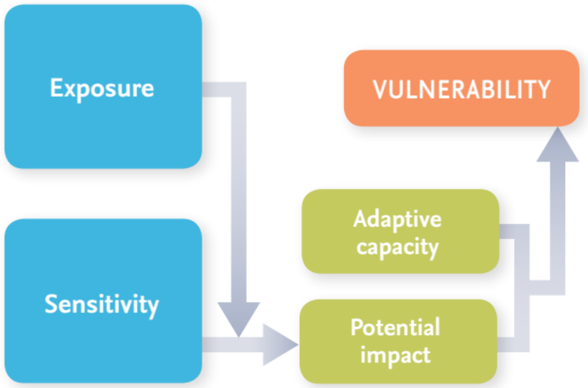
http://oneworldgroup.co.za/wp-content/uploads/2017/07/SCRiKA-RV-Final-Report_FINAL-6-October-2016-2.pdf

Training Manual: http://oneworldgroup.co.za/wp-content/uploads/2017/07/SCRiKA.TM_.25.10.pdf

Alternatively, please visit http://oneworldgroup.co.za/oneworld-projects/ to view the final deliverables for these projects.

As alluded to in the previous section, this approach is premised by the IPCC (2007) construct of vulnerability, as depicted in Figure 4. Composite indicator modelling of spatial data for these components of vulnerability result in spatial mapping outputs for each of the 5 components. The final result of this process is the risk and vulnerability maps that indicate relative levels of vulnerability, which allow for the identification of high vulnerability areas specific to each sector.

Figure 4: A model of the constituents of vulnerability after the IPCC (2007) and used in the mapping of spatial indicators to depict climate vulnerability



The chief components of vulnerability, exposure and sensitivity, are a function of climate drivers and environmental conditions respectively. These determine the potential impact of climate change over a specified time horizon. By identifying important drivers of vulnerability, the resulting maps provide insights into which adaptive responses are likely to have the highest impacts on development and livelihoods in specific hotspot areas. Coupled with a construct of adaptive capacity, our proposed mapping processes define the vulnerability and map prevalent hazards for the relevant sphere of influence for the City of Cape Town.

The values of these component input layers are standardised and combined to provide an immediately accessible graphic representation of vulnerability across the relevant sphere of influence. The individual layers are also weighted accordingly in order to let those input layers, which are considered more relevant, from a more reliable source, and of higher resolution, to have more of an influence on the final summary layers.

Despite the detail and/or the accuracy of the data that underlies vulnerability, uncertainty cascades through each level of analysis and needs to be addressed to ensure that the applicability of the results are well understood. Box 3 outlines some key sources of uncertainty in vulnerability mapping.

Box 3. Climate modelling – uncertainties and new lines of evidence

The project research on Cape Town's exposure to key climate hazards and the subsequent risk and vulnerability analysis will be based on the most recent and comprehensive sets of projections of future climate change available for the southwestern Cape in South Africa. The starting point of the analysis will be the ensemble of global climate model (GCM) projections of the Coupled Model Intercomparison Project Phase Five (CMIP5), which informed Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC). This large set of projections will be analysed for both low mitigation (e.g. Representative Concentration Pathway 8.5; RCP8.5) and modest-high mitigation (e.g. RcP4.5) scenarios, to quantify the uncertainties associated with the rainfall and temperature futures of the winter rainfall region of South Africa. Since the spatial resolution of the CMIP5 GCMs is low, in the order of 200 km in the horizontal, this analysis will be supplemented with the projections of the set of regional climate models that contributed projections of future climate change over Africa as part of the Coordinated Regional Downscaling Experiment (CORDEX) – including the projections contributed to CORDEX by the Council for Scientific and Industrial Research (CSIR) in South Africa. These projections are also available for both low and modest-high mitigation scenarios, and have been performed at a resolution of 50 km in the horizontal.

However, even at 50 km resolution the key topographic features that strongly control rainfall over the southwestern Cape, including the western escarpment and the Cape folded mountains, are not sufficiently resolved. To address this major shortcoming in both GCM and CORDEX projections, this project will analyse in addition a set of ultra high-resolution projections of future climate change recently developed by the CSIR to study the rainfall futures over the southwestern Cape. These simulations have been obtained at 8 km spatial resolution and have been shown to resolve well orographic rain in the southwestern Cape. This data is unprecedented in spatial detail and will greatly facilitate a spatially detailed risk and vulnerability analysis to be performed. This data set was obtained by downscaling 6 CMIP5 GCMs to high spatial resolution over South Africa for both low and modest-high mitigation futures. The larger sets of CORDEX and CMIP5 GCM projections will be used to determine the portion of the uncertainty envelope described by the 8 km resolution projections.

A major gap in previous analysis of future climate change over the southwestern Cape is the lack of focus on extreme events. For example, it is not necessarily the long-term changes in rainfall that poses the main risk in terms of vulnerabilities over the next 10-30 years, but rather the likelihood of three to five years of consecutive below-normal rainfall to occur – thus leading to major droughts and fresh water scarcity. To this end, our analysis will focus on the changing occurrence of the frequency and intensity of extreme events influencing Cape Town and surroundings:

1) Drought attributes under climate change, including return periods, and the tendency towards repetitive years of drought;
2) Large-scale flooding as induced by cut-off lows and cold fronts;
3) Changes in apparent temperature and heat-waves, with a focus on impacts on human comfort, health, energy demand and agriculture;
4) Changes in the occurrence of high fire-danger days and the potential for the outbreak of mega-fires;
5) First objective analysis of changing storm-tracks over Cape Town and related implications for damaging wind-waves and swells.

While the process of aggregation of multiple datasets into a single indicator of vulnerability can be highly subjective and debatable, this is evaluated by rigorous sensitivity testing of the principal outputs using different combinations and weightings and specifically by validation on the ground, with stakeholders. Stakeholder engagement is a core competency of OneWorld and is crucial to understanding in-situ vulnerability because it varies spatially, controlled by current conditions on the ground.

Ultimately, this approach towards vulnerability, risk and hazard assessment will allow for the identification of the top 5 sources of vulnerability within each sector, as well as the relevant causal pathways that indicate potential entry points for intervention. This initial analysis will be bolstered by a deeper analysis of the climate change implications for each sector, which will be conducted by the relevant sectoral key experts, part of the pool of experts of this team (detailed in section D.3). This assessment will highlight the nature, type and potential magnitude of climate impacts. All the work under this phase will be conducted in parallel with ongoing engagement with the relevant sectoral officials.

The outcome of this phase (D-2) will be a report detailing the findings of the analysis, accompanied by a set of spatial maps showing vulnerability hotspots for each of the sectors.

D.2.1.3 Phase 3 - Consolidated hazard, vulnerability and risk assessment

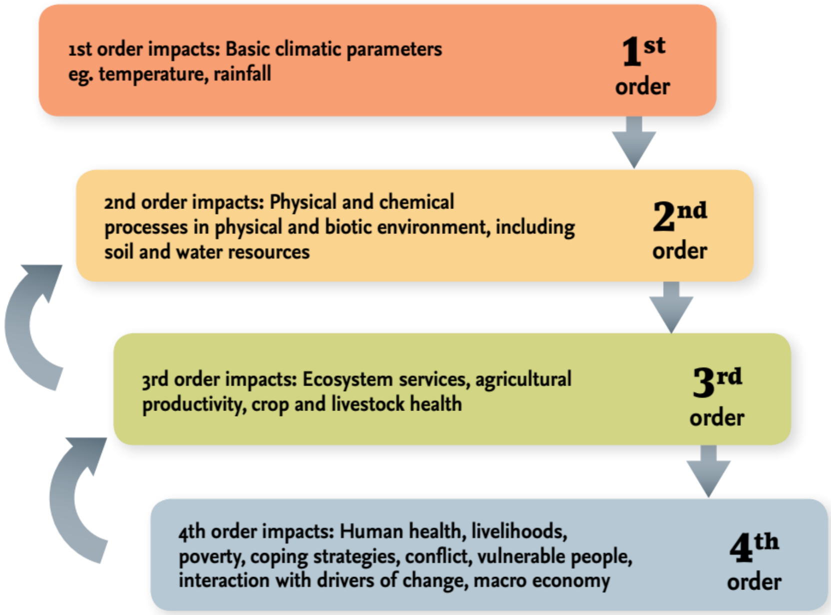
This phase builds off the approach and outputs developed during phase 2 of this project. As previously discussed, this study is aimed at addressing key gaps in existing climate change related work, through considering the possible overlapping, stacking and/or cumulative effect of multiple hazards. The sectorally disaggregated vulnerability, risk and hazard assessments conducted under Phase 2, will be systematically combined to provide a consolidated picture of risk and vulnerability for the City of Cape Town. The logic of this approach is based on the underlying analysis of the key drivers of vulnerability and risk in each sector (e.g. droughts induced by the poleward displacement of cold fronts may be the largest driver of vulnerability to the agricultural sector). Thus, by sequentially aggregating the risk and vulnerability assessments for each sector, one can deduce the relative contributions of each driver, and therefore determine the potential for synergistic and/or antagonistic impacts on individual sectors and combinations of sectors. In other words, the impacts of multiple drivers of vulnerability can be determined by systematically combining sectoral vulnerability layers using all possible combinations (i.e. 9 sectors would make 81 possible combinations), to show which drivers stack, overlap or accumulate by process of elimination.

A key aspect of this approach is to consider the impacts of a projected increase in frequency of extreme events on the ability of biophysical and economic systems to recover between events. This is where the adaptive capacity assessments will be key. Successive aggregation of the sector-specific adaptive capacity assessments will indicate which sectors are more resilient to specific changes in climate. Considering that adaptive capacity is the component of vulnerability that can be most easily improved through human intervention, understanding the relative and combined levels of adaptive capacity for different sectors will be pertinent to effective investment and development planning.

As mentioned in Phase 2, participatory analysis is a key component of assessing vulnerability. This is of particular importance when assessing overlapping, stacking or cumulative impacts of climate change because as the uncertainty increases (i.e. because more layers are being combined from different sectors), local experience and knowledge becomes more important. Not only does engaging with stakeholders improve the evidence-base from which decision are made, it also creates awareness for a particular problem and promotes stakeholder buy-in, which is a key factor in Component 2 (phases 4-5) of this project.

The first participatory workshop will be convened with all relevant stakeholders from the City and other interested parties with the aim of this workshop being twofold: i) to validate the outcomes of the sectoral vulnerability assessments (Phase 2) through informing the weighting of different indicators and potential for alternative options; and ii) inform the assessment of stacking, overlapping and cumulative climate change impacts with local knowledge. Figure 5 presents the 1st-4th Order Impact Assessment model that will be used to guide the participatory analysis. This framework provides a systematic approach to analysing how climate change impacts cascade through ecological and socio-economic systems. The cause and effect nature of this exercise makes it possible to identify and then rank different systemic impacts throughout the impact system. Ultimately, this process will facilitate the development of a detailed set of criteria to be used to rank areas and drivers of exceptional risk within the relevant sphere of influence.

Figure 5: The 1st-4th Order Impact Assessment Model evaluating the cascading impacts of climate change



Ultimately, the approach will facilitate an analysis of the stacking, overlapping and/or cumulative effects of multiple climate risks, vulnerabilities and hazards. Subsequent participatory analysis will allow for the ranking of risks and hazards to identify the areas and drivers of exceptional risk. The outcome of these activities (D-3) will be a **draft** report detailing the findings of the analysis, accompanied by a set of spatial maps showing vulnerability hotspots of areas facing exceptional risk as a result of cumulative, stacking or overlapping hazards and vulnerabilities.

The second participatory workshop will be convened with all relevant stakeholders from the City and other interested parties with aim of this workshop being twofold: to i) validate the outcomes of the assessment of stacking, overlapping and cumulative climate change impacts with local knowledge; and ii) validate the ranking of areas of exceptional risk with on-the-ground assessments. The outcome of this phase (D-4) will be a **final** report detailing the findings of the analysis, accompanied by a set of spatial maps showing vulnerability hotspots of areas facing exceptional risk as a result of cumulative, stacking or overlapping hazards and vulnerabilities. This deliverable will include an assessment of the learnings made from the participatory analysis.

F.2.3 D.2.2 Approach and Methodology – Component 2

Climate change impacts in coastal cities around the world are expected to represent a major challenge this century, with millions of exposed people and thousands of billions of USD of exposed assets at the global scale (Hanson et al. 2011). As discussed, Cape Town, with its extensive coastline and coastal asset base, is no exception. As a developing, or emerging economy, Cape Town also has populations that are more at risk than others to the impacts of climate change, with high levels of inequality and suburbs and settlements that are very poor and also highly exposed to climate hazards and risks. To put this in perspective for this study, it is important to consider Cape Town's specific inequalities in the context of climate risks. For instance, 63% of the populations living in the suburbs of Khayelitsha and Mitchells Plain fall with in the low-no income category as shown in Table 1 above. Both are sprawling suburbs, otherwise known as townships located on the Cape Flats which is a densely populated area characterised by a high-water table and inadequate infrastructure, leaving the area prone to severe flooding. Furthermore, although the aquifer under Khayelitsha is considered to be relatively safe from sea level rise, it is expected that the water table will rise as a result of climate change, affecting housing in this densely populated area (Fairhurst, 2008). With this, recommendations have been made that a sea water barrier be constructed to prevent or minimise the Cape Flats aquifer system form being compromised. If severe flooding occurs, the result could be that sewage is pumped into the aquifer (Fairhurst, 2008).

This is an example of the results anticipated from the consolidated assessments conducted through phases 2-4. Many recommendations, such as the sea barrier, for climate risk adaptations have been made over the past decade in various studies, including the Fairhurst, 2008 report. The objective of this component is to use the science and analysis to consolidate all risks and recommendations and translate these into socio-economic risks with a view to prioritising response options.

Townships such as Khayeltisha and Mitchells Plain (and there are many others in Cape Town, including others on the cape Flats and in other low-lying areas, lying just beyond Cape Town's coastline, such as Macassar and Strandfontein) can be considered to have an adaptation deficit. The populations of poor areas in Cape Town (and globally) are more heavily affected by extreme weather events (e.g. floods and droughts) than richer areas. This discrepancy is widely referred to as the adaptation deficit. The deficit is driven by poor infrastructure and institutional capacities. Given the complex nature of Cape Town's economic structure as outlined in section D.1.2, it will be critical to identify the extent of the adaptation deficit in Cape Town's geographies and populations and then to assess how to close or narrow the gaps.

Based on the findings from Component 1 (Hazard, Vulnerability and Risk Assessment), Component 2 will focus on understanding the impacts of climate risks and hazards for Cape Town's economy, and using this analysis to better understand - and justify investment and adaptation priorities for the City of Cape Town. This component therefore comprises three key aspects: i) economic risk analysis, particularly for GDP and for jobs; ii) overarching high-level investment planning based on identified vulnerabilities and City requirements and priorities, conducted in close collaboration with the relevant City officials, and; iii) prioritising and costing of key adaptation options per and across sectors. Including climate change adaptation in City planning allows for heightened resilience of vulnerable communities, assets and natural systems to climatic risk. It also paves the way for more accurate budget allocations for climate investments from domestic, bilateral and multilateral resources.

Following the economic risk assessment (where the impacts identified in component 1, as informed by science, will be felt hardest, in terms of geographies and populations, and earliest, in terms of immediate variability and longer term, more gradual climate changes) this phase will apply a risk assessment framework that considers:

- **policy oriented approaches** that aim to strengthen key adaptive capacities early on in the climate impact lifecycle, with a view to addressing the identified adaptation deficit
- **entry points for mainstreaming**, or the integration of adaptation, into existing policies and decision-making processes
- **phasing and timing of adaptation** to simultaneously respond to the immediate and more gradual, and/or longer-term climate risks facing populations, infrastructure and eco-systems

Mainstreaming and strengthening of adaptive capacities are synergistic in that both consider the overarching policy objectives of the City, non-climate drivers, that nonetheless interact with climate drivers, multiple objectives of multiple level and scale actors (government, civil society, private sector, investors), and ancillary costs and benefits.

Assessments of the costs and benefits over time of adaptions have revealed that the most important impacts of climate change are likely to arise in the future (around 2040 and beyond) and as indicated earlier, the costs of these investments are often incurred much earlier than the occurrence of the change (Watkiss, 2015). The uncertainty surrounding climate change means that few are prepared to make these investments without clarity that the benefits will be realised. Therefore, the focus needs to be on no, or low regret investments coupled with an evaluation and learning process that informs and improves future strategies and decisions.

Ultimately, the findings from this Component will be critical for the development of the new Climate Change Adaptation Action Plan by and for the City of Cape Town (Plan). The remaining phases and deliverables of this study, as outlined below, are intended to inform the development of the Plan.

D.2.2.1 Phase 4 - Economic risk analysis

Broadly, we suggest that the Loss and Damage approach underpin the economic risk assessment as well as the subsequent risk evaluation and ranking of risks. Although Loss and Damage, or the impacts of climate-related stressors that occur despite efforts to reduce greenhouse gas emissions and adapt to climatic changes, continues to be divisive for international climate negotiators, the approach importantly recognises that some adverse impacts are already 'locked in' as a result of past, current and projected future global emissions. The links between Loss and Damage and the adaptation deficit, and limited adaptation are critical to the proposed risk assessment framework, as discussed in Box 4).

Box 4: Loss and Damage, the Adaptation Deficit, and Adaptation Limits

Avoidable loss and damage (L&D) through climate response actions (adaptation and mitigation) is generally related to both short-term aspects of reducing adverse climate effects, particularly disasters or extreme events. Depending on their scope and scale climate change adaptation interventions, can result in the reduction of potential impacts of climate change.

Residual L&D is typically the portion that accrues after adjusting for the reduction that climate change adaptation interventions has made on the adverse impacts. The quantum of L&D is the unavoidable, irreducible or inevitable damage after allowing for the positive effects of adaptation interventions and hazard mitigation activities such as capacity building, disaster risk reduction/prevention, and governance activities. Given that it is likely that existing hazard mitigation actions will not prevent all dangerous climate change related impacts, townships such as Khayelitsha and Mitchells Plain are likely to still be left with residual L&D even with accelerated adaptation interventions. Those climate change impacts that we are unable to prevent through existing and immediate future risk mitigation and adaptation efforts, are what will define the future response to climate change.

Thus, deepening the understanding of how closely social vulnerability and social resilience interact with climate hazards, risks and impacts is important. The objective of this phase (4) is to translate climate change impacts into L&D for Cape Town's society, noting the existing inequalities and those that may increase because of unchecked climate impacts. Critically, both adaptation deficit and limits to adaptation can result in residual L&D (Warner et al, 2012). Quantifying the adaptation deficit and understanding the bounds of existing adaptation limits, will constitute a key outcome of the economic risk assessment.

In this context, Disaster Risk is considered as a non-linear function, determined by a combined effect of exposure, vulnerability and hazard:

$$DR = f(E,V,H)$$

- **E** (Exposure) is determined by infrastructure and its accessibility to poor populations, such as functional water and sanitation systems, or housing;
- **V** (Vulnerability) is determined by income levels and socio-economic inequalities, social safety nets, or insurance mechanisms available to populations to protect them through severe hazards that impact on their socio-economic and environmental or ecological systems, as well as by sustainable living conditions;
- **H** (Hazard) is an intervention of external cause or origin, such as a flood, or extended drought. The intensity of the impacts of H, or the flood/drought, is influenced by the prevailing conditions of **E** and **V**. Disastrous results occur when **E** and **V** and **H** are simultaneously high.

DR is usually best minimised by addressing **V** and is thus a strong feature of climate change adaptation interventions. For the City, climate change adaptation priority interventions are likely to be characterised by investments that promote or strengthen inclusivity, close that adaptation deficit gap and respond to existing and future limits of adaptation. Specifically put, priority interventions are likely to be needed to address infrastructural and access inequalities and increase livelihood and income options for the poor. Notably, the latter includes ensuring that existing job creating economic activities are protected and even enhanced. For instance, Paarden Eiland lies in a vulnerable coastal zone that is home to job creating industries, rather than households. Ensuring that these sorts of areas are protected from climate hazards and risks is important – noting that their adaptation deficit is likely to be much lower than those of Khayeltisha or Mitchells Plain.

A multidimensional approach to risk assessment is recognised as a prerequisite to climate integrated urban development programmes (Mehrotra 2009). The risk assessment conducted in phases 2 and 3 focuses on climate hazards and evaluates and differentiates risks between sectors, systems and populations. The economic dimension will balance this focus throughout this component. Particularly, this phase aims to provide insights into the differential risks depending on the exposure to hazards on the spectrum of vulnerabilities of urban households, neighbourhoods, sectors and industries. Insights are as important from the most vulnerable communities living on flood plains characterised by poor infrastructure as from the adaptive capacity of local government to responds to these challenges. *Specifically, the intention is to understand which response may be more cost-effective as well as under what socioeconomic conditions is it desirable and feasible.*

Thus, this phase will analyse the economic impacts, including any economic opportunities, which could arise from the analysed climate risks. Based on the findings from the sectoral vulnerability analysis and the stacking of hazard events analysis in phases 2 and 3, the study will identify specific economic sectors which are most at risk to climate change impacts – direct and indirect. The economic sectors will be selected in terms of the degree to which their contribution towards Gross Domestic Product (GDP), Gross Value Add (GVA) and employment are expected to be affected.

Our approach is based on an iterative analytical process, that involves City stakeholders at key junctures of the decision-making process (e.g. determining key adaptation responses per sector; developing criteria for prioritisation and ranking risks and response options). As indicated, the starting point of the analysis is the consolidated hazard, risk and vulnerability assessment, which is designed to highlight spatial and sectoral risk and vulnerability with stacked or cumulative risks. The economic risk analysis will develop a typology of risks for each sector, before evaluating the likelihood of each risk occurring, its potential magnitude and the extent of the risks. This typology and analysis will underpin the manual of options required as an output of subsequent phases. It will contrast risks against each other to assess whether the impact of the risk is likely to be minimal or significant. Expert and stakeholder analysis will inform this contrast evaluation, using the 1st to 4th order impact assessment model (see figure 5) developed by OneWorld during its implementation of the DFID funded Regional Climate Change Programme (RCCP) across Southern Africa.

From the sectors and systems highlighted as vulnerable, the economic analysis will assess which of these sectors already, or are likely to make the greater contributions to GDP and employment. Both economic indicators are important; for example, in the Western Cape Climate Change Strategy and Action Plan conducted by OneWorld in 2006-2008, we found that agriculture made an important contribution to the Province's GDP, but a much greater contribution to employment. The sector's vulnerability was therefore substantially increased by its importance to employment. In this example, the knock-on effects for other sectors, such as tourism, were found to be high. This placed agriculture high on the list of priority sectors requiring climate adaptive investments.

This will bring the evaluation to a point of narrowing down, and understanding, population differentiated impacts. The analysis will include determining the 'best' (minimal impact) and 'worst' (significant impact) possible scenario impacts for each of the identified sectors and sub-sectors. A demographic analysis of the most vulnerable population groups to the impacts to these economic sectors will be conducted. In addition, an analysis of any potential economic opportunities arising from taking climate change adaptation actions in these sectors will be conducted. While poorer people are generally more vulnerable to climate hazards and shocks than those in higher income groups, across rural and urban geographies throughout vulnerable 'hotspot' regions such as Africa, in the context of cities, many climate induced challenges are often neglected. Complex urban systems with high and increasing population densities, such as the City of Cape Town, tend to exacerbate or highlight inequalities, a key indicator of population vulnerability. This is because certain population groups or communities are less able to relocate away from highly vulnerable locations such as the coastal areas described earlier, or from floodplains, or fire prone zones. Sea level rise and enhanced flooding in coastal cities can also lead to changes in the spatial distribution and density of formal and informal settlements. The 1st-4th order impact assessment model, applied frequently by OneWorld in understanding the cause and effect pathways of climate impacts and how these cascade through a system, routinely highlights that there can be wide range of risks flowing from a climate impact, such as sea level rise or temperature increase. Risk assessment frameworks that focus on cost accounting exercises, such as the Stern Review on the Economics of Climate Change (Stern, 2007), and the OECD Reports (Hunt & Watkiss, 2007 and Hallegatte et al., 2008) are important for cities, with population density and agglomeration of populations in locations highly exposed to hazards. This is because they define risk as the cost of catastrophe weighted by the probability of extreme events.

Box 5 provides an example of how we propose to identify and cost measures that reduce risk, based on the risks associated with sea-level rise, drawing and building upon existing data and information available to the City of Cape Town. The findings from this phase will be detailed in an economic risk analysis report (D-4).

Box 5. Economic assessment of risk mitigation measures to counter sea level rise

"The City of Cape Town administers approximately 307 km of coastline, arguably its single greatest economic and social asset" (Cartwright, 2008, p3). It creates a wide range of socio-economic opportunities including housing, recreation and tourism. As an ecological system, it also supports biodiversity and important ecological systems and services (Cartwright, 2008). Critically, the report assesses the contribution of Cape Town's coastline asset to GGP. It highlights that the projected 2.5 meter sea-level rise event would cost the City >ZAR 5billion in foregone GGP – out of a total ZAR165 billion GGP projected for 2008.

The Cartwright et al 2008 report models sea level changes (the outcomes of which will be used in phases 2 and 3 of this project) while also identifying areas of high risk that are prone to high impact, thus contributing significantly to this component of the project. It also contributes to the identification of measures that can reduce risk. It does this by assessing the broad costs and merits of different approaches used to counter the impacts of sea level rise.

This report describes general sea level rise adaptation approaches and then breaks down options for Cape Town into 'no-regret' and 'additional' options. A decision framework is presented for selecting appropriate adaptation measures. 'Additional' options are usefully broken down into physical, biological and institutional approaches.

In looking selecting the most appropriate adaption options for sea level rise, the report identified that these will necessarily be site specific and dependent on geological, social, financial and ecological conditions in areas impacted by climate induced sea level rise. The following are among the criteria suggested for prioritising options that are proposed for inclusion in this project's methodological framework - which uses a multi criteria analysis (MCA) approach:

- Options that present the greatest opportunity for protection at the least cost (Cost Benefit Analysis)
- Options that, as defined in the IPCC glossary, "generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs" (low regret options).
- Options that permit alternative or additional measures to be taken as opposed to ruling out alternatives
- Applying combined options as these reduce the most risk for a risk such as sea level rise that is multifaceted in that it impacts through a range of mechanisms and over different spatial and temporal scales
- Options that are the least likely, or are not likely, to result in maladaptation, or unforeseen consequences
- Available means of implementation, such as technology, capacity and finance.

Finally, and in accordance with the economic risk assessment will identify and classify types of risks, according to policy options, mainstreaming and/or phasing and timing. This framework will in turn allow for the categorisation of investment options in the final phases of the project.

D.2.2.2 Phase 5 – Investment Planning and Adaptation Options

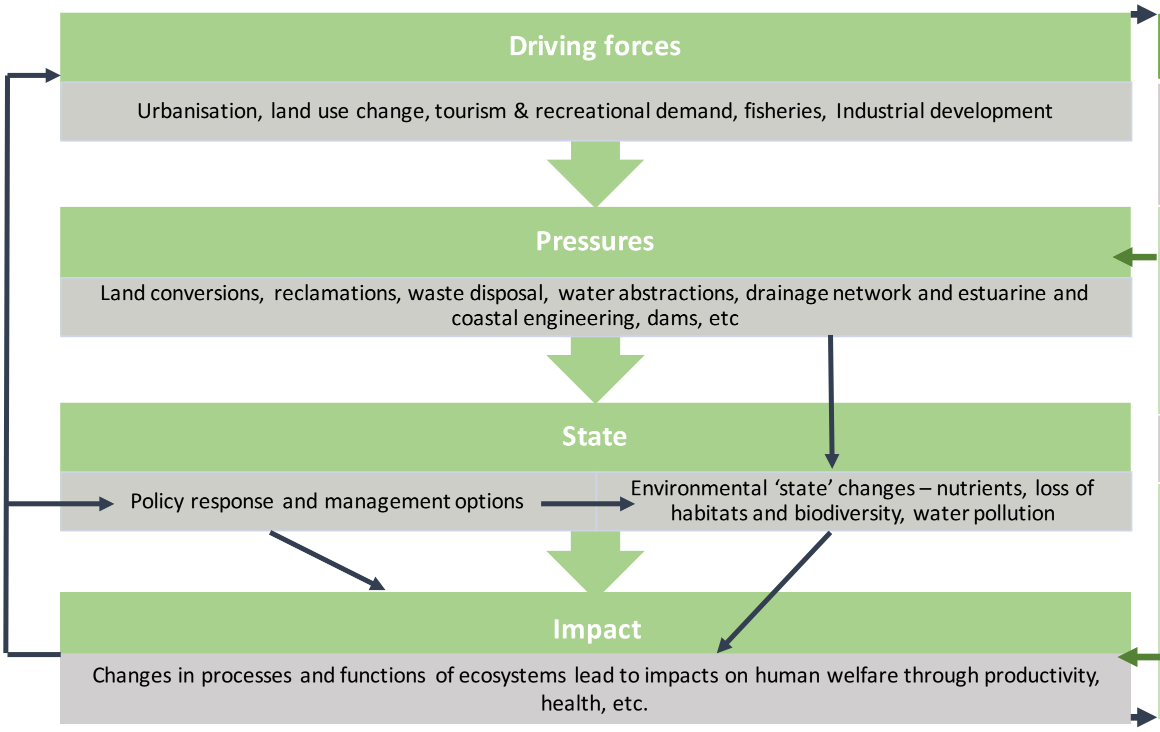
Adaptation implies behavioural change in response to the changing conditions and projected impacts. These changes are expected to reflect as appropriate measures in development planning (for example, implementing standards and guidelines for the built environment) and changes in demand-side management. As noted, geography, politics, economics, biodiversity, natural resources and people influence the system, meaning that a political or development decision in one part of the city can have ramifications across the city, as can climatic shocks, such as a flood event, which can multiply vulnerabilities. Coherent adaption planning that takes a systems approach is critical as population pressure, urbanisation and climate change combine to place enormous pressure on renewable resources and infrastructure. The already climate-stressed Cape Town system, located in a semi-arid sub-region or province that depends heavily on the city, combined with its high levels of social inequality, needs it more than most.

The options manual required under this project's terms of reference, is envisaged as the 'go-to' investment guideline for all investors motivated to build city-wide climate resilience. In effect, it is a "tool" for the city's custodians (who are also sometimes the city's investors) to deploy in directing and guiding investments towards resilience-building activities that are scalable and which aim to transform the way the city is developed and managed. To this end, the manual will include an investment action matrix, that considers high risk sectoral (or preferably, multi-sectoral options) against the dimensions of means of implementation, such as finance, technologies, capacities and political will. These means of implementation, or their collective availability, will provide the basis for a high-level feasibility test. In other words, the gap assessment enables an analysis of whether a priority intervention can in fact be implemented because the means for doing so are available, or can be accessed in time. This analysis can also act as an investment guide, helping to identify not only the priority interventions, but also the gaps in the means of implementation. For example, the technology for building a sea wall to protect the Cape Flats aquifer systems may be accessible, but the capacities to manage and build this infrastructure may not be, denoting what investment is needed for this intervention.

Furthermore, the manual will categorise risks for economic appraisal. It will do so by applying the risk assessment framework from phase 4 and will categorise types of adaptation interventions according to whether they address immediate risks (the adaptation deficit), immediate decisions which have a long lifetime (e.g. infrastructure planning and investments), and future, longer term risks that require some form of early action. In this way, the manual can remain within the line of sight of policy makers.

The structure of the manual will evolve with the study and its key stakeholders. However, its organisation is likely to be against a causal framework that describes the interactions between society and climate risks and hazards, as found through phases 2-4 for the City. The components of such a framework have been frequently used in studies such as this, including Cartwright (2008) making it efficient and useful to apply in this study as a means of organising complex findings and information and showing how these lead to priority interventions. Figure 6 provides an example of the Driving forces-Pressure-State-Impact-Response (DPSIR) framework as applied in integrated coastal zone management (ICZM).

Figure 6: DPSIR framework - linking society to climate hazards and risks and priority



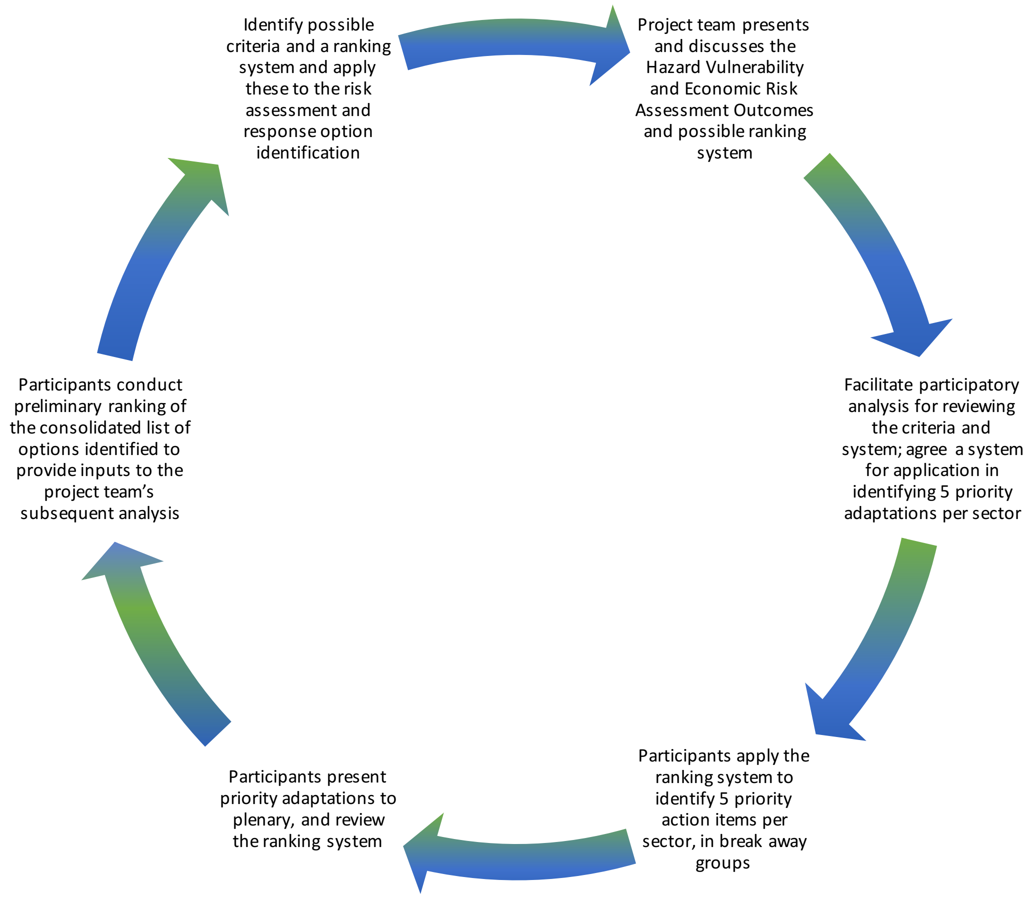
Response option	Type
Sustainable land management practices	Policy
Protected coastal infrastructure (e.g. dune management, sea barriers)	Infrastructure (hard)
Rehabilitation of biodiversity	Infrastructure (soft)
Equal waste management and treatment and water and sanitation systems between income groups	Policy & infrastructure

interventions

The evidence from the Hazard, Vulnerability and Risk assessment will be key to enabling the City to make informed decisions with regards to adaptation planning, and making a strong case for action. This will be done in two main stages.

First, a workshop will be convened with relevant officials, including sectoral officials, from the City (Task 5.1 under D-5), where the findings from Component 1 and a possible ranking system, including criteria, will be discussed and validated. City officials will be facilitated through an iterative process of using and testing the ranking system criteria to identify the five priority adaptation options in each sector, and subsequently to rank the consolidated options, as reflected in Figure 7.

Figure 7: An iterative, and applied process for developing and testing an options ranking system



Based on these findings as well as the circumstances and priorities as identified by City officials, options will be discussed for inclusion in an overarching and high-level Climate Change Adaptation Investment Plan (not a deliverable of this project, rather, a city output that this project's study will inform). The objective will be to prioritise options with the aim of reaching a balanced investment portfolio. The Investment Plan will enable the City to incorporate adaptation options into development planning and their Integrated Development Plan (IDP), allocate resources to adaptation priority areas and to ensure that timely actions are taken to address climate change impacts.

Based on the outcomes from the investment planning stage, a matrix of adaptation options will be developed, which will form the basis of the adaptation options identification and planning stage. Once this matrix has been developed, a high level economic costing analysis of these adaptation options will be conducted. The results from this analysis will provide the basis for a high-level costing of each option (including the potential benefits, such as reducing the avoidance of GGP from coastal assets as a result of sea level rise).

This deeper analysis will include a socioeconomic and environmental assessment, drawing on the pool of sectoral experts, available to the core project team. It is anticipated that specific focus will be placed on several infrastructure-related options, such as land use planning (including biodiversity and tourism), disaster risk management (DRM) with relation to the built environment, and water and sanitation.

The options will be prioritised through a multi-criteria analysis, the criteria for which will be agreed at the sectoral officials' workshop as discussed. The criteria will include, but will not be limited to the following:

- technological and methodological approaches for implementation

- Capacity to implement (financial and human)
- socioeconomic impacts
- cost-effectiveness
- unforeseen circumstances, or maladaptation

The prioritisation of adaptation options will be led by a number of key questions. These questions will include but are not limited to:

- What are the best practice adaptation strategies (i.e. from the literature) in the identified areas/ sectors?
- What are the most appropriate adaptation strategies for the City of Cape Town, bearing in mind the complexities of the local socioeconomic context?
- What are the costs involved in implementing suggested adaptation strategies?
- Which are the most cost-effective and economically efficient options? Are they market-based mechanisms?
- Are these options explicitly about climate change or do they have other co-benefits/ advantages?
- How important is climate change as a factor when considering these options?
- What is the lifetime of the options proposed?
- Which climate variables are likely to be the most important when considering these options? (i.e. climate change scenarios)
- What are the criteria for recognising a successful outcome?
- What are the legislative requirements / constraints?
- Who are the key stakeholders affected by the proposed adaptation options for the City of Cape Town?

The methodology described herewith will be refined and finalised during the inception phase of the study, in collaboration with the City. In terms of further developing the methodology a useful approach is to draw lessons from existing studies.

The key outcome of this phase of the project (D-5) will be an Options Manual, outlining and comparing the prioritised adaptation options and highlighting the high level costs, and benefits, for each.

D.2.2.3 Phase 6 - Presentation of Findings

As a final deliverable (D-6), a presentation will be prepared and delivered to the City's transversal working group on Green Procurement, Green Economy, Atlantis SEZ, Climate Change Mitigation, and Climate Change Adaptation (GEACC) of all the results and outcomes of each of the phases of this study.

F.2.4 D.2.3 Data Collection

The project team anticipates collecting data from a variety of sources, such as:

- Existing data and research, particularly on socio-economic profiles of the City, global climate change and adaptation, flood risk mapping, sea level rise, disaster risk profiles, etc. (available through the public domain and from the City
- Project team networks and own data (the team has a wide, combined network and access to quality local and global datasets with established relationships with providers)

The study will be informed by existing data and research, in particular by the following previous studies (as outlined in the ToR):

- Global climate change and adaptation - A sea-level rise risk assessment for Cape Town (2009).
- Climate Change Projections for the City of Cape Town: An update based on the most recent science (2016)
- Flood risk mapping undertaken by the City
- Disaster risk profiles and plans compiled by the City

Periodic and timely collection and analysis of high quality data under each phase and in cooperation with team members and relevant stakeholders at the City is integral to the approach – and success - of this study. It will enable outcomes tracking and reporting, including of the levels of satisfaction with project activities and deliverables. We expect that the project counterpart staff within the City will facilitate access to all local data and maps required.

Local data is particularly critical because the adaptive capacity layer in the spatial vulnerability mapping and reports is heavily reliant on available local data and local validation processes. Therefore, the Inception phase of the study will be critical for agreeing data collection and validation parameters and processes for the duration of the project.

The data collected during the implementation of the study will be stored in a safe repository and will be made available to the City for future reference and use.

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2019

Elaboration of a “Climate Change Hazard, Vulnerability and Risk Assessment” Study to the benefit of the City of Cape Town

Vulnerability and Hazard Assessment Report

Réf. AFD/DOE/EBC/CLD | ACH-2017-026

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PROJECT BACKGROUND

This report is submitted under the French Development Agency (AFD) project: Elaboration of a "Climate Change Hazard, Vulnerability and Risk Assessment" Study to the benefit of the City of Cape Town. The project falls under the CICLIA Framework Agreement for Studies and Technical Assistance for the Cities and Climate Change Initiative in Sub-Saharan Africa, funded by the French Development Agency (AFD), EU and the Swiss State Secretariat for Economic Affairs (SECO). This report is submitted on the back of the outcomes of Phase 2 and the Participatory Analysis Workshop with the City of Cape Town (CCT) held on the 18th of January 2019, in accordance with the requirements of the Contract for Réf. AFD/DOE/EBC/CLD | ACH-2017-026. As such, this report constitutes Deliverable 2 under this contract and includes: i) a summary of preliminary findings; ii) climate change projections and hazard assessment; iii) risk and vulnerability assessment; iv) thematic assessment of key risks and vulnerabilities and v) a brief discussion on the way forward.

ACKNOWLEDGEMENTS

We would like to thank all representatives of the City of Cape Town who participated in the Inception Workshop.

Thank you to our leading experts and OneWorld Team who delivered the objectives of this report: Belynda Petrie, Jonty Rawlins, Francois Engelbrecht, Arthur Chapman and Rob Davies.

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Abbreviations and Acronyms

AAO	Antarctic Oscillation
ACCESS1-0	Australian Community Climate and Earth System Simulator
AFD	French Development Agency (Agence Française de Développement)
AMO	Atlantic Meridional Overturning
AR5	Assessment Report 5
CBD	Central Business District
CCAM	Conformal-Cubic Atmospheric Model
CCSM	Community Climate System Model
CCT	City of Cape Town
CNRM-CM5	National Centre for Meteorological Research Coupled Global Climate Model, version 5
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DM	District Municipality
ENSO	El Niño Southern Oscillation
FFDI	Forest Fire Danger Index
FGD	Focus Group Discussion
GCM	Global Climate Model
GFDL-CM3	Geophysical Fluid Dynamics Laboratory Coupled Model
GIS	Geographic Information Systems
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
MPI-ESM-LR	Max Planck Institute Coupled Earth System Model
NorESM1-M	Norwegian Earth System Model
R&V	Risk and Vulnerability
SAM	Southern Annular Mode
SST	Sea Surface Temperature
WCWSS	Western Cape Water Supply System

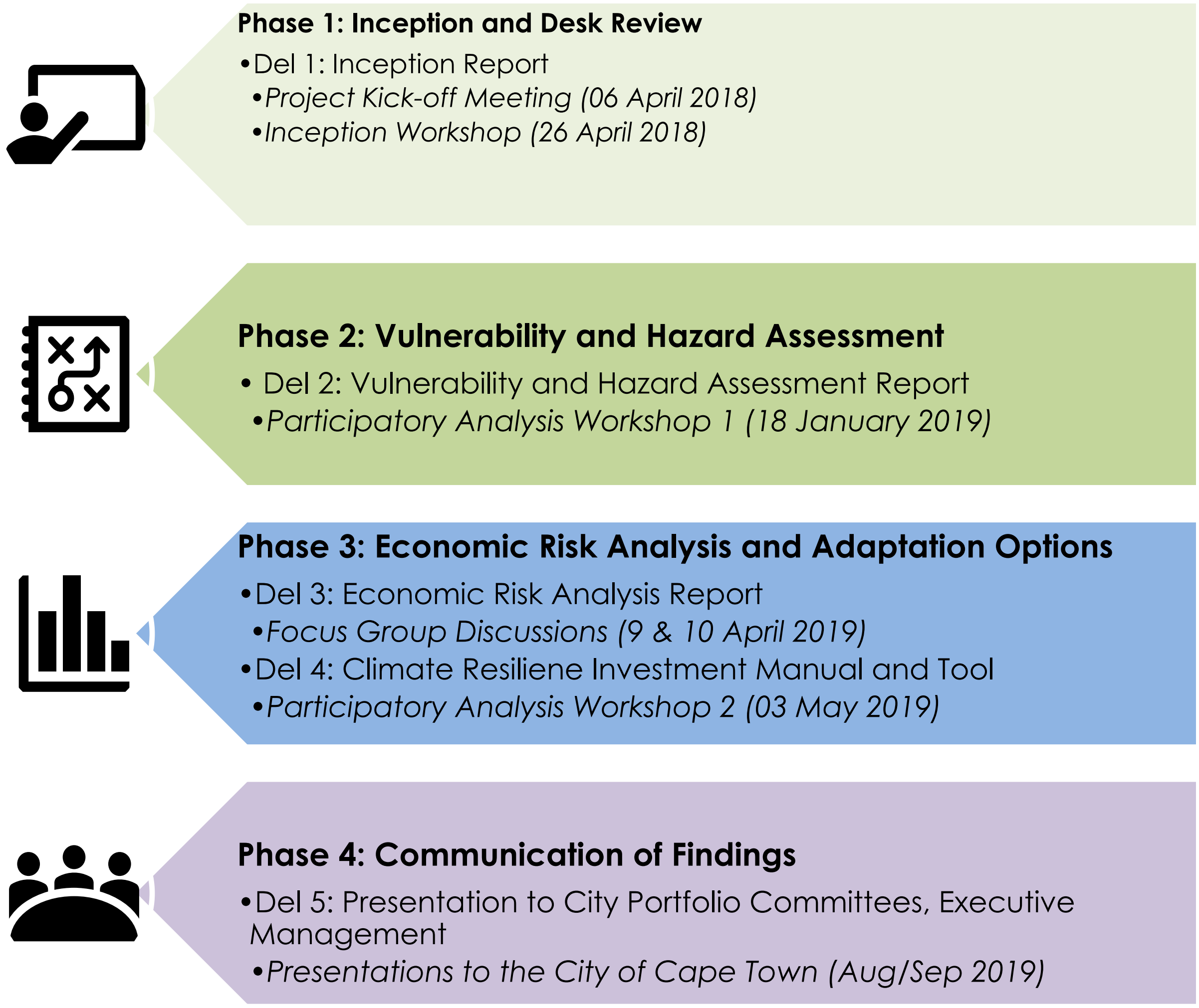
A. Introduction

This report is Deliverable 2 of the project **Elaboration of a "Climate Change Hazard, Vulnerability and Risk Assessment" Study to the benefit of the City of Cape Town**, commissioned by the French Development Agency (AFD).

Réf. AFD/DOE/EBC/CLD | ACH-2017-026.

The project is being delivered in line with a four-phased approach, with key deliverables and fieldwork activities under each phase, as illustrated in Figure 1. Building on the outcomes of Phase 1 and the Participatory Analysis Workshop with the City of Cape Town (CCT) held on the 18th of January 2019, this report includes: i) a summary of preliminary findings; ii) climate change projections and hazard assessment; iii) risk and vulnerability assessment; iv) thematic assessment of key risks and vulnerabilities and v) a brief discussion on the way forward.

Figure 1: Phased Project Approach



A.1 Summary of Key Findings

Cape Town is expected to experience a drier and significantly warmer future. Changes in these first order climate parameters have widespread impacts throughout biophysical, social and economic systems in around the City. The key climate-related hazards that pose the greatest risk to Cape Town are:

1. Drought
2. Fire
3. Heatwaves
4. Floods
5. Strong Winds

The Western Cape Water Supply System is highly exposed to drought, which poses direct risks to the economy of Cape Town, the natural environment and livelihoods of residents. The indirect impacts of drought are also far reaching and pose risks both within and beyond the City boundaries. Fires pose significant threats to human life, livelihoods and both low- and high-value properties. The areas most at risk within the City are those that have limited access to services and resources to buffer the impacts of shocks and respond to incremental challenges of long-term stressors.

The risks associated with these climate hazards are significant and manifest through multiple pathways that impact people, the economy and the environment. Complex interlinkages and cumulative impacts between the thematic areas of livelihoods, poverty and inequality, the built environment and disaster risk highlight that **building resilience is the key to reducing vulnerability in Cape Town.**

B. Climate Change Projections and Hazard Assessment

B.1 Background and Overview

Climate change is projected to impact drastically in southern Africa during the 21st century under low mitigation futures (Niang *et al.*, 2014). African temperatures are projected to rise at ~1.5 to 2 times the global rate of increase (James and Washington, 2013; Engelbrecht *et al.*, 2015). Moreover, the southern African region is projected to become generally drier under enhanced anthropogenic forcing (Christensen *et al.*, 2007; Engelbrecht *et al.*, 2009; James and Washington, 2013; Niang *et al.*, 2014). These changes in climate will have a range of impacts on the South African environment and economy, including impacts on energy demand (in terms of achieving human comfort within buildings and factories), water security (through reduced rainfall and enhanced evapotranspiration) and agriculture (in terms of changes in crop yield) (Engelbrecht *et al.*, 2015). Box 1 defines the notions of hazard and risk and differentiates between them.

Box 1: Definitions of hazard and risk

Hazard - The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources (IPCC, 2012: 560). For example: floods, droughts and fires.

Risk - The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. (IPCC, 2012: 1772). For example, drought poses different types and levels of risk through different pathways affecting multiple people, assets, etc., in different ways.

However, climate change impacts will not only manifest through changes in average temperature and rainfall patterns, but also changes in the intensity and frequency of extreme weather events. For the southern African region, generally drier conditions and the more frequent occurrence of dry spells are likely over most of the interior (Christensen *et al.*, 2007; Engelbrecht *et al.*, 2009). Tropical cyclone tracks are projected to shift northward, bringing more flood events to northern Mozambique and fewer to the Limpopo province in South Africa (Malherbe *et al.*, 2013; Muthige *et al.*, 2018). Flood events related to cut-off lows are also projected to occur less frequently over South Africa (Engelbrecht *et al.*, 2013) in response to changes in the wind regime and displacement of frontal systems towards the south pole. Intense thunderstorms are likely to occur more frequently over South Africa in a generally warmer climate (e.g. Engelbrecht *et al.*, 2013).

Recent climate change risk and hazard research (Brundrit, 2016; Fairhurst, 2008; Cartwright, 2008; Jack *et al.*, 2016) indicates that Cape Town is currently facing four key climate change challenges:

- A decrease in annual average rainfall and a change in the seasonality of rainfall;
- An increase in mean annual temperature: higher maximum temperatures, more hot days, and more frequent and intense heat-waves;
- An increase in average wind strength; and
- An increase in both the intensity and frequency of storms: short, high intensity rainfall events and increased size and duration of coastal storms.

These changes, already observed to some or other extent, will continue to occur, in addition to sea level rise. This climate change induced sea level rise will further exacerbate the severity of storm surges and therefore their impact (Brundrit, 2009). As with other extreme events, the recovery period between storm events is expected to shorten, leaving economies and livelihoods more vulnerable than they already are.

B.1.1 Section and Methodological Overview

This section presents the climate change projections and accompanying hazard assessment. These build on the findings of existing studies related to climate change risks in Cape Town (discussed above), using the most recent and most detailed projections of future climate change available for the southwestern Cape in South Africa.

The analysis is based on the Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC), and complemented by the recent IPCC Special Report on Global Warming at 1.5°C (SR1.5). We have based the spatial analysis of high impact climate events on the most spatially detailed projections of climate change over southern Africa obtained to date, through the Centre for High Performance Computing (CHPC) of the Meraka Institute of the CSIR in South Africa. The findings corroborate and contrast the existing body of evidence and latest insights into future changes in the frequency and intensity of extreme events over the southwestern Cape in South Africa, with a focus on extreme events that impact directly on Cape Town. See Box 2 for an outline of the specific experimental design for the climate change projections.

Box 2: Experimental design of climate change projections

The OneWorld team analysed an ensemble of high-resolution climate model simulations of present-day climate and future climate change projections over southern Africa, over the southwestern Cape. The regional climate model used is the conformal-cubic atmospheric model (CCAM), a variable-resolution global climate model (GCM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor 2005; McGregor and Dix 2001, 2008). CCAM runs coupled to a dynamic land-surface model CABLE (CSIRO Atmosphere Biosphere Land Exchange model). Six GCM simulations of the Coupled Model Intercomparison Project Phase Five (CMIP5) and AR5 were obtained for the low-mitigation emission scenario described by the Representative Concentration Pathway 8.5 (RCP8.5).

The simulations span the period 1960-2100 and the project team initially downscaled them to 50 km resolution globally. The GCMs downscaled include the Australian Community Climate and Earth System Simulator (ACCESS1-0); the Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM3); the National Centre for Meteorological Research Coupled Global Climate Model, version 5 (CNRM-CM5); the Max Planck Institute Coupled Earth System Model (MPI-ESM-LR); the Norwegian Earth System Model (NorESM1-M) and the Community Climate System Model (CCSM4). In these simulations CCAM was forced with the bias-corrected daily sea-surface temperatures (SSTs) and sea-ice concentrations of each host model, and with carbon dioxide, sulphate and ozone forcing consistent with the RCP8.5 scenarios.

Several reports have extensively demonstrated the model's ability to realistically simulate present-day southern African climate (e.g. Engelbrecht et al., 2009; Engelbrecht et al., 2011; Engelbrecht et al., 2013; Malherbe et al., 2013; Winsemius et al., 2014; Engelbrecht et al., 2015). Most current coupled GCMs do not employ flux corrections between atmosphere and ocean, which contributes to the existence of biases in their simulations of present-day SSTs – greater than 2 ºC along the West African coast. The bias is computed by subtracting the Reynolds (1988) SST climatology (for 1961-2000) from the corresponding CGCM climatology for each month. The bias-correction is applied consistently throughout the simulation. Through this procedure the climatology of the SSTs applied as lower boundary forcing is the same as that of the Reynolds SSTs. However, the intra-annual variability and climate-change signal of the CGCM SSTs are preserved (Katzfey et al., 2009).

A multiple-nudging strategy was followed to obtain the 8 km resolution outputs. After completion of the 50 km resolution simulations described above, CCAM was integrated in stretched-grid mode over southern Africa, at a resolution of about 8 km (0.08° degrees in latitude and longitude). The high-resolution part of the model domain was about 2000 x 2000 km2 in size and centred at 28°E, 25°S. The higher resolution simulations were nudged within the quasi-uniform global simulations, through the application of a digital filter using a 600 km length scale. The filter was applied at six-hourly intervals and from 900 hPa upwards.

The model integrations performed at a resolution of 8 km over South Africa offer a number of advantages over the 50 km resolution simulations. Firstly, the influence of convective rainfall is partially resolved in the 8 km simulations, implying that the model is less dependent on statistics to simulate this intricate aspect of the atmospheric dynamics and physics. Secondly, important topographic features such as the eastern escarpment and Cape Fold mountains are significantly better resolved in the 8 km resolution simulations, indicating that the topographic forcing of temperatures, wind patterns and orographic rainfall can be simulated more realistically. The 8 km resolution results represented here may therefore be regarded as potentially providing new insights into the futures of extreme weather events over South Africa under a changing climate.

B.2 Regional Climate Change Projections

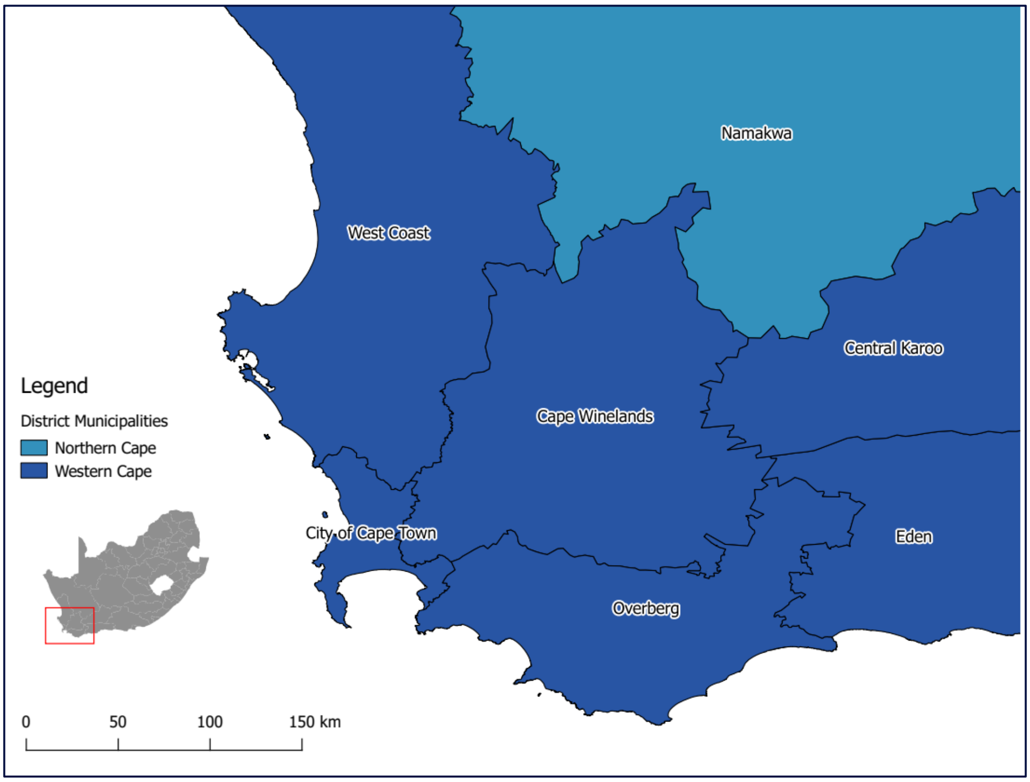
This section presents the projected changes of several climatological variables, including extreme weather-event metrics, for a domain covering the southwestern Cape. The projected changes in each metric are subsequently shown for the time periods 2021-2050 (mid-future) and 2070-2099 (far-future) relative to the baseline period 1961-2000 for the low-mitigation scenario (RCP 8.5). Three maps are presented for each climate metric, for both mid-future and far-future periods. These maps show the 10th, 50th (median) and 90th percentiles of projected changes for the entire ensemble of projections outlined in Box 2. In this way, it is possible to gain some understanding of the uncertainty range that is associated with the projections. Finally, the projections are shown for the region 35 °S to 31 °S and 17 °E to 23 °E, that is, for a domain covering the southwestern Cape. A list of the climate and hazard metrics analysed in this report is provided in Table 1.

Table 1: Key Climate and Hazard Metrics

Metric	Description and/or units
Average, maximum and minimum temperature	°C (Degrees Celsius)
Very hot days	A day when the maximum temperature exceeds 35 °C. Units are number of events per grid point per year.
Heat-wave days	The maximum temperature exceeds the average temperature of the warmest month of the year by 5 °C for at least 3 days.
High fire-danger days	McArthur fire-danger index exceeds a value of 24. Units are number of events per grid point per year.
Rainfall	mm (Millimetres)
Extreme rainfall	More than 20 mm of rain falling within 24 hrs over an area of 64 km^2. The occurrence of extreme convective rainfall is used as a proxy for the occurrence of storms that produce lightning. Units are number of events per grid point per year.
Windspeed	Annual average windspeed, metres per second (m/s)

Figure 2 illustrates the locations of the district municipalities (DMs) in the southwestern Cape region, for reference when analysing the spatial distribution of the metrics above.

Figure 2: District Municipalities of the Southwestern Cape



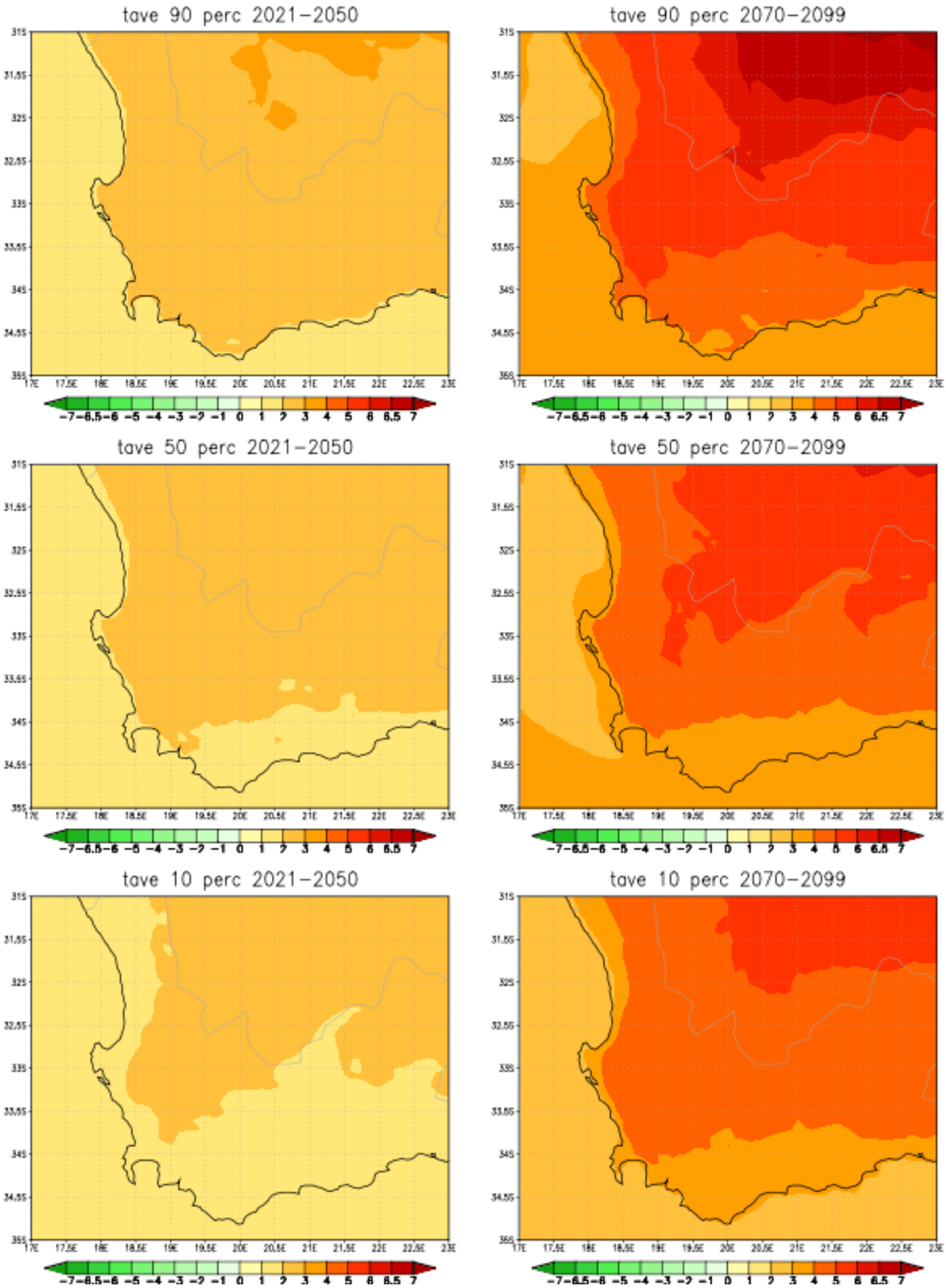
B.2.1 Average, maximum and minimum temperature

Projected changes in annual average temperature, as well as average maximum and average minimum temperatures are shown in Figures 3, 4 and 5, respectively. The following is evident from these figures, in conjunction with the AR5 assessment of Niang et al. (2014), Engelbrecht et al. (2015) and the SR1.5 assessment of Hoegh-Guldberg et al. (2018):

- Rapid rises in the annual average, maximum and minimum near-surface temperatures are projected to occur over the northern interior (Namakwa DM) of the Western Cape during the 21st century – temperature over this region is projected to rise at about 1.5 to 2 times the global rate.
- **For the mid-future period**, temperature increases of 2 to 3 °C may plausibly occur over most of the Western Cape. Over Cape Agulhas and further to the east along the Cape south coast (southern Overberg and Eden DMs) it is likely that temperature increases will be slightly less, in the order of about 2°C. These relatively smaller increases are due to the moderating effects of the ocean. Cape Town DM shows a variable 0-2 °C increase throughout the municipality.
- **For the far-future period**, temperature increases of more than 4°C are projected to occur over the northern interior regions (Namakwa DM) of the Western Cape, with increases of about 3°C projected for the southern coastal regions (southern Overberg and Eden DMs). Maximum temperatures are projected to rise faster than minimum temperatures over the south-western Cape (Cape Town DM). Temperature projections vary from 2-4 °C from the southern to the northern parts of the Cape Town DM.

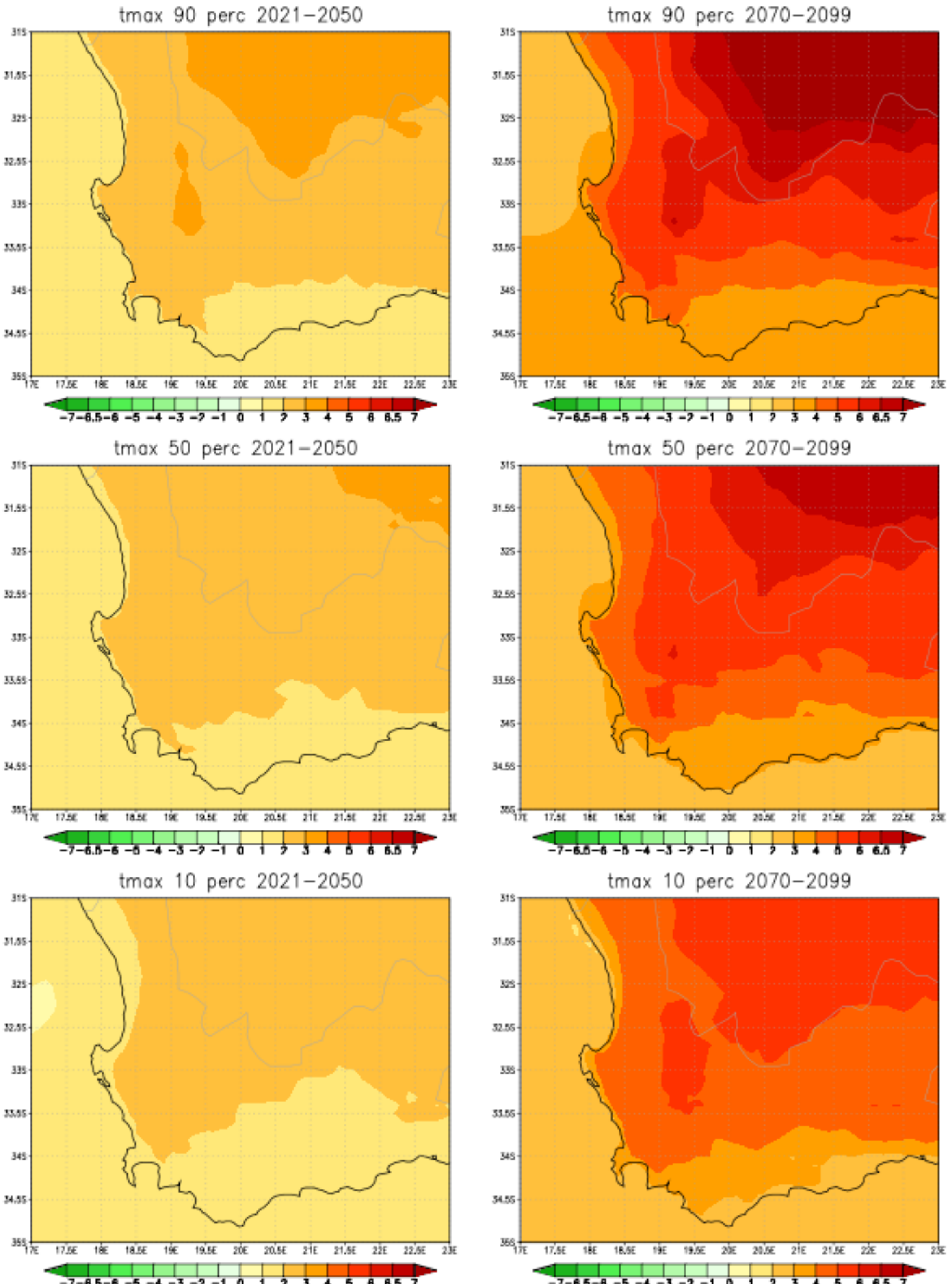
Impacts: Such drastic temperature increases will have significant impacts on numerous sectors, including agriculture, water and energy. Increasing temperatures, already by the mid-future, and more so by the far-future, would contribute to enhanced evaporation of soil-moisture and also from surface water resources. Associated increases in temperature extremes are likely to impact directly on human health, crop yield, livestock, the household demand for energy, as well as migration and general fire risk.

Figure 3: Projected change in the annual average temperature (°C)



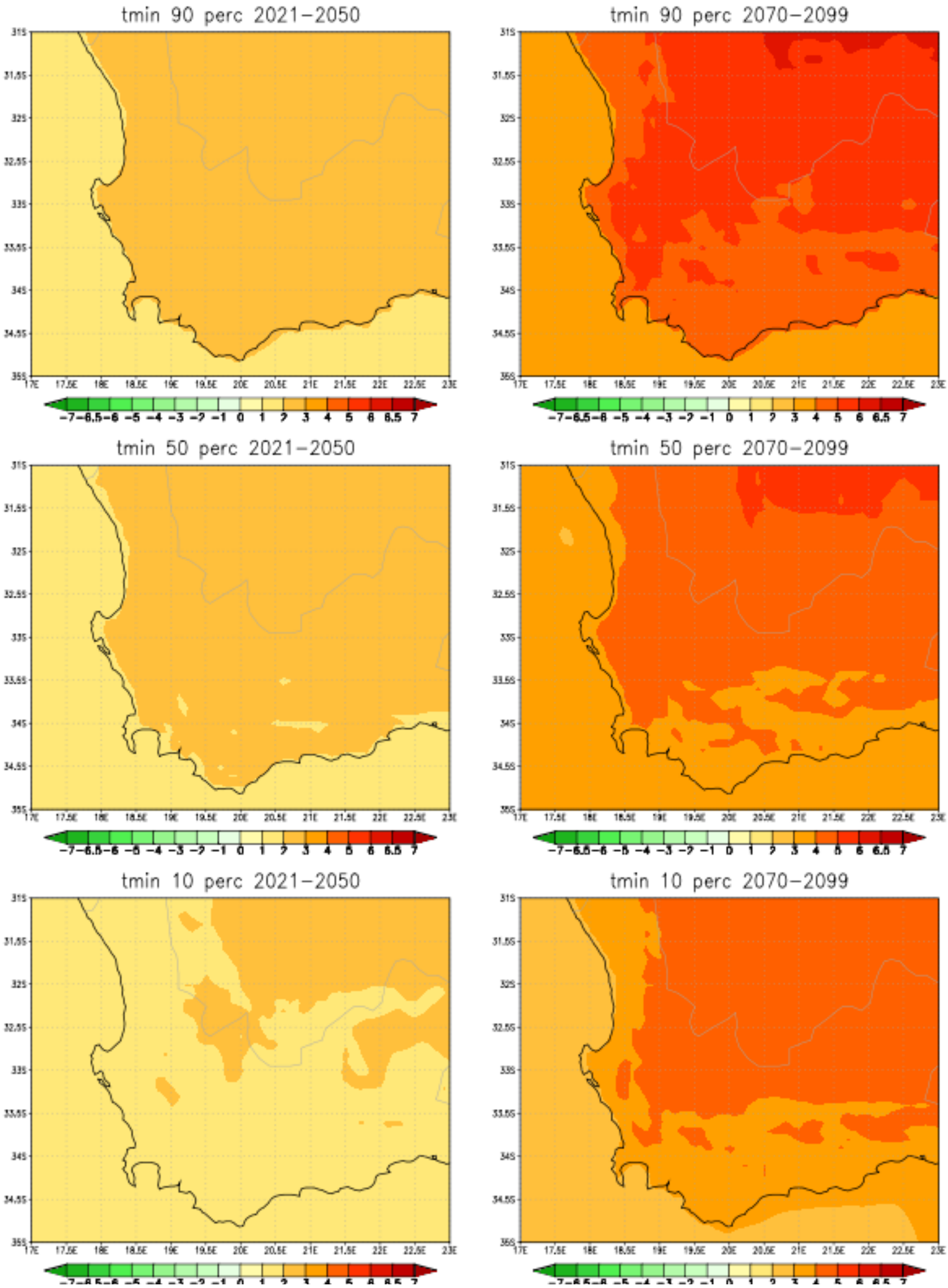
Projected change in the annual average temperature (°C) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low-mitigation scenario (RCP8.5).

Figure 4: Projected change in the annual average maximum temperature (°C)



Projected change in the annual average maximum temperature (°C) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low-mitigation scenario (RCP8.5).

Figure 5: Projected change in the annual average minimum temperature (°C)



Projected change in the annual average minimum temperature (°C) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low-mitigation scenario (RCP8.5).

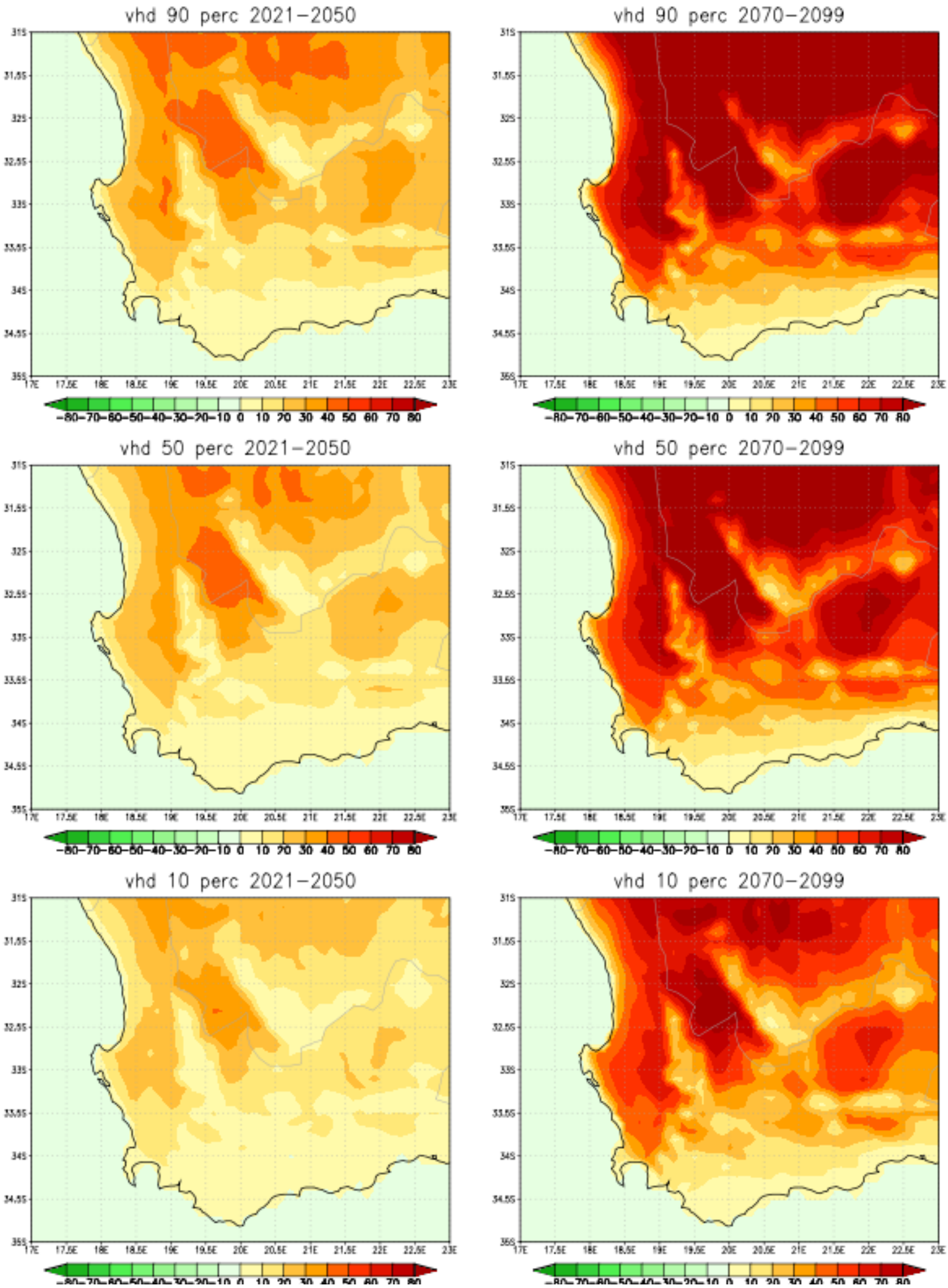
B.2.2 Very hot days

Projected changes in the annual average number of very hot days are shown in Figure 6. The following is evident from the figure, in conjunction with the AR5 assessment of Niang et al. (2014), Engelbrecht et al. (2015), Garland et al. (2015) and the SR1.5 assessment of Hoegh-Guldberg et al. (2018):

- In association with drastically rising maximum temperatures (Figure 5) the frequency of occurrence of very hot days is also projected to increase drastically under climate change.
- **For the mid-future period**, very hot days are projected to increase by about 10 days per year over the southern coastal areas (southern Overberg and Eden DMs) and in a narrow strip along the west coast, by 10-20 days per year over the central parts of the province (Cape Winelands and Central Karoo DMs) and by more than 30 days per year over the northern parts of the southwestern Cape (Namakwa DM). Projected increases in very hot days vary from 0-20 from the southern to the northern parts of the Cape Town DM.
- **For the far-future period**, very hot days are projected to increase by about 10 days per year in the narrow strip along the Cape south coast (southern Overberg and Eden DMs). A meridional (north-south) gradient exists in the projected increase in the number of very hot days across the province, with an increase of 80 or more such days per year projected for the northern interior regions (Namakwa DM) – a drastic and potentially devastating increase. Projected increases in very hot days vary from 0-50 from the southern to the northern parts of the Cape Town DM.

Impacts: Increases in the occurrence of very hot days occur in association with projected increases in the frequency of occurrence of heat-wave days and high fire-danger days (see Appendix 1). These changes may impact on human and animal health through increased heat stress and are likely to impact negatively on crop yield. They are also likely to increase the probability of veld and forest fires.

Figure 6: Projected change in the annual average number of very hot days



Projected change in the annual average number of very hot days (units are days per grid point per year) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low-mitigation scenario (RCP8.5).

B.2.3 Heat-wave days

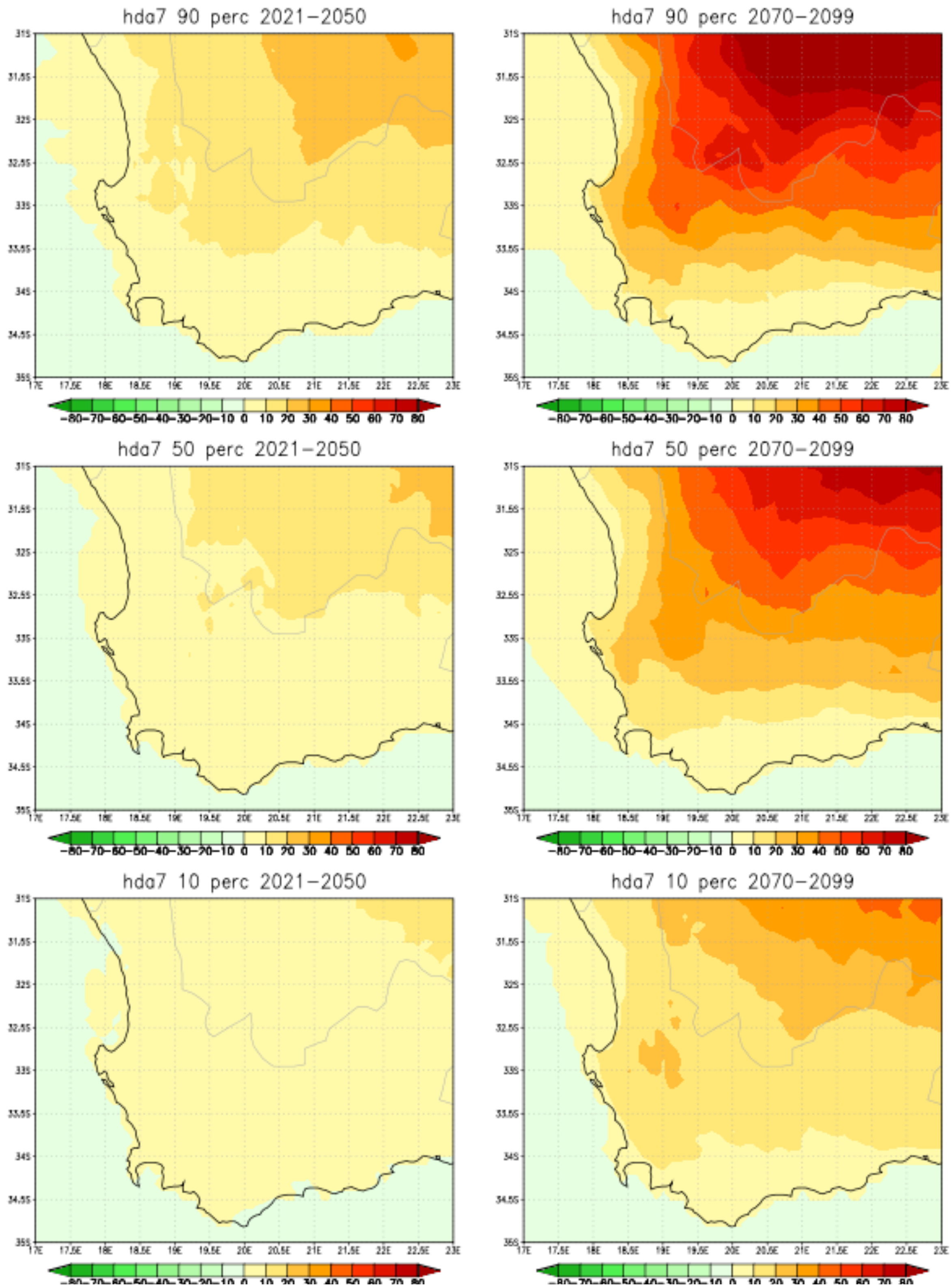
A heat-wave is defined as an event when the maximum temperature at a specific location exceeds the average maximum temperature of the warmest month of the year at that location by 5 °C, for a period of at least three days. The total number of days occurring within a heat-wave is referred to as "heat-wave days". Heat-waves are rare events in terms of South Africa's present-day climate, with very few locations experiencing more than 10 heat-wave days on the average per annum.

Projected changes in the annual average number of heat-wave days are shown in Figure 7. The following is evident from the figure, in conjunction with the AR5 assessment of Niang et al. (2014), Engelbrecht et al. (2015), Garland et al. (2015) and the SR1.5 assessment of Hoegh-Guldberg et al. (2018):

- In association with drastically rising maximum temperatures (Figure 5), the frequency of occurrence of heat-wave days is also projected to increase drastically under climate change.
- **For the mid-future period**, heat-wave days are projected to increase by less than 10 days per year over most of the Western Cape and plausibly by 10-20 days per year over most northern parts of the province (Namakwa DM). Projected increases in heat-wave days vary from 0-10 from the southern to the northern parts of the Cape Town DM.
- **For the far-future period**, heat-wave days are projected to increase drastically and with a south-north gradient across the province, reaching increases of 40-50 days per year over the northern parts of the Western Cape (Namakwa DM). Projected increases in heat-wave days vary from 0-20 from the southern to the northern parts of the Cape Town DM.

Impacts: Significantly increased numbers of heat-wave days will impact on human, plant and animal health through increased heat stress. Increased numbers of such days are also likely to impact negatively on crop yield and increase the likelihood of veld and forest fires.

Figure 7: Projected change in the annual average number of heat-wave days



Projected change in the annual average number of heat-wave days (units are days per grid point per year) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low-mitigation scenario (RCP8.5).

B.2.4 High fire-danger days

Projected changes in the annual average number of high fire-danger days are shown in Figure 8. Fire danger is a combination of factors that affect initiation, spread and the ease of controlling fires. High fire-danger days are days when the McArthur Forest Fire Danger Index (FFDI) exceeds a value of 12, where units are the number of days per model grid point. Note that the FFDI has been used extensively to study Fynbos Fire risk over the southwestern Cape and Cape south coast regions (e.g. Van Wilgen et al., 2010).

The following is evident from the figure, in conjunction with the AR5 assessment of Niang et al. (2014), Engelbrecht et al. (2015), Garland et al. (2015) and the SR1.5 assessment of Hoegh-Guldberg et al. (2018):

- In association with drastically rising maximum temperatures (Figure 5), the simulation shows that the frequency of occurrence of high fire-danger days is also projected to increase drastically under climate change.
- **For the mid-future period**, high fire-danger days are projected to increase by up to 10 days per year along the southern coastal regions (southern Overberg and Eden DMs), with larger increases to the north (Namakwa and West Coast DMs), reaching values of 20-30 days per year over the northern parts of the south-eastern Cape. Projected increases in high fire-danger days vary from 0-20 from the southern to the northern parts of the Cape Town DM.
- **For the far-future period**, high fire-danger days are projected to increase, with more than 80 days per year over the far northern parts of the province (Cape Winelands, West Coast and Namakwa DMs). Substantial increases are projected in the Fynbos regions of the Cape Fold mountains. It is only along the Cape south coast regions (southern Eden and Overberg DMs), under the moderating influence of the ocean, where increases are likely to be restricted to about 10 days per year. Projected increases in high fire-danger days vary from 0-60 from the southern to the northern parts of the Cape Town DM.

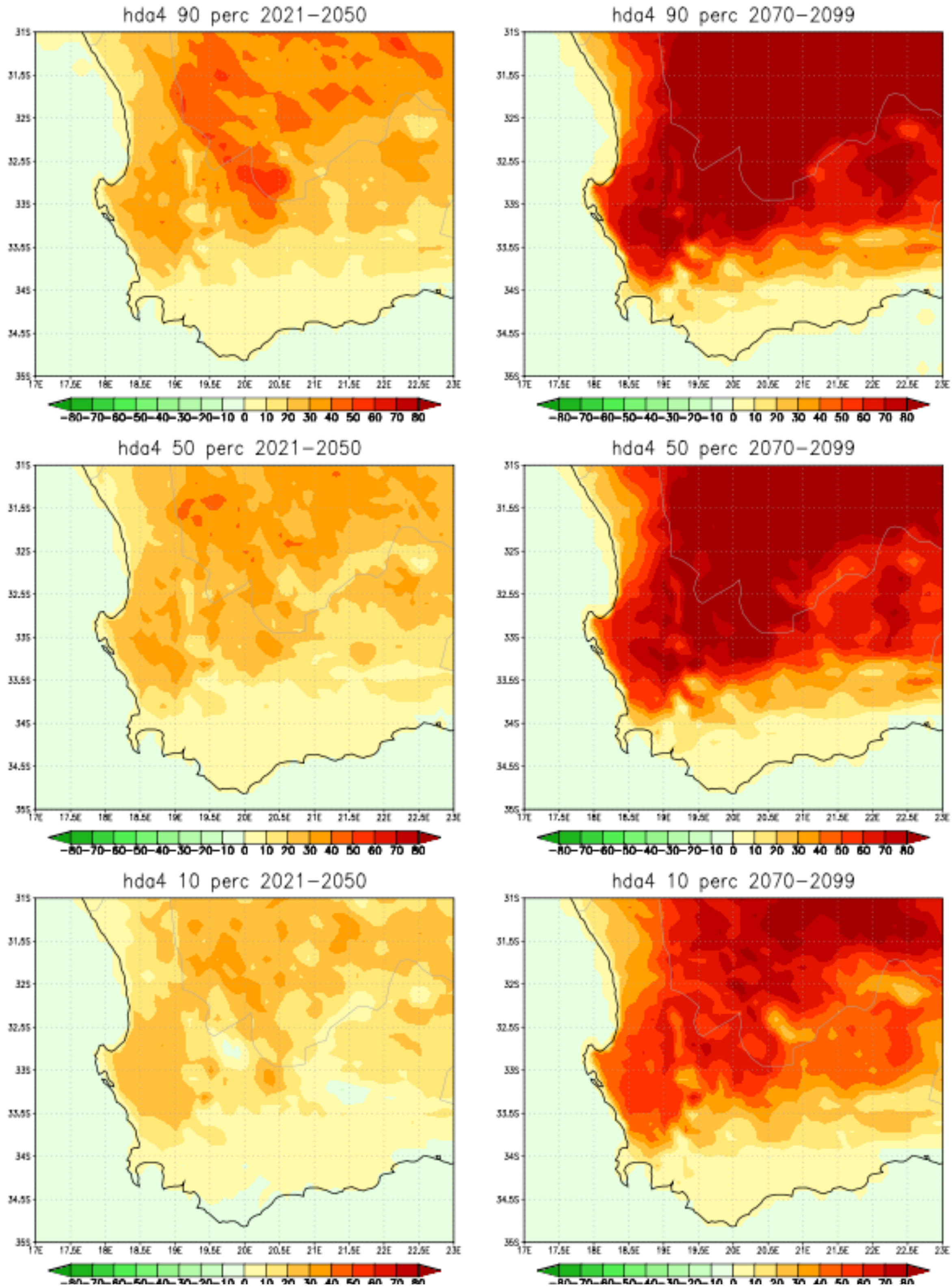
Impacts: Notable increases in high fire-danger days will impact directly on human, plant and animal health, as well as threaten physical and natural infrastructure. This could impact significantly on crop yields, tourism, property values, emergency services, etc.

B.2.4.1 Seasonality of fire risk

High fire-danger days have a seasonal cycle, which is related to the increasing risk for runaway veld and forest fires. The Fynbos biome has evolved over hundreds of thousands of years in the cool, wet winters and dry, warm summers of South Africa's winter rainfall region. Fire thus occurs as a natural phenomenon in the Fynbos biome during the dry summer months, following the production of biomass during the wet seasons. However, climate change is projected to significantly alter the seasonal cycle in rainfall over the southwestern Cape.

Appendix 1 provides an examination of the projected changes in the seasonal cycle of the number of high fire-danger days for two cases, of Cederberg, in the south-west, and Vermaaklikheid (on the Cape south coast). These cases illustrate two contrasting examples of projected change in fire risk in the southwestern Cape. At Vermaaklikheid along the Cape South coast region, the FFDI is indicative of a notably smaller change in fire risk than over the Cederberg region to the north. Although projections indicate high fire risk days will increase over the mid- and far-future periods for both regions, the Cederberg will experience more high-risk days. Projected changes in temperature, wind speed, relative humidity and drought conditions influence the future fire risk. Thus, based on the temperature (Section B.2.1), wind (see Section B.2.7) and rainfall (Section B.2.5) projections, Cape Town will experience up to 20-60 more high fire risk days per year (see Section B.3). It should be noted that the FFDI is focused on assessing risk of wildfires. Although the underlying climate conditions that influence the likelihood of urban fires are largely the same, the physical pathways through which fire risk manifests are different (discussed further in Section D.).

Figure 8: Projected change in the annual average number of high fire-danger days



Projected change in the annual average number of high fire-danger days (units are days per grid point per year) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low-mitigation scenario (RCP8.5).

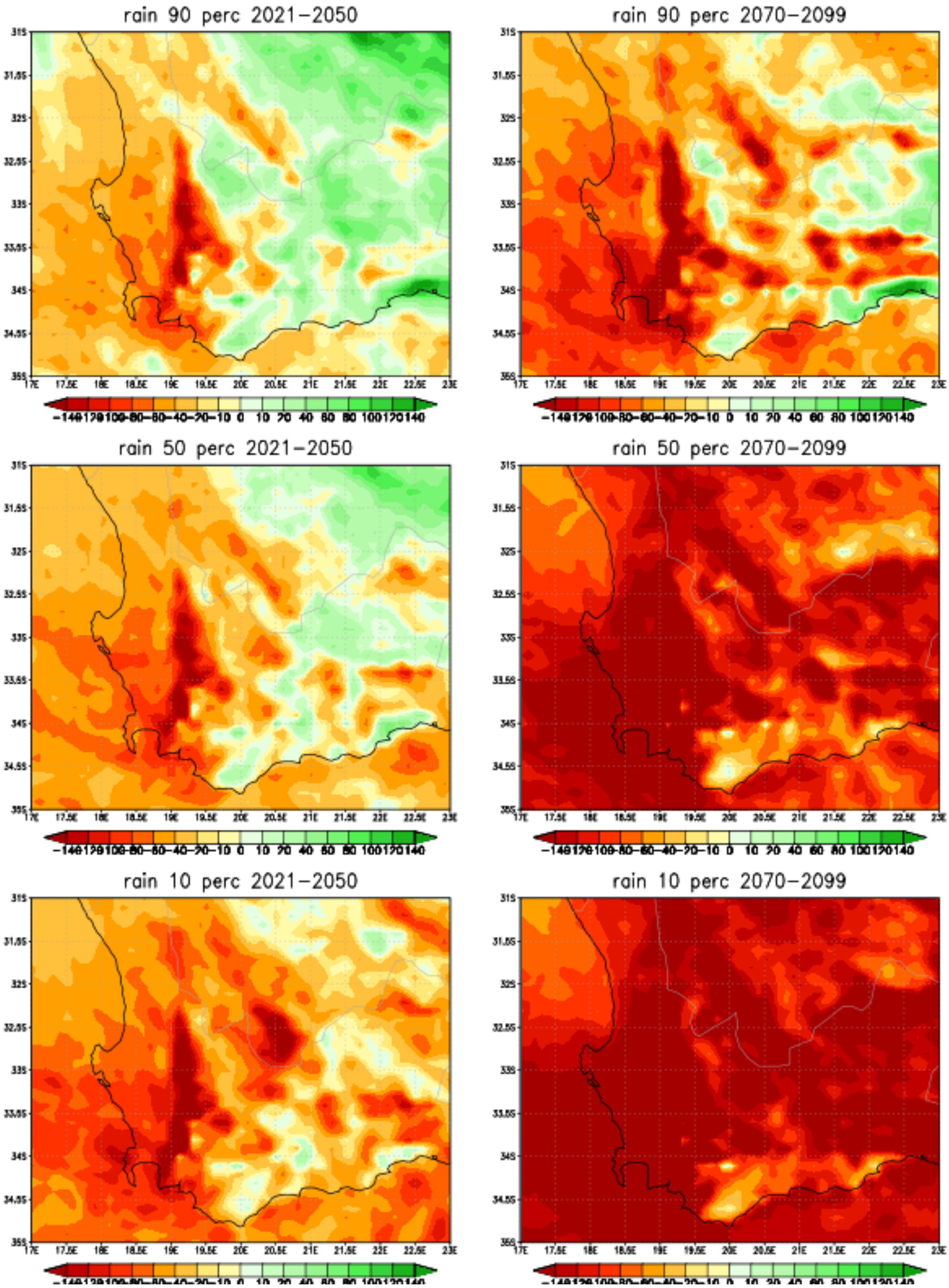
B.2.5 Rainfall

Projected changes in annual average rainfall are shown in Figure 9. The following is evident from the figure, in conjunction with the AR5 assessment of Niang et al. (2014), Christensen et al. (2007), Engelbrecht et al. (2009), Engelbrecht et al. (2015) and the SR1.5 assessment of Hoegh-Guldberg et al. (2018):

- A general decrease in average rainfall is likely to occur over the winter rainfall region of South Africa under enhanced and continued human-induced climate change.
- **For the mid-future period**, rainfall is projected to decrease substantially along the south-north aligned Cape Fold mountains north of Cape Town (West Coast and Cape Winelands DMs), including over the important catchment areas of the Cape Town dams. Over the eastern interior (Cape Winelands, Central Karoo and Eden DMs), rainfall increases are projected by some projections. This results from an increase in the occurrence of convective storms over this region. Projected decreases in rainfall vary from 60-120mm from the northern to the southern parts of the Cape Town DM.
- **For the far-future period**, rainfall is projected to decrease substantially across the Western Cape. The largest decreases are projected to occur over the meridionally aligned and zonally aligned Cape Fold mountains (West Coast, Cape Winelands and Overberg DMs). The displacement of frontal systems towards the South Pole under low mitigation futures is the main dynamic mechanism underpinning the projected decreased in rainfall. Increases in the strength of the subtropical high pressure reduce the signal of increasing convective rainfall in the east, so that this signal is weaker compared to the mid-future period. Projected decreases in rainfall vary from 80-160mm from the northern to the southern parts of the Cape Town DM.
- Reductions in rainfall will manifest as soon as the 2021-2050 (mid-future) period. Nevertheless, the rainfall projections display more uncertainty than in the case of projected changes in temperature. This implies that adaptation policy makers need to take into account a range of different rainfall futures (i.e. drier and wetter), in particular for the eastern interior of the Western Cape.

Impacts: Notable reductions in annual average rainfall will have a myriad of impacts on all sectors within and around Cape Town. Long term water supplies will be compromised and negatively impact water and food security. This will have a number of ripple effects throughout the economic, social and environmental systems.

Figure 9: Projected change in annual average rainfall totals (mm)



Projected change in annual average rainfall totals (mm) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low-mitigation scenario (RCP8.5).

B.2.6 Extreme rainfall events

Projected changes in extreme rainfall events are shown in Figure 10. Here an extreme rainfall event is defined as 20 mm of rain occurring within 24 hours over an area of 64 km^2. The following is evident from the figure, in conjunction with the AR5 assessment of Niang et al. (2014), Engelbrecht et al. (2009), Engelbrecht et al. (2013) and the SR1.5 assessment of Hoegh-Guldberg et al. (2018):

- **For the mid-future period**, consistent with the projected decreases in rainfall, extreme rainfall events are projected to decrease in frequency over most of the southwestern Cape. This is true in particular for the south-north aligned Cape Fold mountains region (West Coast and Overberg DMs), and the catchment regions of the Western Cape Water Supply System (WCWSS) dams. A number of projections show increases in extreme rainfall events over the eastern parts of the interior of the Western Cape (Central Karoo and Eden DMs), as a consequence of convective rainfall increasing over this region. Projected decreases in extreme rainfall events vary from 0-3 days throughout the Cape Town DM.
- **For the far-future period**, extreme rainfall events are projected to decrease further in frequency over the Western Cape. This signal of decreasing extreme events also extends to the eastern interior regions of the Western Cape (Central Karoo and Eden DMs), implying that in the far-future the strengthening of the subtropical high-pressure belt and associated subsidence will be the dominant change in circulation. The relatively large decreases in extreme rainfall events projected for the Cape Fold mountains are important from the perspectives of run-off and water security. Projected decreases in extreme rainfall events vary from 0-5 days throughout the Cape Town DM.

Impacts: Extreme rainfall events, such as those occurring over the eastern part of the Western Cape interior, are mostly caused by intense thunderstorms, which often also cause lightning, hail, damaging winds and flash floods. Adaptation policies therefore need to take into account the possibility that extreme rainfall events may increase in frequency, in the mid-future, over the eastern interior regions of the Western Cape. Box 3 explores the uncertainties in projections of extreme rainfall in the Western Cape.

Box 3: Understanding Extreme Rainfall Projections

As the air temperature rises, the air can hold more water. This amount is about 7% more water vapour per 1°C rise in air temperature per unit volume of atmosphere at ambient conditions, according to the Clausius-Clapeyron equation (Trenberth et al., 2003). This means that with global warming and more moisture in the atmosphere, storms will become more energetic (the extra water condensing into rainfall releases additional latent heat). It also means that convection storms will become more intense, releasing greater amounts of water.

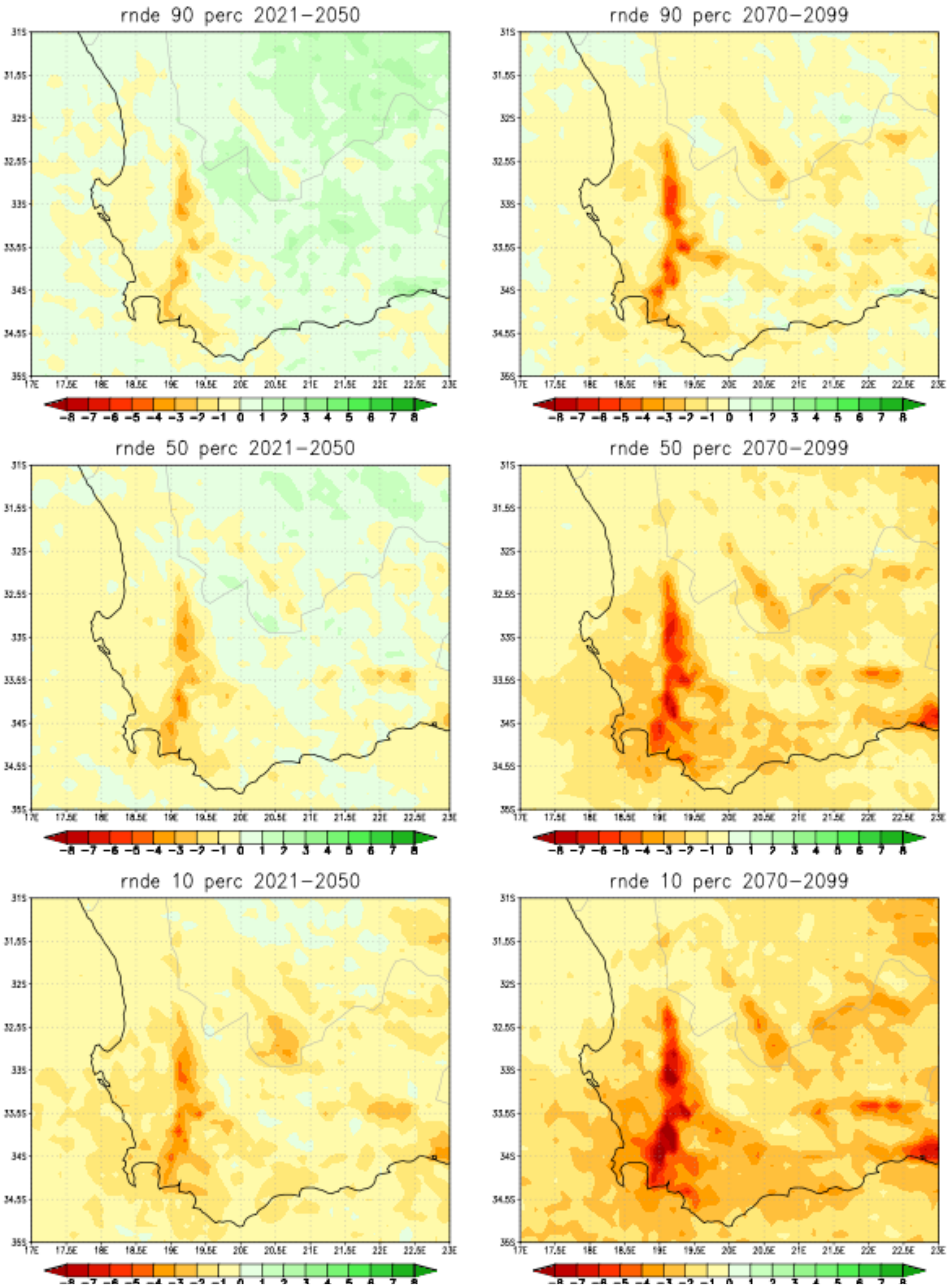
These effects are not always seen in climate models because many do not resolve convective clouds and rely on statistical methods to describe the probability of convective precipitation occurring across model cells (Lenderink et al., 2017). Convection-permitting models also often show stronger precipitation responses than models in which convection is parameterised, but must be run at much finer scales (Kendon et al., 2014). For example, climate models with inter-nodal distances of 1.5 km usually show increases in intensities of short-duration rainfall at the high thresholds that lead to localised flooding.

Larger-scale models or those with larger inter-nodal distances are less able to represent local-scale storm dynamics. Modelling convection systems at significantly finer scales leads to a higher number of convective extremes and rainfall intensities increase as a result of warming (Kendon et al., 2014). *The implications are that climate models at the larger model inter-nodal distances can underestimate convection intensity with rising atmospheric temperatures.*

Increased intensities of rainfall with a warming atmosphere have already been observed in Australia by Wasko and Sharma (2015) and Guerreiro et al. (2018). This same phenomenon has tentatively been identified over the Western Cape by Pharoah et al. (2016), in which cut-off low storm systems in summer have caused more damage than those in winter because rainfalls were more intense. Further, de Waal et al. (2017) have shown recent increases in storm intensity in the Western Cape based on observed trends.

In summary, climate modelling shows a reduction in extreme rainfalls over the Western Cape and Cape Town over time, but local observations support the notion that increasing intensities of rainfall have fallen in recent years. Objectively, warming air masses will be able to hold more water and this must precipitate somewhere. Prudence will dictate that the City of Cape Town concern itself also with a possible future of increasing intensity of extreme rainfall, and all that that entails with respect to infrastructure and the management of storm water and settlement patterns.

Figure 10: Projected change in the annual average number of extreme rainfall days



Projected change in the annual average number of extreme rainfall days (units are days per grid point per year) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low-mitigation scenario (RCP8.5).

B.2.7 Wind Speed

Projected changes in annual average wind speed are shown in Figure 13, following after Box 4. The following is evident from the figure, in conjunction with the AR5 assessment of Niang et al. (2014), Engelbrecht et al. (2009), Engelbrecht et al. (2013) and the SR1.5 assessment of Hoegh-Guldberg et al. (2018):

- **For the mid-future period**, slight to moderate windspeed increases are projected fairly uniformly across the City of Cape town, with the southern Peninsula expected to experience slightly higher increases in annual average wind speed. However, these moderate increases in annual average windspeed are not uniform over the broader southwestern Cape, with small pockets of higher windspeed increases in the Cape Winelands DM and significant areas projected to experience slight decreases in windspeed towards the northwest and southeastern parts of the region (West Coast, Eden and Central Karoo DM).
- **For the far-future period**, variable increases in windspeed are projected across the City of Cape town, with the southern parts of the City expected to experience higher increases in annual average wind speed. However, these increases in annual average windspeed are not uniform over the broader southwestern Cape, with small pockets of higher windspeed increases in the Cape Winelands DM and significant areas projected to experience moderate decreases in windspeed towards the northwest and southeastern parts of the region (West Coast, Eden and Central Karoo DM).

Impacts: Increased average wind speeds will have a variety of ripple effects on other climate-related hazards such as fires and coastal storms (discussed in Box 4). Strong wind events can cause damage to infrastructure, most notably informal structures that aren't designed to withstand strong gusts of wind. Moreover, increased windspeeds will influence the overall evaporation rates of the dams and rivers in the region. Box 4 discusses wind as a climatic driver for extreme events and conditions.

Box 4: Wind as a climatic driving force for extreme conditions

High wind speeds and gust velocity are important factors in posing a hazard to exposed assets. In a limited number of examples referenced below across the southern Cape, strong winds have been important contributary factors in creating severe social and economic loss, including death and injury (Table 2). The average and 1-hour gust wind speeds are data from the Global Forecast System (GFS), abstracted from the weather modelling system Ventusky. Over the years, Cape Town has experienced many destructive fires driven by strong winds and the data presented in Table 2 is only a small sample of these.

Table 2: Recent fire damage in the southern Cape, enhanced by high wind speeds.

Incident	Damage	Date	Avg. Wind Speed (km/h)	1hr Gust Wind Speed (km/h)	Reference
Franschoek pass closed	Road closed to travel	19-Feb-19	7	20*	(Seleka, 2019)
Betty's Bay	31 houses destroyed, 28 damaged, 1 injured	11-Jan-19	54	90	(Ngqakamba, 2019)
Karwyderskraal	Commercial property threatened	26-Dec-18	41	60	(Mitchley, 2019)
Cape St Francis	12 houses destroyed, 21 damaged	18-Dec-18	47	61	(Sicetsha, 2018)
Karatara, Southern Cape	8 dead, 2 women, 6 children	30-Oct-18	30	76	(Pijoos, 2018)
Capricorn Park, Cape Town	500 informal dwellings destroyed	26-Oct-18	18	35	(Isaacs, 2018)
Khayelitsha, Cape Town	4000 displaced, 1 dead	20-Oct-18	37	50	(Head, 2018)
Knysna, Southern Cape	9 dead, 900 houses destroyed, 2000 jobs lost, R2+ billion in damages	08-Jun-17	50	82	(Forsyth et al., 2019)

* Steep and variable topography creates funnel systems which dramatically increase local wind speeds

Current fire danger rating systems used by the South African Weather Service (SAWS), as a means of predicting impending fire danger, are not sufficiently representative of the various local weather conditions that give rise to extreme fire danger (Forsyth et al., 2019; Kraaij et al., 2018).

Hourly wind run (the distance wind has travelled over a period of an hour) observed at Cape Town airport for the period 1960 – 2001 indicates not only increasing wind runs but also increasing 1-hour gust speed (Figs 11 and 12). Figure 11 shows the trends in average wind run increase for every month of the year and particularly in the high fire danger months of January, February and March. Figure 12 shows that the trend in maximum annual 1-hour gust velocity has increased substantially during the observation period. If this trend is valid through to 2019 and beyond, the trend has significant implications for increasing fire danger on windy days, or for the increased possibility of structural damage as a result of very strong winds. Most damage occurs during the extreme conditions, not during average conditions. Other research supports these observed increases in wind speed with observations from the surrounding oceans (Young and Ribal, 2019). Wind speeds in the coastal areas are substantially affected by oceanic wind speeds.

Figure 11: Mean increases in wind run at Cape Town airport over the period 1960-2001.

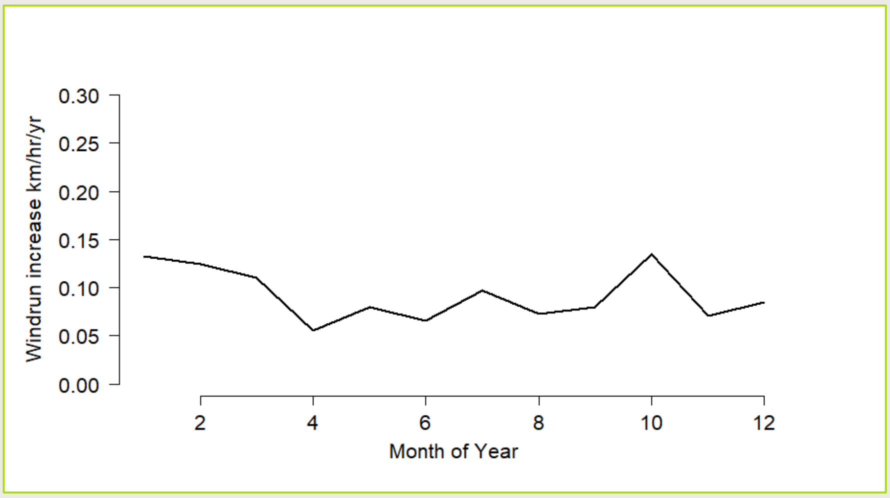


Figure 12: The trend in 1-hour gust wind speed at Cape Town airport for the period 1960-2001

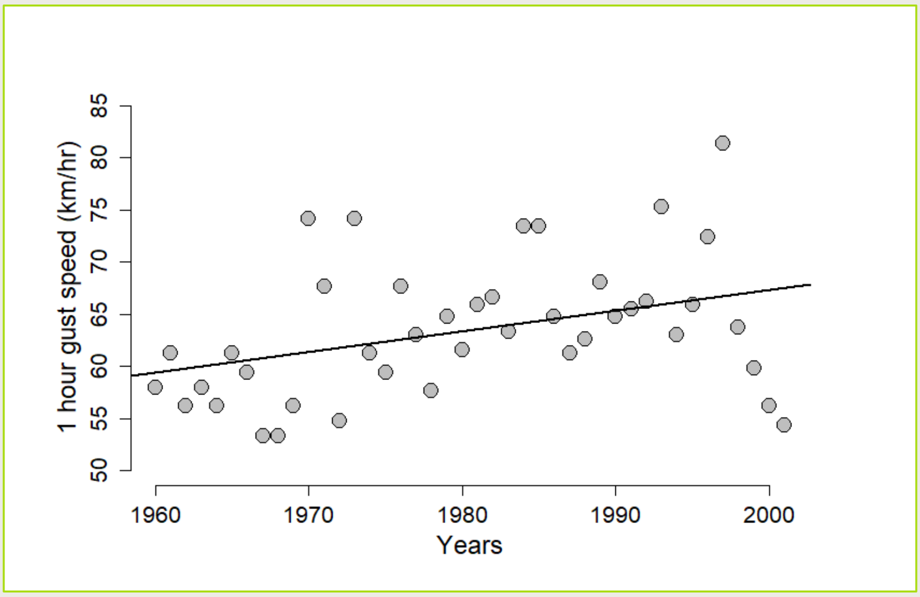
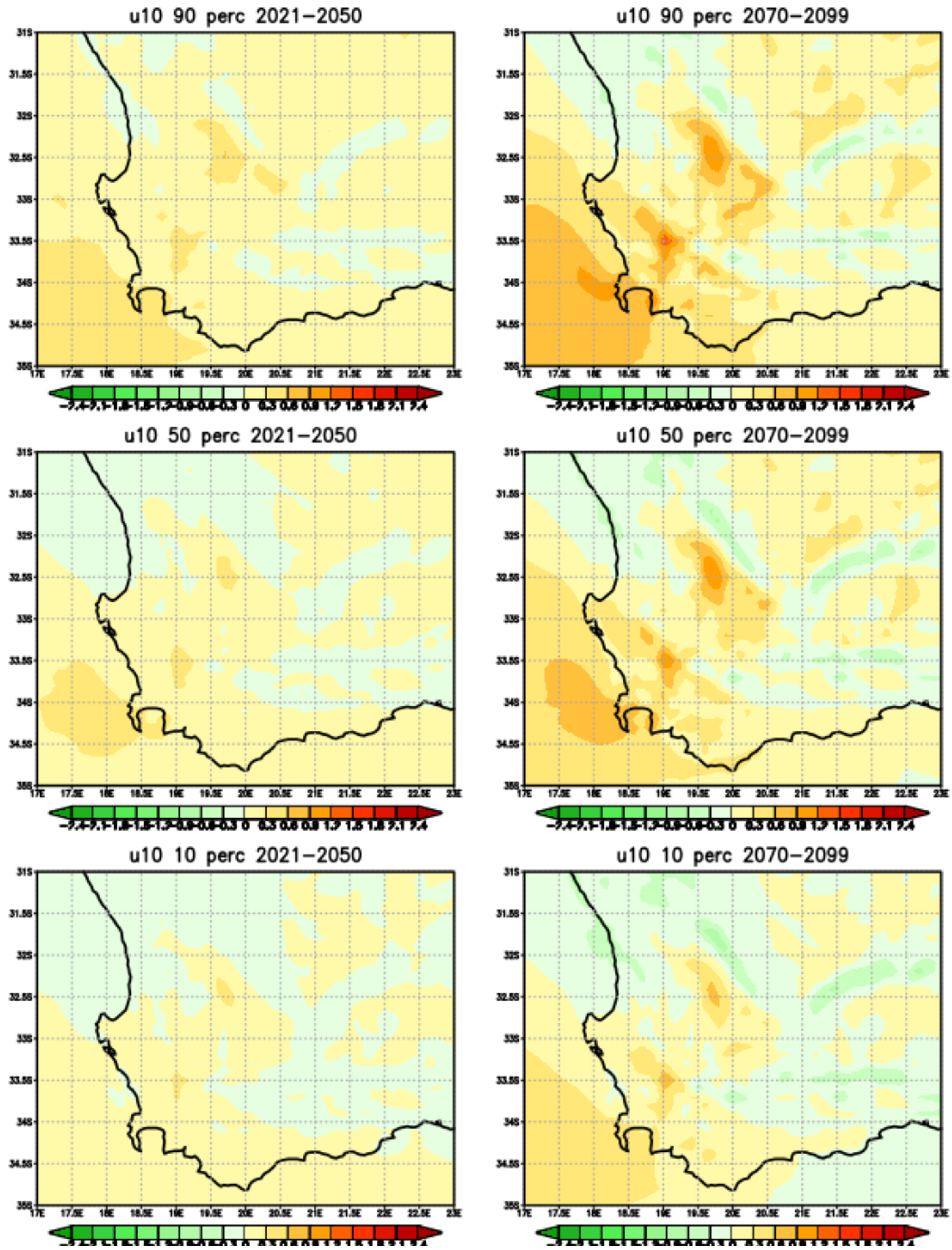


Figure 13: Projected change in the annual average wind speed (m/s)



Projected change in the annual average wind speed (m/s) over the southwestern Cape in South Africa at 8 km resolution, for the time period 2021-2050 relative to 1961-1990 (left) and for 2070-2099 relative to 1961-1990 (right). The 10th, 50th and 90th percentiles are shown under a low mitigation scenario (RCP8.5).

B.2.8 Sea-level Rise and Coastal Storms

South Africa's Third National Communication on Climate Change (2018) states that the observed rate of sea-level rise along the west coast of South Africa over the last few decades was recorded to be 1.87 mm/year, with a rate of +1.48 mm/year recorded on the south coast. These values are somewhat lower than the global rate of sea-level rise. However, both the global rate of sea-level rise and the regional rates of sea-level rise along the South African coastline are likely to increase during the 21st century under enhanced levels of global warming.

A general southward displacement in the Southern Hemisphere westerlies is projected under low mitigation climate change futures. This change is to occur in association with a southward displacement of the Southern Hemisphere storm tracks, including the frontal systems that bring rain to the southwestern Cape and the Cape south coast of South Africa (Engelbrecht et al. 2009). It is this poleward displacement of the Southern Hemisphere westerlies that is the main reason for the expected decreases in rainfall over the winter rainfall region of South Africa (e.g. Christensen et al. 2007; Engelbrecht et al. 2009; Niang et al. 2014; Hoegh-Guldberg et al. 2018). A further consequence of the poleward migration of the Southern Hemisphere westerlies is a projected decrease in the number of cold-core cut-off low pressure systems occurring over southern Africa (Engelbrecht et al. 2013).

A consequence of these changes is that coastal erosion events caused by wind-waves and swells associated with deep low-pressure systems occurring close to the west coast or Cape south coast may plausibly occur less frequently under climate change. However, this does not imply that the risks for coastal erosion will diminish in a changing climate. In fact, under a systematic poleward displacement of the westerlies, southeasterly winds are to occur more frequently over the southwestern Cape, which may lead to slight increases in annual average wind speed over the region (Figure 13, on the previous page). Such a change in average synoptic circulation would also imply changes in the prevailing directions of wind waves and swell impacting on the west coast and Cape south coast. In fact, a recent study based on altimeter readings detected increases in wave height along the west coast and south coast of the southwestern Cape over the period 1985-2018 (Young and Ribal, 2019). The magnitude of these changes is in the order of 2 cm/s/yr and 4 cm/s/yr for average and extreme winds, respectively. Corresponding increases can be detected on the Cape south coast in average significant wave height and extreme values of significant wave height, with the trends being in the order of 0.33 cm/yr and 1 cm/yr, respectively (Young and Ribal, 2019). Given that these increases in significant wave height are also to occur in conjunction with changes in the prevailing direction of wind-waves and swell, the associated impacts on coast erosion and also on sedimentation in harbours need to be investigated rigorously. Numerical projections of the quantitative changes in wind waves and swells (periodicities and amplitudes) under climate change and associated impacts (coastal erosion, sedimentation and operations) remain largely unexplored for all South African harbours.

Sea-level rise inundation projections that were derived from basic contour inundation models are used to provide greater spatial distribution of sea-level rise risk across the City of Cape Town. These projections are captured in the Risk and Vulnerability Assessment in Section C.

B.3 Climate Hazard Assessment: Cape Town

Climate-induced hazards or high-impact weather events pose a significant risk to Cape Town in the context of climate change under a low-mitigation future. Impacts will be both direct (e.g. human health impacts of increasing temperatures and heat-waves; water security impacts of increasing drought frequencies) and indirect (e.g. food security impacts of increasing temperatures and decreasing rainfall in agricultural areas; increased in-migration resulting from threats to rural livelihoods). These indirect impacts or knock-on effects will manifest both within and beyond the boundaries of Cape Town, thus understanding future climate change projections within and beyond City limits is critical. Especially considering some of the projected impacts of climate change are partially moderated in the City region due to the influence of the near-proximity to the ocean.

Based on the assessment of projected changes in climate and associated hazards for the southwestern Cape (Section B.2), specific impacts on Cape Town can be summarised as shown in Table 3, noting that there is notable variation within the City boundaries (discussed further in Section C).

Table 3: Impact of projected climate change and associated hazards on Cape Town

Climate Variable	Projected Impact on Cape Town	
	Mid-Future Period (2021-2050)	**Far-Future Period (2070-2099)**
Average, maximum and minimum temperature	**↑ 1-3 °C**	**↑ 3-4 °C**
Very hot days	**↑ 0-20 Days**	**↑ 0-50**
Heat-wave days	**↑ 0-10 Days**	**↑ 0-20 Days**
High fire-danger days	**↑ 0-20 Days**	**↑ 0-60 Days**
Mean Annual Rainfall	**↓ 60-120 mm**	**↓ 80-160+ mm**
Extreme Rainfall days	**↓ 0-3 Days**	**↓ 0-5 Days**
Average Wind Speed	**↑ 0-0.3 m/s**	**↑ 0.6-0.9 m/s**

For the most part, this assessment corroborates the research findings related to climate change risks for Cape Town (discussed in Section B.1). Specifically:

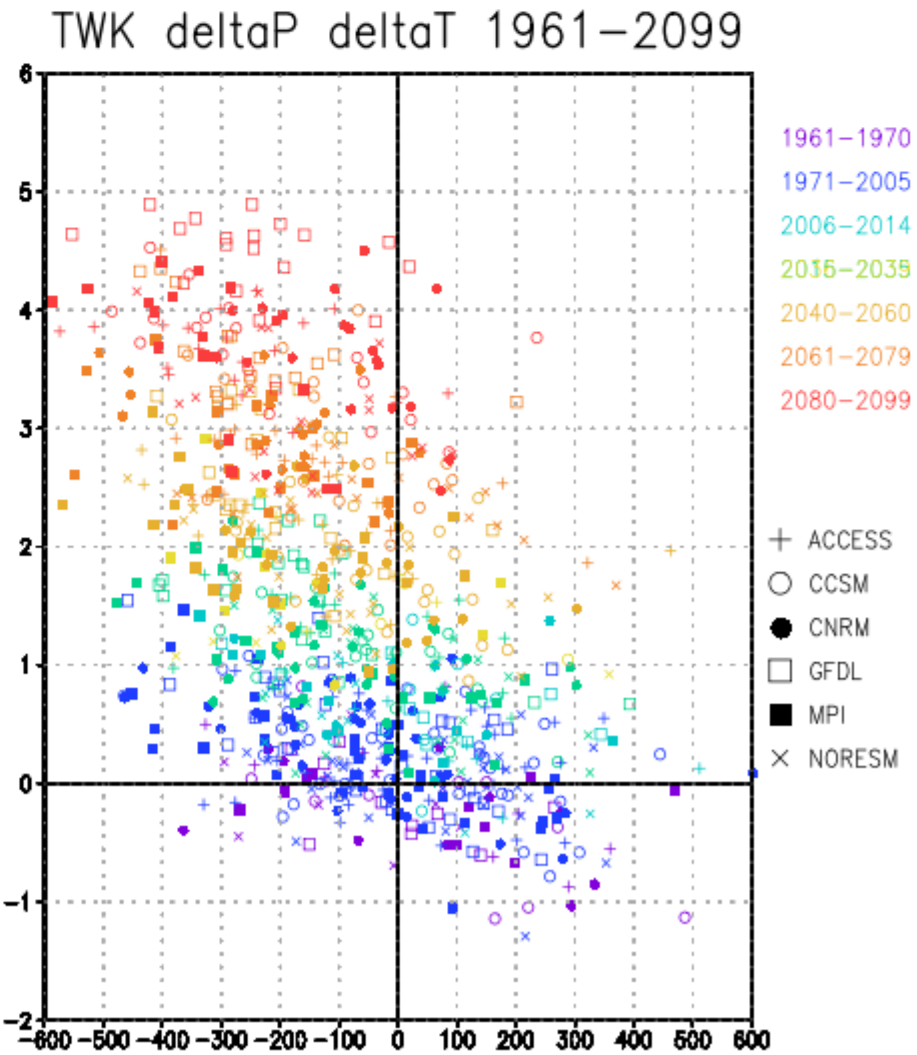
- a decrease in annual average rainfall;
- a change in the seasonality of rainfall, as the primary winter rainfall generating mechanism becomes weaker;
- an increase in mean annual average, maximum and minimum temperatures;
- more hot days, heat-waves and high fire-danger days; and
- an increase in average wind speeds.

However, these findings reveal that over the City area, the frequency of heavy rainfall events is expected to systematically decline as we progress through the 21st century. Our research finds no evidence to support the notion that heavy rainfall events are likely to become more frequent over time. It is essential to understand how these projected changes in climate translate into potential hazards when assessing risk and vulnerability and planning for both resilience-building and disaster response investments.

B.3.1 Combined Temperature and Rainfall Stressors

Figure 14 illustrates the combined projected changes in rainfall and temperature over time for the southwestern Cape. These multiple ensembles show the projected trends towards lower rainfall and higher temperatures in the future. Of particular importance is the rate at which average rainfall and temperature is changing and the relative levels of uncertainty between model projections. Overall, the general trend is towards a significantly hotter and somewhat drier future, which will influence multiple climate-related hazards that may threaten Cape Town in one way or another.

Figure 14: Simulated trends in anomalies in average annual rainfall (x-axis) and temperature (y-axis)



Simulated trends in average annual temperature anomalies (y-axis) and annual rainfall anomalies (x-axis) for the historical period 1961-2099 (bias-corrected using observations) and projected trends until 2099, under a low-mitigation scenario (RCP8.5).

B.3.2 Drought

Meteorological drought, or lower than average rainfall over an extended period of time, is the primary first order climate-related hazard threatening Cape Town. Moreover, decreases in extreme rainfall events, typically the types of rainfall events that induce large amounts of run-off and thereby drive streamflow, are projected. It is likely that the return period of multi-year droughts such as the 2015-2017 drought in Cape Town will decrease during the 21st century, including the mid-future period of 2021-2050. In other words, the likelihood of these multi-year droughts occurring in the future is increasing (i.e. it is likely they will occur more often going into the mid and late periods of the 21st century).

These meteorological drought conditions are compounded by increasing temperatures which increase evapotranspiration and evaporation, leading to decreased overall water supplies and streamflow (i.e. hydrological drought), as well as soil water deficiencies and resulting plant water stress (i.e. agricultural drought). Moreover, these combined stressors on natural available water supplies lead to **multiple stressors across ecosystems** (i.e. ecological drought).

The vulnerability of the City of Cape Town to the occurrence of multi-year droughts has recently been seen, in the 2015-2017 drought, which came close to causing the city to run out of water (the so called "day zero"). Figure 14, on the previous page, indicates significantly enhanced risks of day zero events occurring over the next 30 years, and increasingly so deeper into the 21st century. It has been estimated that the probability of such severe droughts occurring has already increased by a factor of 3 as a consequence of anthropogenic induced climate change (Otto et al., 2018). Box 5 below outlines some of the key global and regional climate drivers that influence the likelihood of drought in the Western Cape Region.

Box 5: Global and Regional Climate Drivers

Oceanic oscillations are large-scale changes in sea-level air pressure, sea temperature and wind direction, over time scales of several months up to several decades. These changes tend to oscillate between one state and another (hence the term oscillation) and be characterised by shifts of cool and warm (relatively) pools of ocean water. These oscillations are associated with changes in weather over land elsewhere and of importance to southern Africa, control the intensity of wet and dry seasons.

El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM) or Antarctic Oscillation (AAO) - these two are essentially the same, and the Atlantic Meridional Overturning (AMO), are the ocean-climate oscillations that have an influence on the seasonal weather of southern Africa.

Of all the oscillations, winter rainfall in the south-western Cape region is likely most strongly related to the state of the AAO (Reason and Rouault, 2005). For the period 1948 – 2004, six of the eighth driest winters occurred during a positive AAO phases, which are negative pressure anomalies over the Antarctica and positive pressure anomalies over the mid-latitudes. The state of the AAO has the strongest effects on south-western Cape weather because it is related to shifts in the sub-tropical jet, to changes in fluxes of atmospheric moisture above the surrounding oceans and which in turn alters low-level convergence, mid-level atmospheric lift and vorticity, all of which control the amount of moisture available in the atmosphere for precipitation (Reason and Rouault, 2005).

There is some hint of an effect on Western Cape droughts by the IOD and AMO (Richman and Leslie, 2018), but this relationship is relatively weak. The El Niño phase of ENSO has a negative relationship to Western Cape rainfall, such that during an El Niño, the Western Cape tends to get increased rainfall (Philippon et al., 2012).

Using proxy records Abram et al. (2014) show that the AAO is at its strongest positive point for a millennium and has been increasingly positive for the last 500 years, the trends being attributed to anthropogenic climate forcing. The increasingly positive the AAO index implies declining rainfalls in the Western Cape.

Smoothed AAO indices and annual rainfall values in the Western Cape have a relatively strong correlation, which is strengthened if the AAO index leads rainfall by two years, indicating the possibility of using the AAO as a leading indicator of possible multi-year droughts and thus providing forewarning to water resource managers (Reason and Rouault, 2005). More work is required on this promising relationship.

To directly link the projected changes in rainfall to future dam levels, state-of-the art hydrological modelling of streamflow in combination with water yield modelling of the Theewaterskloof and Berg River dams should be applied, with these simulations forced by detailed projections of future rainfall and temperature patterns over the catchments. Such a modelling system also needs to include different options for decision making in terms of managing dam levels, human behaviour in terms of water use, water allocation strategies and future population and urban growth of the City of Cape Town. Although such a modelling endeavour falls outside the scope of this project, the basic concepts may be illustrated through the application of a first order statistical model that links future dam levels to streamflow.

Projected future Theewaterskloof Dam levels for the period 1961-2100 (y-axis) as a function of annual rainfall anomalies (x-axis) are shown in Figure 15. The rainfall anomalies are based on the 1961-1990 baseline period, as before. This statistical model is comprised of three basic responses of Theewaterskloof dam level to rainfall:

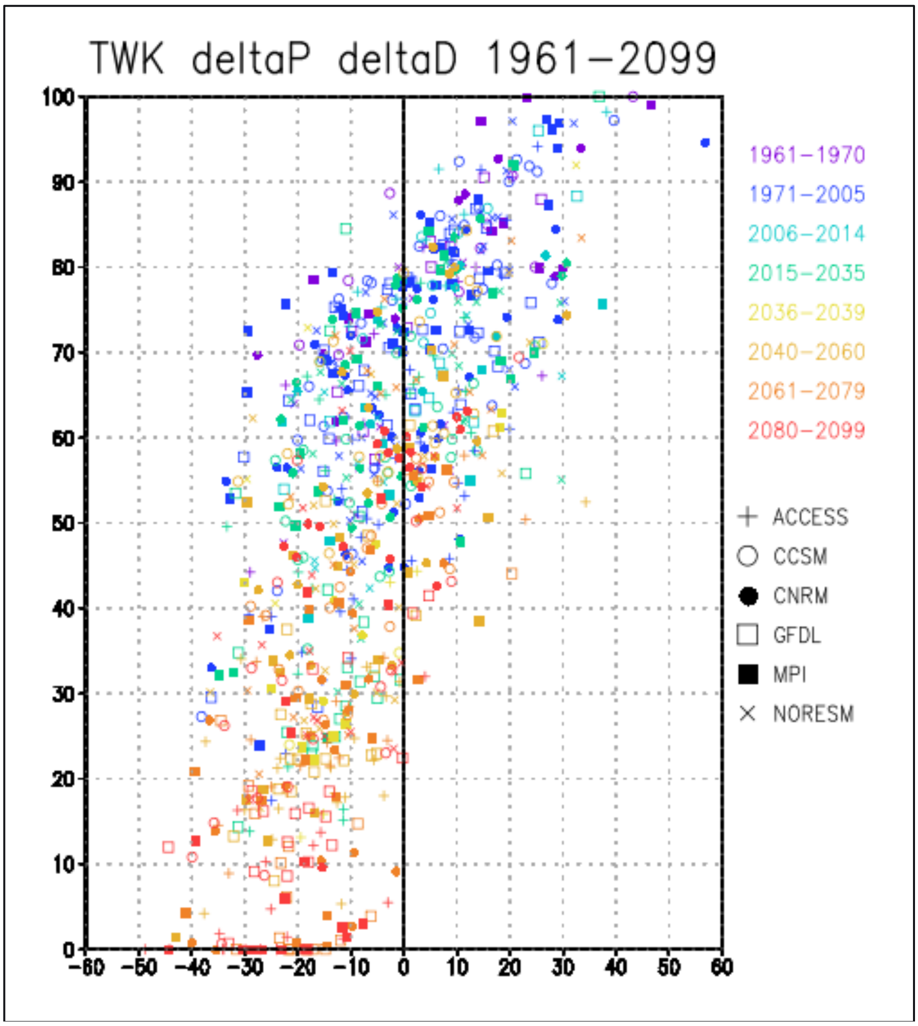
i) when the dam level is high with no immediate threat of drought, dam levels fall or rise in linear correlation to rainfall, as observed during such years;

ii) when dam levels approach the full capacity, water usage increases; and

iii) when dam levels drop to below 50%, water usage greatly decreases.

Under such straightforward modelled responses of dam level to rainfall and the existing state of water security, the statistical model suggests the possible occurrence of day zero events (where dam levels drop to below 20%) already for the period 2015-2035. Such events are projected to occur with increasing frequency deeper into the 21st century. Although this first order statistical model should not be applied for quantitative planning, it serves to demonstrate the sobering realisation that the CCT is in the need of transformational adaptation in terms of its future water security.

Figure 15: Simulated trends in anomalies in rainfall (x-axis) and dam levels (y-axis): Theewaterskloof



Model simulated trends in average annual Theewaterskloof dam levels (y-axis) and annual rainfall anomalies (x-axis) for the historical period 1961-2099 (bias-corrected using observations) and projected trends until 2099 (RCP8.5 emission scenario).

B.3.3 Fires

Fires are another major climate-related hazard threatening Cape Town. The drastic increases projected in the number of high fire-danger days are to a large extent driven by increases in temperature. Both natural fires (veld fires) and urban fires are likely to become more frequent as a direct result of a changing climate. High temperatures, low humidity or available moisture and high windspeeds all contribute towards higher risks of fire. Greater wind strength and prolonged winds create further challenges for fighting and containing fires that have started, which ultimately will influence the potential damage fires can cause. Apart from the obvious risk to human life and health, and to properties and informal settlements and public infrastructure, fires present a significant environmental risk to the Cape Floral Kingdom. Moreover, heatwaves are a significant climate hazard projected to increase throughout the 21st century, which presents further risks to human, plant and animal health, as well as increased demand for water and electricity, among others.

B.3.4 Extreme rainfall events and flooding

On the other hand, extreme rainfall days are projected to systematically decline as a result of climate change. This finding diverges from previous findings that projected an increase in the intensity and frequency of high-intensity rainfall events. It is important to note that this finding is based on the change in the primary rainfall-generating mechanism (i.e. mid-latitude cyclones bringing frontal rainfall moving southward). This is despite observed data in extreme rainfall events throughout the Western Cape Province showing a slight positive trend from the first to the second half of the 20th century (De Waal et al. 2017). Figure 14 above further emphasises the relative uncertainty of the future rainfall projections. Nevertheless, it is critical to incorporate the most advanced scientific knowledge available to date when planning adaptation investments, especially in the rapidly advancing field of climate science.

Based on these projected reductions in extreme rainfall days, it is plausible that all types of flooding are likely to systematically decrease within Cape Town as we move further into the 21st century. However, the extent and magnitude of flood events – be it fluvial (riverine), coastal or pluvial (surface water) – are influenced by numerous biophysical, infrastructural and meteorological factors aside from rainfall. Moreover, a decrease in extreme rainfall days and the storm events associated with them, will likely reduce coastal erosion impacts that result from coastal storm conditions. However, if observed trends continue and extreme rainfall days continue to increase slightly, these all types of flooding events are likely to have greater impacts. Again, it is critical to acknowledge the multiplicity of environmental and human influences on the extent and magnitude of coastal erosion aside from rainfall.

For example, changes in wind and swell direction and strength were cited as factors that have increased impacts of coastal erosion in recent years at the Participatory Analysis Workshop with CCT. Ultimately this highlights the complex environmental and biophysical interlinkages between changes in climate phenomena and their associated influences on hazards that threaten the City. It is out of the scope of this study to develop and include a detailed wave and swell model or integrated flood model, which attempt to account for the myriad of causal pathways of effect through complex systems. Therefore, the role of flooding, sea-level rise and changes in wind patterns and strength will be further assessed through the following R&V assessment (Section C), whether through empirical data or expert analysis of the key risks and associated causal impact pathways.

C. Risk and Vulnerability Assessment

C.1 Overview

The assessment of climate change risk and vulnerability in and around Cape Town builds directly off the hazard assessment and climate change projections. Based on the overarching adaptive management approach adopted to undertake this study, the technical approach towards assessing climate change risk and vulnerability has evolved.

Vulnerability to climate change is assessed as a function of **exposure** to climate impacts, and the level of **resilience** of the impacted systems. These terms are explained under the relevant sections that follow. The resilience assessment is a combination of relative **adaptive capacity** and **sensitivity indicators**. This is for two main reasons:

- The concept of resilience is well developed and entrenched in CCT (the City will launch its Resilience Strategy in 2019 and has already adopted the 100 Resilience Indicators, developed by the Rockefeller Foundation);
- The notion of resilience is better suited to urban environments where there are overlaps between many indicators of sensitivity and adaptive capacity (as discussed in the project Inception Workshop).

This section presents and discusses the initial outcomes of the R&V assessment. Relative levels of exposure, resilience and vulnerability are presented graphically in maps extending over the broader southwestern Cape region, focusing on Cape Town. Box 6 below explains how to interpret these maps.

Box 6: Interpreting the risk and vulnerability maps

For the **exposure summary maps** (see Figures 16, 17 and 18), yellow reflects relatively high exposure and purple indicates relatively low levels of exposure. This is despite the fact that all areas within the project extent are projected to be exposed to negative changes in climate. The exposure summary maps are scaled from low to high across the three different time periods (current, mid-future and far-future). Hence, exposure over the region is seen to systematically increase over time as the effects of anthropogenic climate change take hold. The same colour scheme applies for the **vulnerability hotspot maps** ((see Section C.4, Vulnerability Assessment: Figures 21, 22 and 23).

In the **resilience summary map** (see Figure 20): blue reflects high levels of resilience, whereas red indicates relatively lower levels. It is important to note that the extent of the exposure assessment is greater than the City boundaries, whereas the resilience assessment was limited to the spatial limits of the Cape Town Municipality.

The scoring and associated colour gradients affect the relative intensity of colours, so that areas of deep blue or red cannot be directly compared with each other in terms of intensity, between different indicators. For example, even though certain areas show up as dark red for low levels of the 'access to electricity' indicator, the absolute level of access to electricity might still be considered generally high. It is only low in relation to other areas of the City. The relative levels of exposure, resilience or vulnerability can only effectively be compared within an individual map and through the assessment of the underlying drivers (i.e. different indicators that contribute to resilience and exposure). Moreover, the R&V summary maps do not illustrate absolute levels of vulnerability in relation to global benchmarks. This means that even though some areas may appear less vulnerable than others to climate change, they are likely vulnerable to different impacts of climate change in one way or another, and vice-versa.

Note: Maps of Cape Town's Major Suburbs are shown in Appendix 2 for reference throughout this section.

This section presents and describes how the project team carried out the cumulative risk assessment in terms of overlaying the different indicators of exposure and resilience. Moreover, the ranking of risks and most vulnerable areas is discussed in relation to the outcomes of the R&V assessment.

C.2 Exposure Assessment

Exposure is defined as the presence (location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage (Lavell et al., 2012: 32).

All the summary maps including exposure (current, mid-future and far-future), resilience and vulnerability hotspots, together with their respective algorithms can be found in Appendix 3.

Figures 16, 17 and 18 illustrate the composite exposure assessment maps for the current, mid-future and far-future time period.

These composite exposure maps show the following:

- Areas further inland from the coast are more exposed in general to current climate variability and climate-related hazards, particularly areas to the east and northeast of the City.
- Within the City boundaries, the northern and eastern extremities show the highest levels of combined exposure, covering areas such as Mamre, Stellenbosch Farms and Strand. Smaller pockets of high relative exposure can be found in central areas of the City going into the far-future.
- Other smaller areas showing relatively high levels of exposure include Paarden Island, Observatory, Pinelands, Stellenbosch Farms, Brooklyn, Maitland, Sir Lowry's Pass and Gordon's Bay.
- Areas that demonstrate relatively low levels of exposure include Cape Point, Simon's Town, Kommetjie, Noordhoek, Camps Bay, Sea Point, Signal Hill / Lions Head, Green Point, Pelikan Park, Mitchell's Plain, Kalk Bay and Melkbosstrand.

However, to understand the underlying drivers of these relative levels of exposure, the various indicators of exposure need to be explored in greater depth, in the following section (see Section C.2.1).

Figure 16: Exposure to Harms Summary Map (Current Conditions)

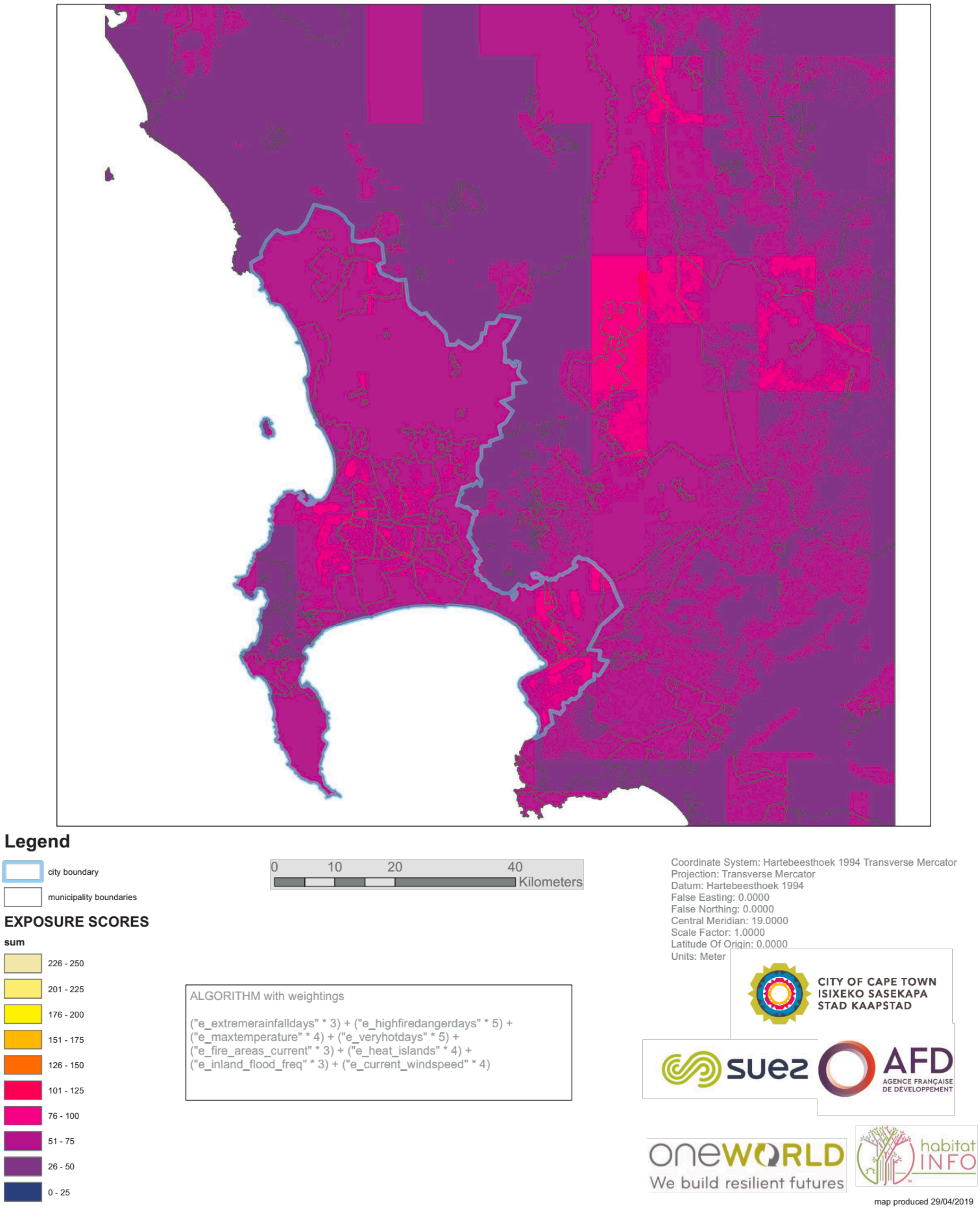


Figure 17: Exposure to Harms Summary Map (Mid-future Conditions).

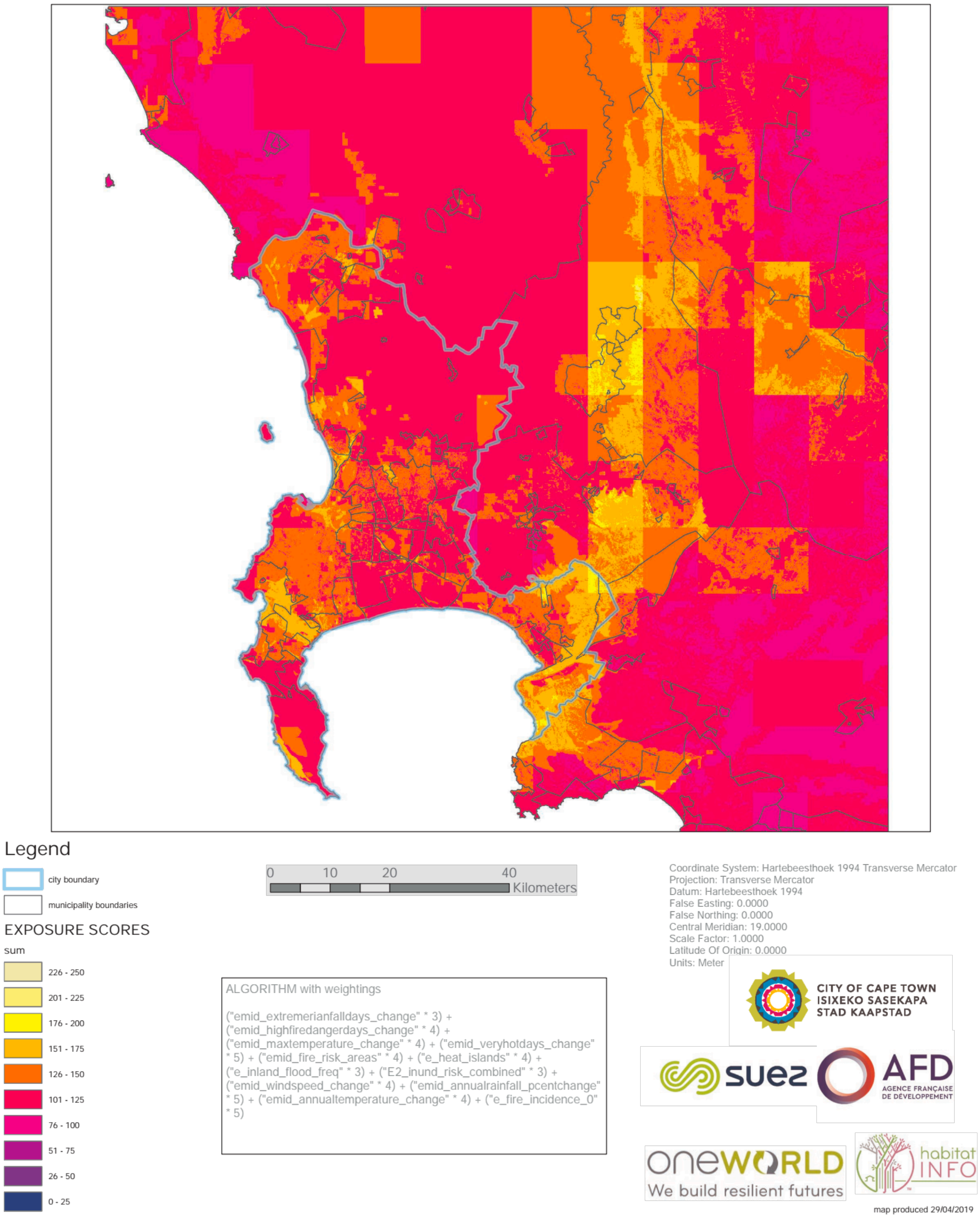
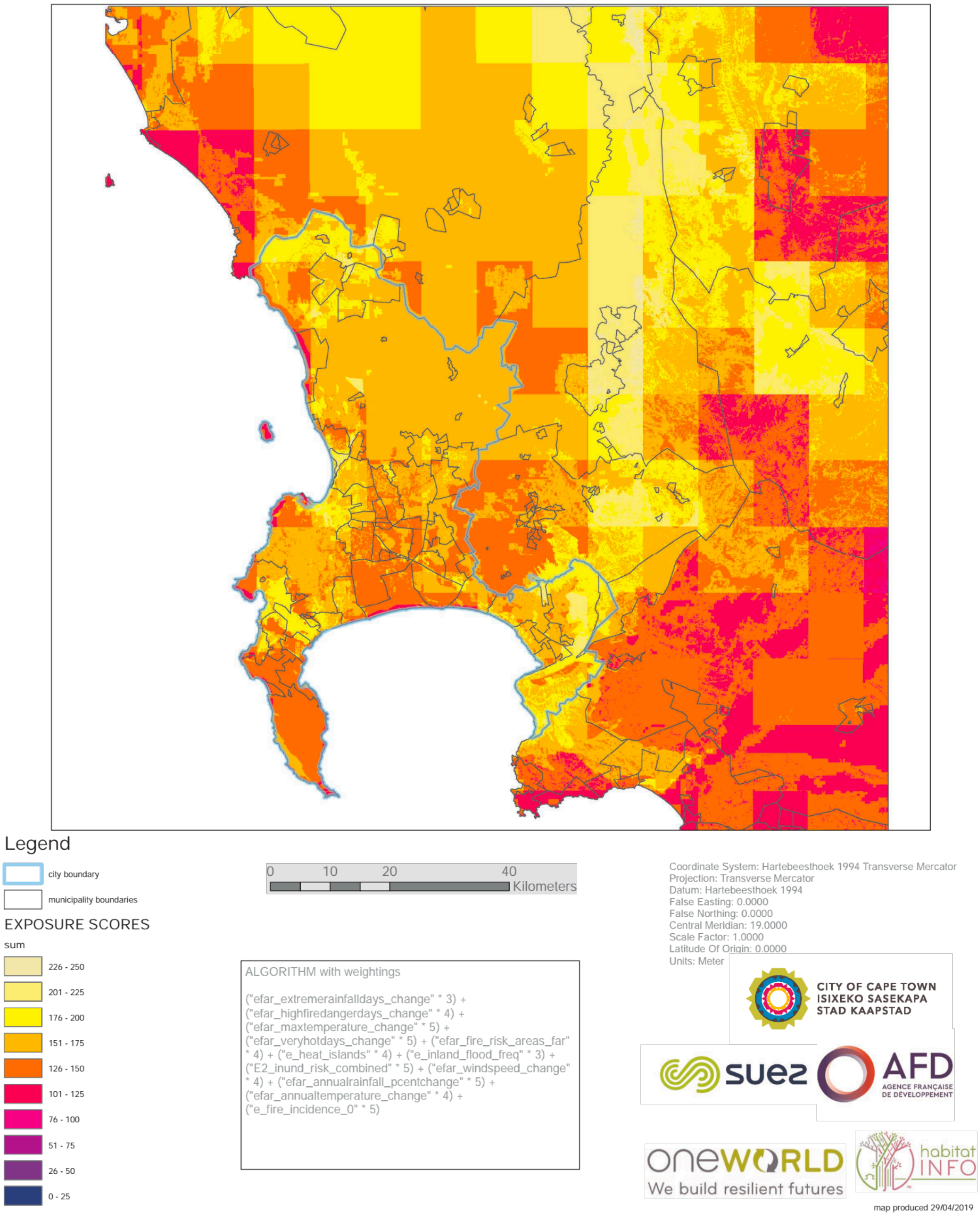


Figure 18: Exposure to Harms Summary Map (Far-future Conditions)



C.2.1 Indicators of Exposure

Table 4 outlines the various indicators of exposure and their associated weightings for the three different time periods of assessment. The table therefore illustrates how the climate projections have been interpreted into the R&V model, amongst other key indicators. The maps showing the spatial distribution of these various input indicators of exposure are provided in Appendix 4.

The weighting scale ranges from 1 (lowest weighting) to 5 (highest weighting) for each indicator that makes up exposure (and resilience discussed below). These weightings are determined by three key aspects, as informed by the background research and stakeholder engagement:

- Relevance to the region/area
- Confidence in the accuracy of the data
- The spatial resolution of the data

Exploring these underlying indicators reveals the different drivers of exposure and their associated causal pathways, which ultimately demonstrate the cumulative nature of the assessment and how cumulative exposures to different climate-related harms manifest within the model, to generate the composite exposure summary maps (Figures 16, 17 and 18).

Drivers of exposure differ for different areas. This can be seen in the case of the Malmesbury Farms on one hand, and Observatory area on the other. Although both these areas exhibit relatively high levels of exposure to harms, the underlying drivers of exposure are different and thus the risks manifest through different causal pathways. From examining the input maps in Appendix 4, it is evident that high levels of overall exposure in the Malmesbury Farms area are primarily being driven by relatively high numbers of high fire-danger days, high maximum temperatures and high numbers of very hot days. By contrast, exposure to harms in Observatory is largely being driven by strong heat island effects, moderately high numbers of extreme rainfall days and high maximum temperatures.

Table 4: Indicators of Exposure.

Time Period	Indicator	Description	Weighting
Current	Extreme Rainfall Days	Number of days with >20mm of rainfall within 24 hrs over an area of 64 km^2 per year.	3
	Fire Risk Areas	Correspondence of combustible fuel load with number of high fire-danger days per year.	4
	Fire Incidence	Incidence of urban and wildfires from 2009-2016.	5
	Heat Islands	Heat island intensity determined by ranking and combining land cover type, solar irradiation and wind speed.	4
	High Fire Risk Days	Number of days McArthur fire-danger index exceeds a value of 24 per year.	5
	Inland Flood Frequency	Combined flood frequency data from 2014-2018.	3
	Maximum Temperature	Mean annual maximum temperature.	4
	Very Hot Days	Number of days when the maximum temperature exceeds 35 °C per year.	5
	Average Windspeed	Average annual windspeed in meters per second (m/s).	4
Mid-Future (2021-2050)	Sea-level Rise Inundation Risk	Combined Shuttle Radar estimates and CCT sea-level rise modelling data showing projected areas of inundation from different levels of sea-level rise.	3
	Rainfall Change (%)	Relative (percentage) decline or increase in rainfall relative to current period.	5
	Mean Temperature Increase	Mean annual temperature increase relative to current period.	4

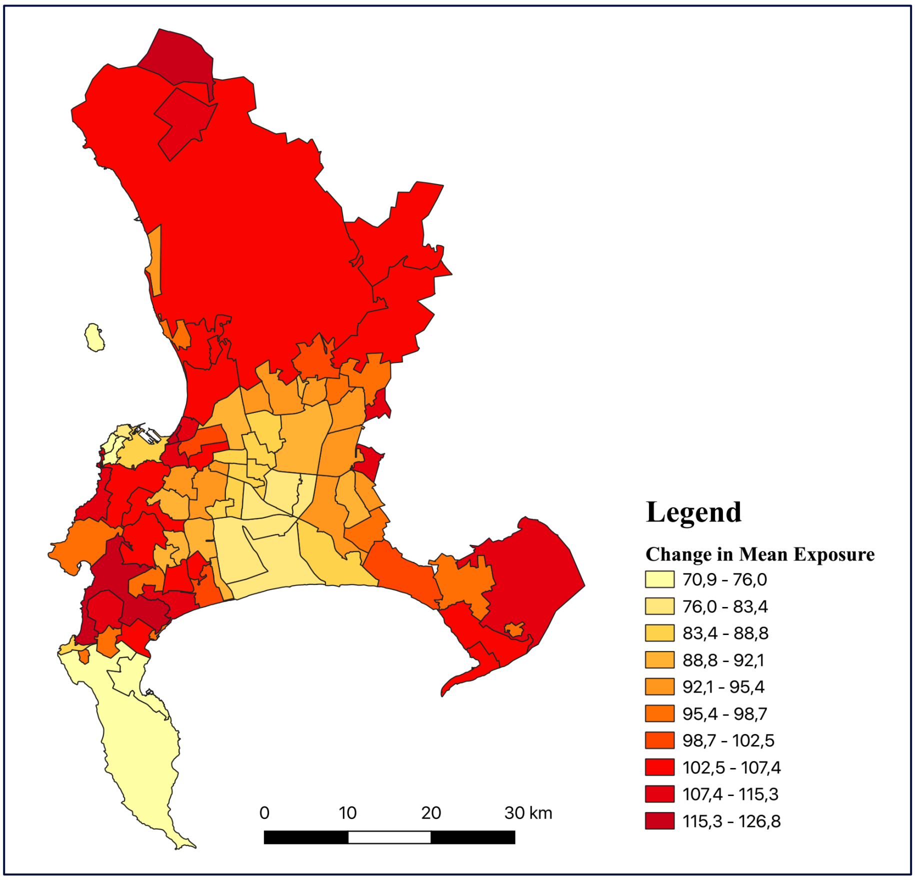
	Extreme Rainfall Days	Projected number of days with >20mm of rainfall within 24 hrs over an area of 64 km^2 per year, relative to current period.	3
	Fire Risk Areas	Correspondence of combustible fuel load with number of high fire-danger days per year.	4
	High Fire Risk Days	Projected number of days McArthur fire-danger index exceeds a value of 24 per year, relative to current period.	4
	Maximum Temperature	Projected mean annual maximum temperature relative to current period.	4
	Very Hot Days	Projected number of days when the maximum temperature exceeds 35°C per year relative to current period.	5
	Average Windspeed	Projected average increase in wind speed relative to current period (m/s).	4
Far-Future (2070-2099)	Rainfall Decline (%)	Relative (percentage) decline in rainfall relative to current period.	5
	Mean Temperature	Mean annual temperature increase relative to current period.	4
	Extreme Rainfall Days	Projected number of days with >20mm of rainfall within 24 hrs over an area of 64 km^2 per year, relative to current period.	3
	Fire Risk Areas	Correspondence of combustible fuel load with projected number of high fire-danger days per year relative to current conditions.	4
	High Fire Risk Days	Projected number of days McArthur fire-danger index exceeds a value of 24 per year, relative to current period.	4
	Maximum Temperature	Projected mean annual maximum temperature relative to current period.	5
	Very Hot Days	Projected number of days when the maximum temperature exceeds 35°C per year relative to current period.	5
	Average Windspeed	Projected average increase in wind speed relative to current period.	4

C.2.2 Future Exposure

Effective responses to climate change risks necessitate both an understanding of current risks, as well as projected changes in future risk. Figure 19 shows the change in mean exposure from the current to the projected far-future period for Cape Town's Major Suburbs. Although all areas within Cape Town are projected to become relatively more exposed to harms going into the future, exposure in some areas will increase moderately more than others.

For example, when assessing the underlying drivers of far-future exposure (see Figure 19), the differences between the underlying drivers of high levels of future exposure in Constantia and Malmesbury Farms (both appear as dark red in Figure 19) are clear. Exposure in Constantia is largely being driven by extreme rainfall days, fire risk and windspeeds, rainfall decline and temperature increase. By contrast, the main drivers of future exposure for the Malmesbury Farms area are increases in mean and maximum temperatures, increases in high fire-danger days, a high percentage decline in rainfall and increases in very hot days.

Figure 19: Change in mean exposure from the current to the far-future period



C.3 Resilience Assessment

Resilience is defined as 'the capacity of individuals, communities, institutions, businesses and systems within a city to survive, adapt and grow no matter what kind of chronic stresses and acute shocks they experience' (100RC, 2019).

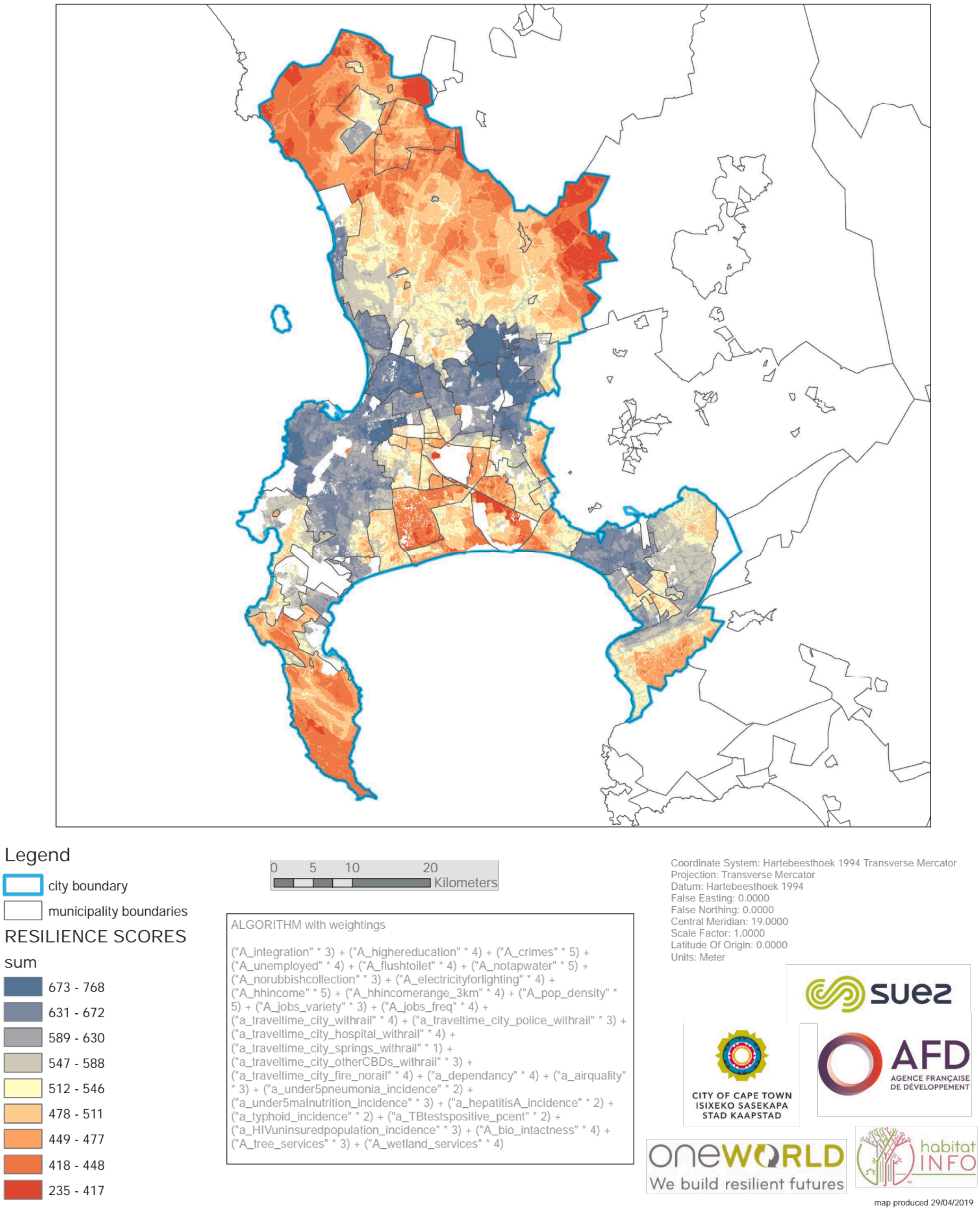
All the summary maps, including exposure (current, mid-future and far-future), resilience and vulnerability hotspots, together with their respective algorithms can be found in Appendix 3. Figure 20 illustrates the composite resilience assessment map.

This composite map shows:

- The spatial distribution of relative levels of economic, social and environmental resilience throughout Cape Town.
- The least resilient areas are found in the northern regions of the City, the 'Cape Flats' and informal settlements, and the southern peninsula to a lesser extent. Specific hotspots of low resilience occur in the suburbs of Philippi, Delft, Blue Downs, Guguletu, Mamre, Langa, Epping, Kalksteenfontein, Khayelitsha, Airport, Bishop Lavis, Cape Farms North, Mitchells Plain, Manenberg, Joostenberg Vlakte and Malmesbury Farms.
- Whereas areas of relatively high resilience occur largely in the higher income residential areas. Specific high-resilience suburbs include: Durbanville, Vredekloof, Eversdal, Pinelands, Newlands, Fish Hoek, Tokai, Kenridge, Brackenfell, Bergvliet, Camps Bay, Somerset West, Wynberg, Melkbos Strand, Kalk Bay, Brooklyn and Muizenberg.

However, as for exposure, to understand the underlying drivers of these relative levels of resilience, the various indicators of resilience need to be explored, in the following section (see Section C.3.1.).

Figure 20: Resilience Summary Map



C.3.1 Indicators of Resilience

Table 5 outlines the various indicators of resilience and their associated weightings. The maps showing the spatial distribution of these various input indicators of resilience are provided in Appendix 5. Exploring these underlying indicators reveals the different drivers of and barriers to resilience and their associated causal pathways. The underlying indicators ultimately demonstrate the cumulative nature of the assessment and how cumulative indicators of resilience manifest within the model to generate the composite summary maps (see resilience summary map in Figure 20).

It is important to note that aside from the differential weighting, not all input indicators are necessarily combined equally to generate the summary map. Where indicators represent the same resilience pathway, these are initially combined into composite indicators and then included in the algorithm as individual treatments. For example, Table 5 shows there are two indicators representing access to potable water ('tap water' and 'tap water inside houses'). Although the indicators are technically measuring different things, they both represent the same resilience pathway (i.e. access to potable water improves resilience to climate shocks and stressors).

An example of different areas with relatively low resilience being driven by different indicators can be seen with Epping and Joostenberg Vlakte. Analysing the underlying drivers of resilience (input maps in Appendix 5) reveals that the relatively low levels of resilience in Epping are being primarily driven by high crime rates, high population density, low access to electricity services, low coverage of flushing toilets, low levels of access to water, poor levels of higher education and poor access to municipal services such as refuse collection. By contrast, the relatively low resilience scores in the Joostenberg Vlakte area are being driven by low diversity of job opportunities, high levels of income inequality and moderate access to municipal services, tap water and electricity.

Table 5: Resilience Indicators.

Indicator	Description	Weighting
Air Quality	Combined average of nitrogen oxide, ozone, sulphur dioxide, carbon monoxide and particulate matter.	3
Crime Rate	Total number of crimes by police precinct area.	5
Dependency	Dependency ratio calculated as the population of non-working age divided by the population of working age.	4
Electricity for Lighting	Percentage of households with access to electricity for lighting.	4
Flushing Toilets	Percentage of households with flush toilets (main sewerage connection and septic tanks).	4
Hepatitis Rate	Incidence of hepatitis in 2017.	2
Median Household Income	Median household income.	5
Range of Household Income within 3km	Measure of income disparity in different neighbourhoods: maximum minus minimum household income within a 3km radius.	4
Higher Education	Percentage of people over the age of 20 with higher education.	4
HIV Rate	Incidence of HIV in 2017.	3
Social Integration	Relative integration of different population groups.	3
Employment Opportunities within 1km	Measure of employment opportunities: ranked zoning areas by potential formal employment opportunities assessed within 1km radius.	4
Employment variety within 1km	Measure of job diversity opportunities: distance from multiple zoning areas related to employment opportunities assessed within 1km radius.	3
Education (no education)	Percentage of the population aged 20+ without any education.	5
Refuse Collection	Percentage of households without municipal refuse collection services.	3
Tap Water	Percentage of households without access to tap water facilities.	5
Toilet Facilities	Percentage of households without access to any toilet facilities.	5
Population Density	Number of people living in an area relative to the size of the area.	5
Tap Water Inside Houses	Percentage of households with tap water inside their house.	4
TB Rate	Incidence of Tuberculosis.	2

Access to Fire Stations	Estimated time required to travel to the nearest fire station.	4
Access Time to Hospitals	Estimated time required to travel to the nearest hospital.	4
Access to Police Stations	Estimated time required to travel to the nearest police station.	3
Access to Freshwater Springs	Estimated time required to travel to the nearest freshwater spring.	1
Access to CBD	Estimated time required to travel to the Central Business District (Cape Town City Centre).	4
Access to All CBDs	Estimated time required to travel to a central employment node within the City of Cape Town.	3
Typhoid Rate	Incidence of Typhoid in 2017.	2
Malnourishment Rate	Incidence of malnourishment in children under 5 years of age.	3
Pneumonia Rate	Incidence of pneumonia in children under 5 years of age.	2
Employment Rate	Percentage of people unemployed in the formal sector.	4
Weekly Solid Waste Collection	Percentage of households with weekly municipal solid waste collection services.	3
Jobs: Population Balance	Measure of job opportunities relative to population densities: combination of job frequency assessment and population densities.	5
Biodiversity Services	Measure of functionality of biodiversity related ecosystem services.	4
Forest and Upper-storey Services	Measure of functionality of forest, tree and upper-story vegetation ecosystem services.	3
Wetland and Watercourse Services	Measure of functionality of wetland and watercourse ecosystem services.	4

C.4 Vulnerability Assessment

Vulnerability is defined as the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including exposure to harm and lack of capacity to cope and adapt (IPCC Glossary, 2014).

Figures 21, 22 and 23 show the composite vulnerability assessment maps, or 'hotspots' maps for the current, mid-future and far-future periods respectively. All the summary maps including exposure (current, mid-future and far-future), resilience and vulnerability hotspots (current, mid-future and far-future), together with their respective algorithms and meta-data can be found in Appendix 3.

The current configuration of the R&V model depicts the north eastern regions of the City to be the most vulnerable to current conditions, with other hotspots occurring around the centre of the Cape Town Municipality and in the far north. The least vulnerable areas are seen in the southern peninsula, southern coast, Table Mountain area and up the west coast.

The future vulnerability hotspots maps show little variation in spatial distribution of vulnerability within Cape Town. It is important to note that these assessments assume a 'business-as-usual' scenario for resilience indicators, that is, that they will remain the same as the current status-quo. Areas that are projected to become more exposed in the future are slightly more vulnerable (specifically in the north eastern parts of the City) and accordingly some areas in the centre of the City area become relatively less vulnerable. However, in absolute terms the entire City will become more vulnerable for both the mid- and far-future periods.

Figure 21: Vulnerability Summary Map (Current Conditions)

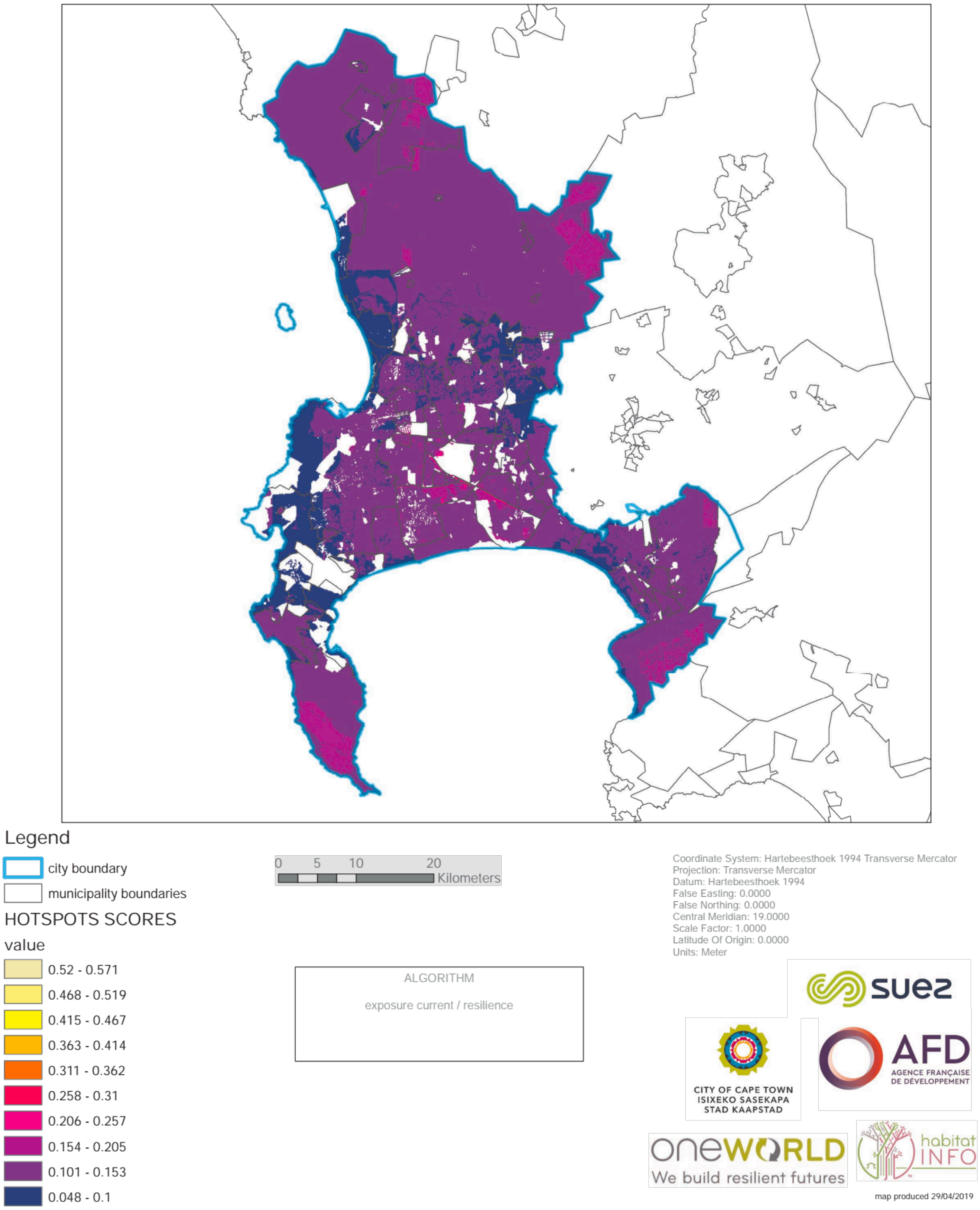


Figure 22: Vulnerability Summary Map (Mid-Future Conditions)

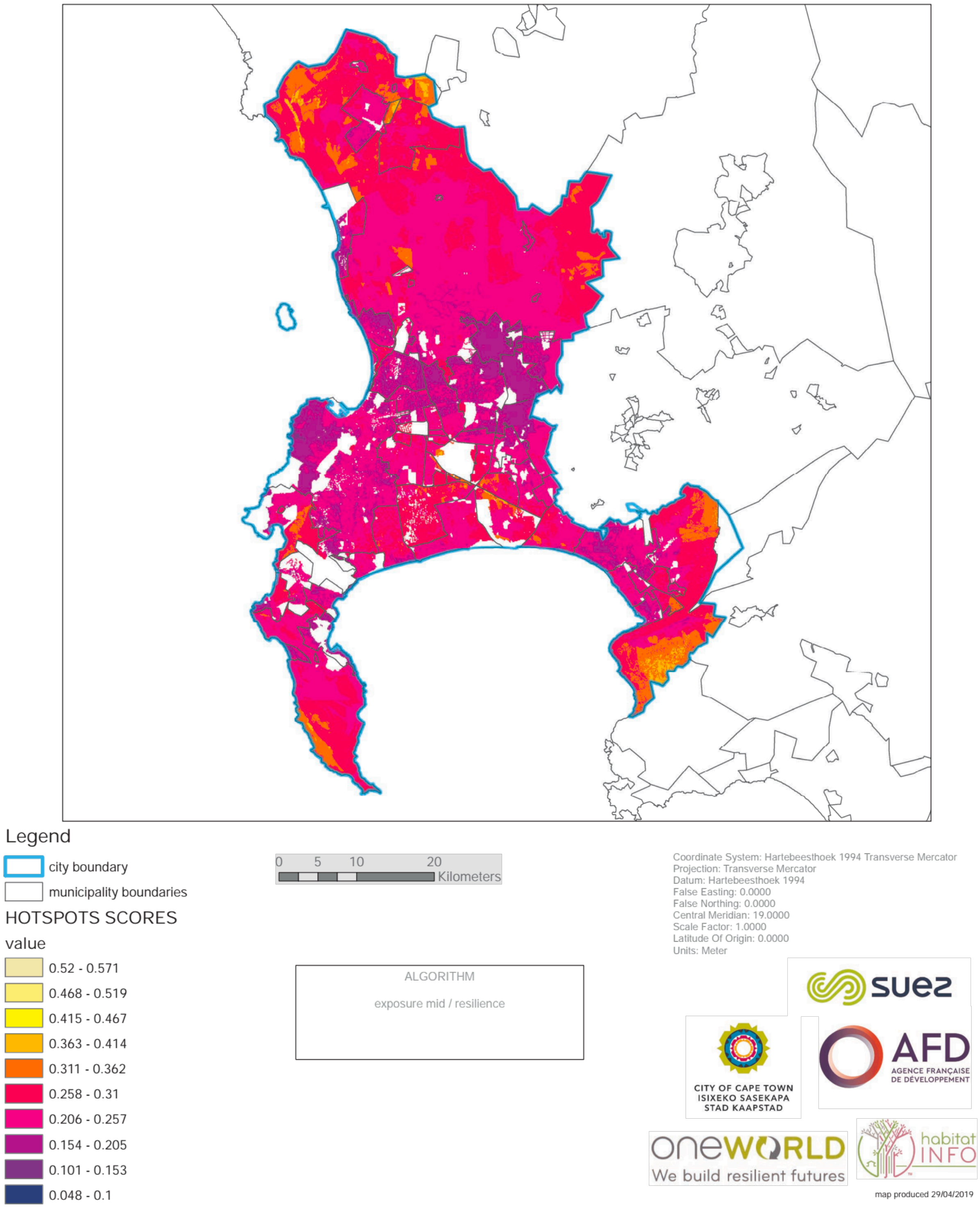
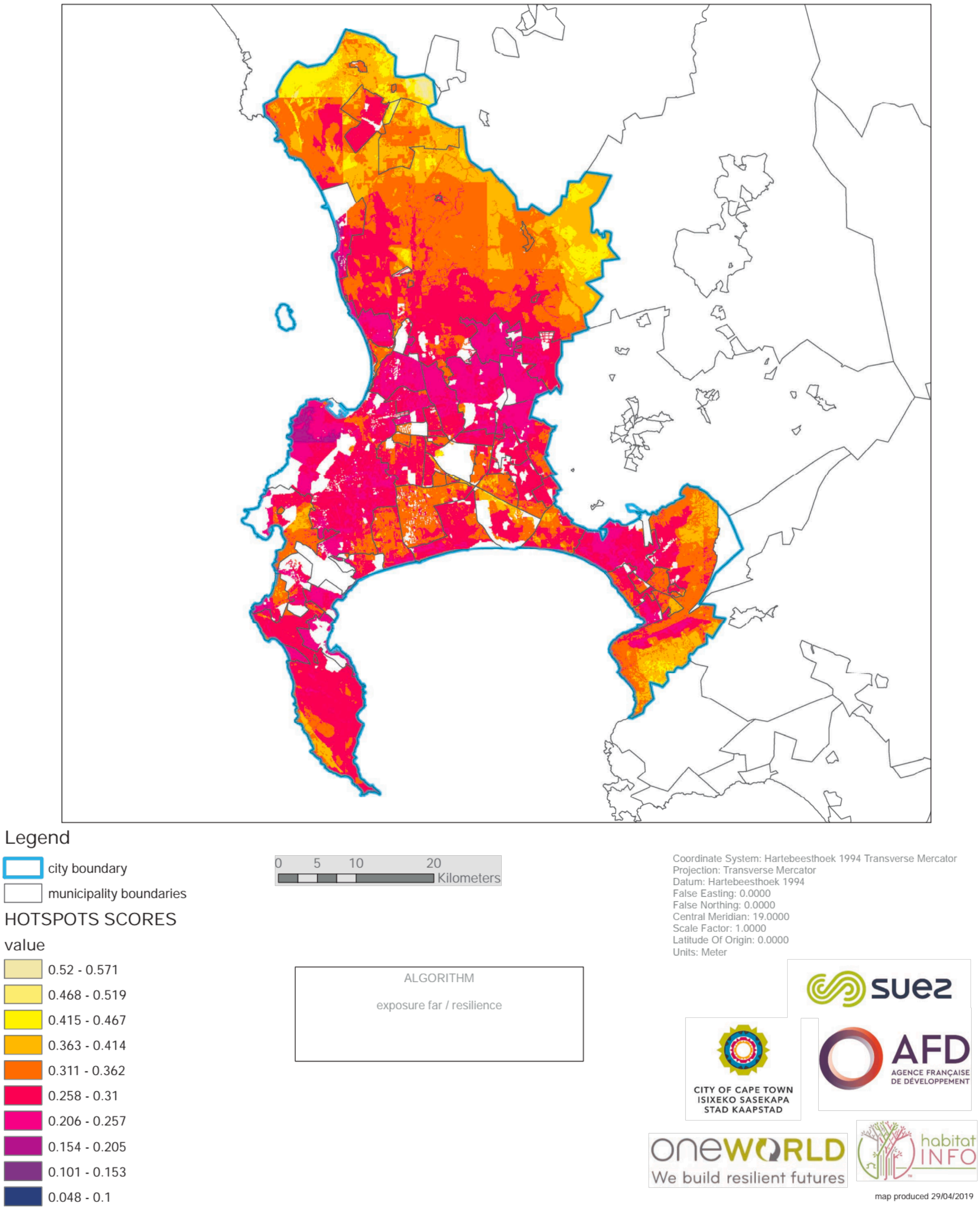


Figure 23: Vulnerability Summary Map (Far-Future Conditions)

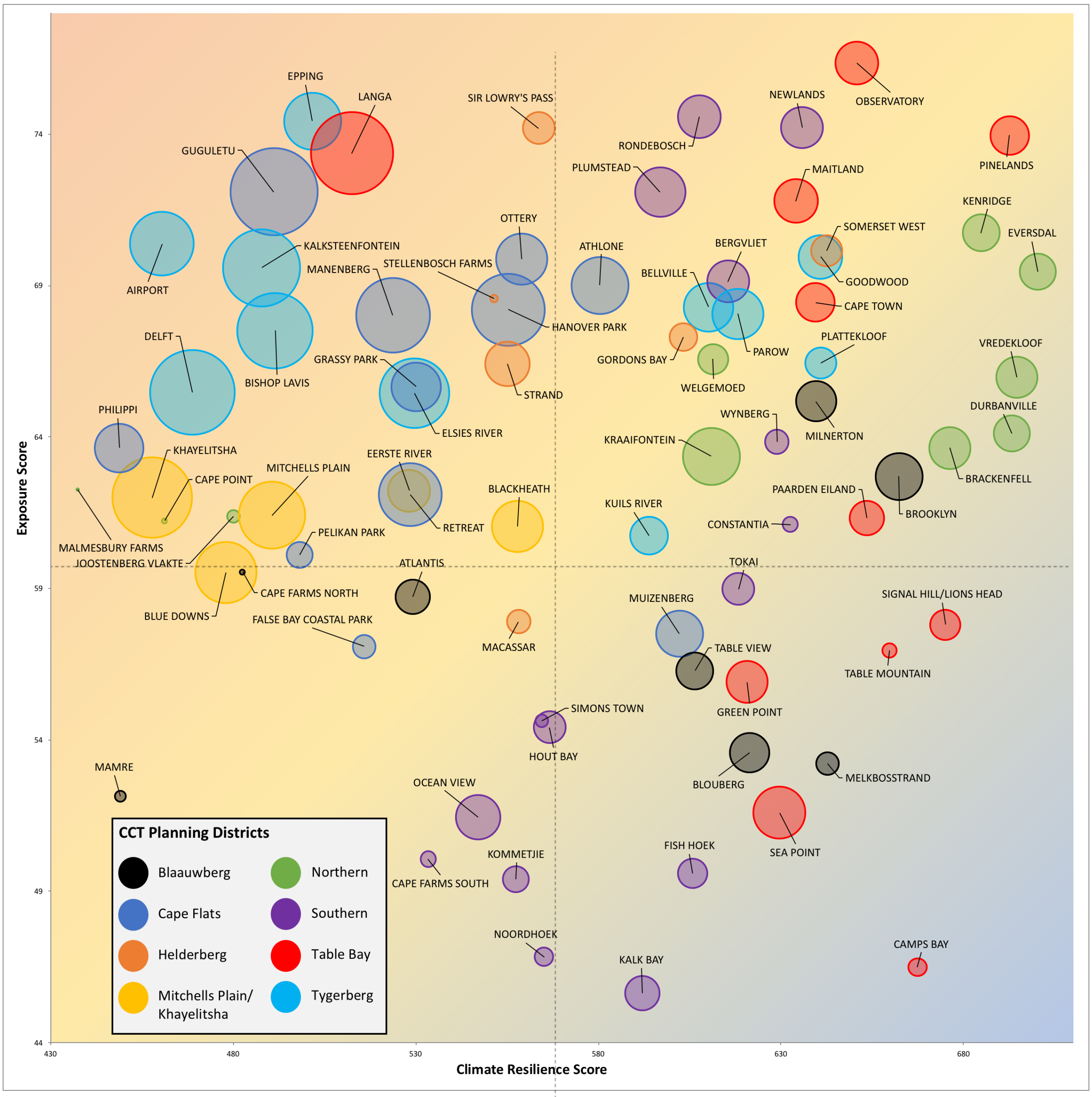


C.4.1 Disaggregating Vulnerability by Major Suburb

Figure 24 presents a vulnerability scatter plot by major suburb in Cape Town, with relative population densities indicated by the size of the bubbles (greater population density = larger bubble). By plotting relative levels of resilience and exposure against one another at the suburb level, it is possible to identify key spatial trends in vulnerability and understand the key drivers of vulnerability in different locations.

Analysing varying levels of vulnerability at this scale has a number of pros and cons. The biggest strength of this analysis is that it allows for spatial differentiation of resilience and exposure for a large number of spatial units, making it easier to identify, rank and prioritise risks and response pathways. Finer resolution spatial units (e.g. census 'small-place' areas) would render the uncertainty of the results too high to be accurately assessed, because much of the input data is captured at a courser resolution. Using any courser resolution units (e.g. CCT's 'master planning districts') would render the analysis too broad to determine the nuanced spatial differences in vulnerability.

Figure 24: Vulnerability Scatter Plot (Current Conditions)



Identifying key trends in vulnerability by investigating the underlying causal pathways is critical for developing context and risk specific adaptation investments. For example, the vulnerability scatter plot in Figure 24 highlights a clear inverse correlation between population density and resilience, even though population density is an indicator of resilience in the model. Although areas such as Observatory, Pinelands and Newlands are relatively exposed to climate change and related hazards, the area is also relatively resilient and is thus not highly vulnerable. On the other hand, suburbs such as Mitchells Plain, Philippi and Khayelitsha score poorly on resilience but are not highly exposed either. Thus, the role of expert input and qualitative analysis is key to untangling the primary causal pathways of vulnerability to identify strategic entry points for adaptation that maximise impact and minimise cost. This process necessitates an understanding of how different risks manifest within a system to be able to rank them.

C.4.2 Ranking Key Climate Change Hazards and Risks

The notion of risk is generally determined as a function of the magnitude of the occurrence, and the likelihood that it will occur. For both acute climate shocks such as floods and fires, and chronic climate stressors such as drought, complex system interactions make it difficult to calculate risk. The multiplicity of impacts and associated knock-on effects further complicate the determination of magnitude. On the other hand, the relative uncertainty of climate models limits the ability to determine likelihood, most notably for rainfall projections (as discussed in Section B).

Risks manifest differently within different sectors, themes (such as livelihoods, poverty, the built environment) and segments of society (discussed in Section D). Therefore, in ranking climate-related hazards in terms of the risk they pose to Cape Town, we use a combined approach that draws on the quantitative outcomes of the R&V assessment, coupled with qualitative expert assessment. Based on this combined assessment, the key climate-related hazards that pose the greatest risk to Cape Town are:

1. Drought
2. Fire
3. Heatwaves
4. Floods
5. Strong Winds

D. Thematic Risk and Vulnerability Assessment

D.1 Overview and Key findings

This section presents a discussion of the findings of the R&V assessment in terms of thematic areas of impact, namely livelihoods (section D.2), poverty and inequality (section D.3), the built environment (section D.4) and disaster risk (section D.5). The analysis focuses on the key risks identified in Section C.4.2 and highlights the different pathways through which these risks manifest under each theme, drawing on key examples from Cape Town. The systemic interlinkages and cumulative impacts of multiple risks are also discussed in relation to key examples. The thematic assessment is deepened through the Economic Risk Analysis (Deliverable 3 for this project) to reflect key economic risks related to human, social, manufactured, financial, natural and intellectual capital.

The analysis in this report highlights the main sources of vulnerability as being drought, heatwaves, fires, floods and strong winds. Sea level rise is also a factor in some parts of the City. The interactions between the drivers of these risks, primarily temperature, wind and rainfall, are likely to manifest in a sharp increase in extreme drought events and fires.

D.2 Livelihoods

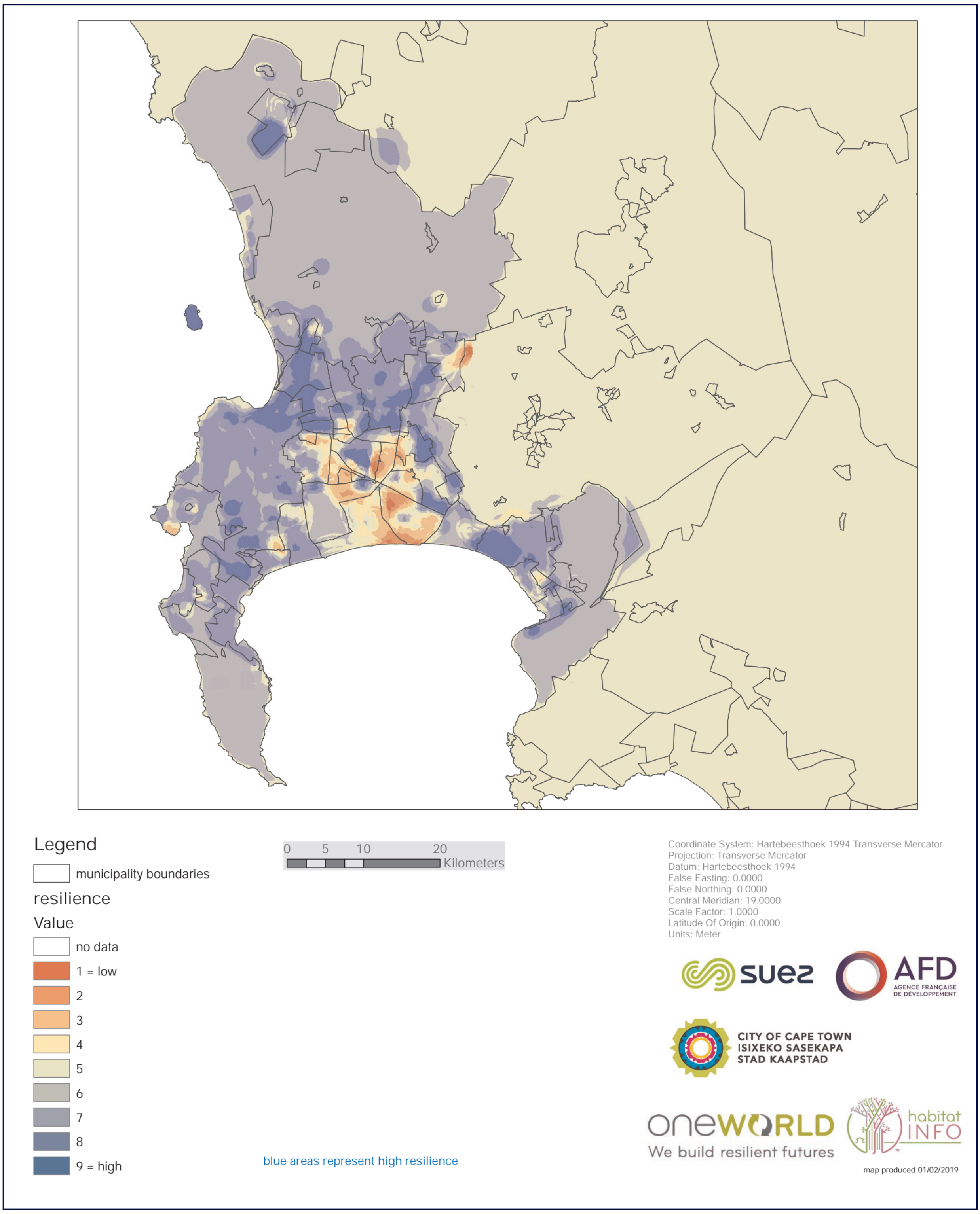
Livelihood strategies in Cape Town are highly variable in terms of their vulnerability to current and future climate-related hazards. High levels of unemployment correlate strongly with low levels of resilience, indicating that the informal sector faces the highest risks of climate stressors and shocks. Understanding the risks faced by workers in the informal sector is challenging because of the lack of reliable data, however the importance of their contribution to the economy cannot be ignored. Herrera et al. (2012) argue that as much as 80% of those who work in developing cities are employed in the informal economy. The Quarterly Labour Force Survey (QLFS) for Quarter 3 of 2018 indicates that from July-September 2018 the total number of jobs in Cape Town was ~1,606,000. The informal sector component of this (non-agriculture) makes up ~179,000 jobs or ~11% of people employed, while agriculture accounts for ~1% of people employed. Moreover, private household employment (e.g. domestic workers) comprises more than 5%, while formal employment (non-agriculture) makes up the majority of ~82%.

Although individual incomes from the informal economy are low, cumulative contributions to the national economy are significant. Moreover, the informal economy provides low-cost inputs and services to and both formal and informal sectors, especially within poorer areas. At the household level, informal activities are often what sustain families living in poorer areas and informal settlements, thus sustaining these activities is central to building resilience and alleviating poverty (Skinner, 2014). Moreover, traditional gender roles and livelihoods are more entrenched in social norms in the informal sector, and woman are often more reliant on informal sector income and are thus more vulnerable to climate risks.

Figure 25 illustrates the analysis of job opportunities and population balance in Cape Town. Red areas provide relatively limited job opportunities in relation to the population density compared to blue areas (See Appendix 5). These areas largely correlate with low income areas and informal settlements, where the informal economy plays the strongest role in maintaining livelihoods.

Although these areas are not highly exposed to changes in rainfall, drought is a serious risk to informal livelihoods because of the location of key dams in the WCWSS. One key example can be drawn from the recent multi-year drought in the Western Cape, which resulted in significant water use restrictions. These restrictions disproportionately impacted the informal economy as many businesses such as informal car washes and cleaning services had to be scaled down or closed, which in turn was reported to have knock-on effects for crime as more people are forced into illegal income generation activities (Saal, February 2018). Moreover, there is limited financial and social redundancy in informal systems as insurance coverage is extremely low and households are forced to get by with limited resources. Thus, when chronic stressors such as a drought limit the water availability of a household through increased tariffs and/or through direct restrictions, these households cannot afford to use much less than they already do. Although the 'free basic allowance' of water for 'indigent households' may buffer these impacts to a certain degree, these households remain trapped in a cycle of poverty; and water consumption by these households remains very low (discussed further in Section D.3).

Figure 25: Job opportunities and population balance in Cape Town



Similar risks threaten the informal economy from shocks such as fires, heatwaves and floods. Without insurance, informal businesses and households face significantly higher relative losses from fires or floods that damage or destroy their home or business infrastructure. Threats to human health and life from heatwaves are likely to disproportionately impact the informal economy as informal sector workers are often exposed to the elements and lack the financial resources to continue working productively in extreme heat (i.e. working outside or without air conditioning, etc.). Heatwaves experienced in Europe in recent summers have also highlighted the particular vulnerability of the aged to extreme heat (Herrmann and Sauerborn, 2018). Again, this affects the poor, who are least able to afford air conditioners.

On the other hand, many water-intensive formal sector livelihoods are threatened by climate-related shocks and stressors. The most obvious interaction is between drought and agricultural jobs. WWF (2018) estimates that ~30,000 jobs were lost in the agricultural sector in the Western Cape as a direct result of the recent drought. Although the majority of these jobs are probably not within the Cape Town Municipality, the ripple effects in the regional economy can be significant for the City, being the economic hub of the province. In-migration to the City is thus a significant driver of vulnerability linked to both in-situ and broader regional impacts of climate change. People moving to Cape Town predominantly settle in the low-income areas and informal settlements, where vulnerabilities are already high. These complex interlinkages between livelihoods, poverty, the built environment and disaster risk further highlight how climate change is a threat multiplier for Cape Town.

D.3 Poverty and Inequality

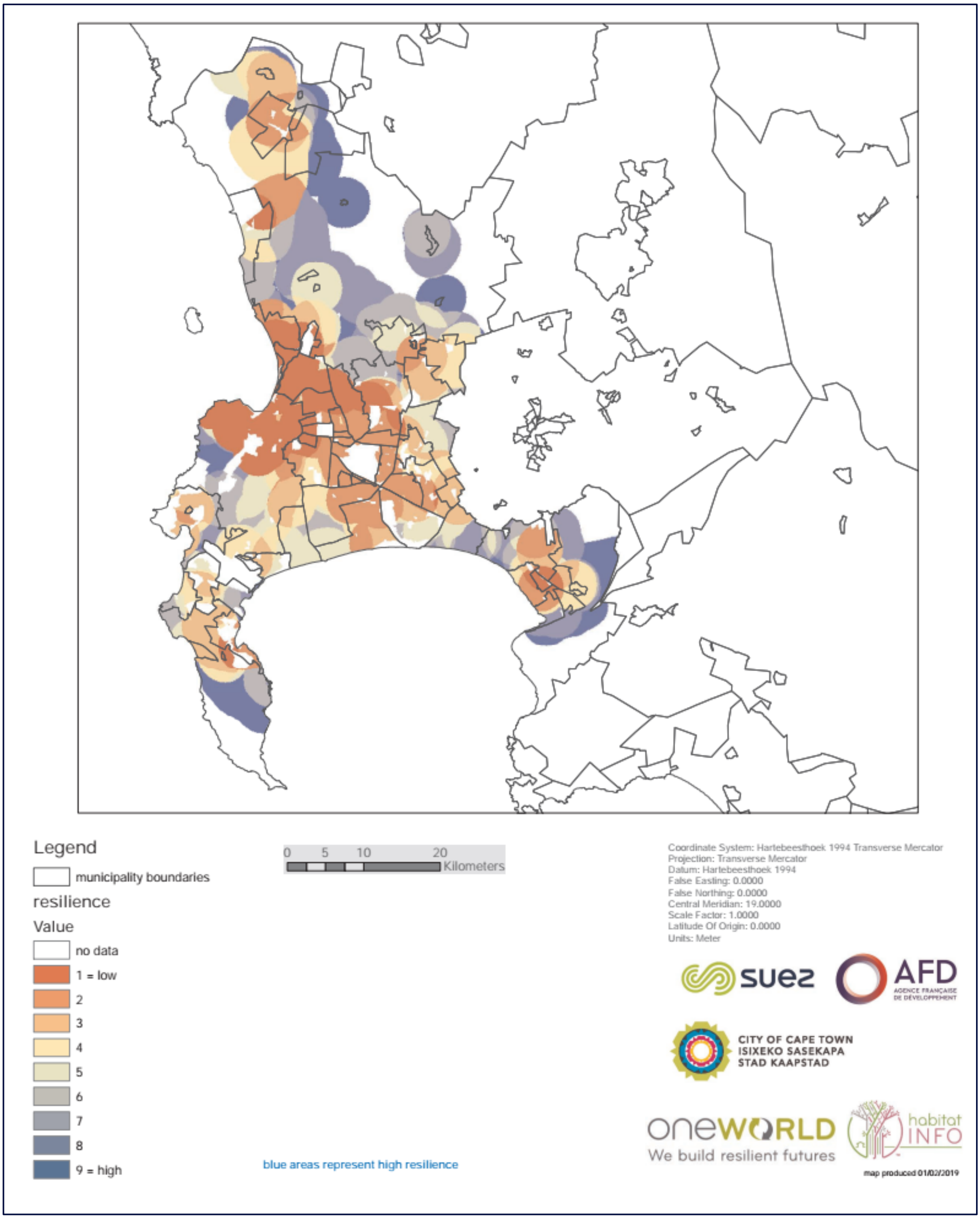
Poverty and inequality are both drivers of climate change vulnerability, and are results of it. The roles of poverty and inequality, which are inextricably linked in South Africa, are central to understanding vulnerability in the context of Cape Town because, as mentioned above, climate change acts as a threat multiplier that exacerbates existing human, social, economic and environmental vulnerabilities through multiple causal pathways. South Africa's high levels of inequality coupled with endemic poverty, mean that the impacts of climate change pose serious challenges for development (ACDI, 2015).

The distribution of poverty within Cape Town is largely contiguous, as evidenced through key resilience input indices such as mean household income, and access to electricity and water services (see Appendix 5). Spatial distributions of high ranges in income inequality underline the inextricable linkages between livelihood opportunities (Figure 26) and poverty and inequality. The relatively high levels of vulnerability of the informal sector is strongly linked to inequality and cycles of poverty, crime and violence in specific areas within the City.

Figure 26 illustrates relative levels of income inequality within a 3km radius of each household income level in Cape Town. In other words, this indicator reveals areas where there are significant differences in household income (red areas), which are often drivers of illegal activity such as crime (Kriegler, 2018) and other activities that limit resilience. Poverty and inequality are multi-dimensional and multi-generational, highlighting the complex causal pathways of vulnerability. For example, Khambule and Siswana (2017) argue that social and economic inequalities undermine social cohesion in South Africa, which ultimately reduces resilience to shocks and stressors. Communities that are able to collectively respond to shocks such as fires, droughts and heatwaves are more resilient. Ultimately, poorer households are less likely to have adequate resources to adapt to change, which are further undermined by the stark levels of inequality that limit social cohesion.

High levels of vulnerability in poorer areas also result in a myriad of City-wide and regional socio-economic impacts that have negative knock-on effects on general levels of vulnerability. For example, resource poor households are more dependent on natural resources from surrounding ecosystems when climate stressors limit livelihood activities. Over-dependence on natural systems may threaten the sustainability of these systems to continue providing essential ecosystem services such as water provision. These cycles further entrench City-wide vulnerabilities by placing increasing pressure on social support systems and economic redistribution mechanisms, further eroding social cohesion in communities and negatively impacting economic sentiment and investment. All of these factors may further contribute to poverty and overall poor levels of resilience.

Figure 26: Range of household income within 3km in Cape Town



D.4 Built Environment

The built environment in Cape Town refers to the vast range of public and private infrastructure and residential households that make up the human-made environment in which the people of Cape Town live, work and travel. The built environment directly and indirectly influences levels of vulnerability through both exposure and resilience aspects. For example, roads and public transport infrastructure provide ease of access to and from critical infrastructure such as hospitals and fire stations.

Moreover, these components of the built environment also face risks from climate shocks and stressors to their overall structural integrity and functional capacity. For example, more intense and frequent heat waves, extreme temperatures and floods present physical risks to critical public infrastructure such as roads, which are constructed to specific thermal and hydrological codes (in relation to heat and stormwater runoff).

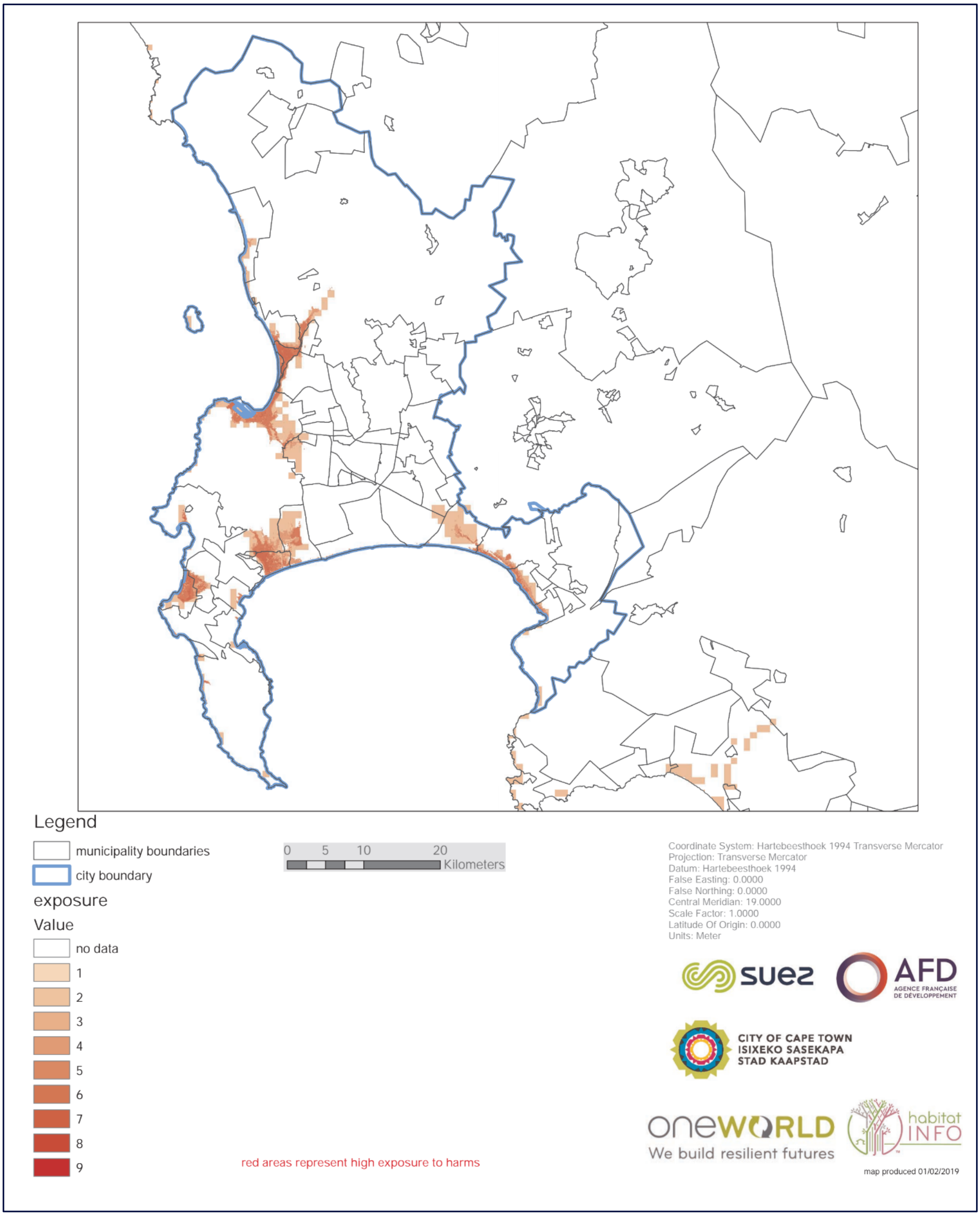
Impacts of urban heat island effects are intensified by both increasing temperatures and physical building density, ultimately increasing heatwave risks impacts and the overall risks associated with increasing temperatures in highly built-up areas.

Urban fires, often exacerbated by climate change impacts such as increased wind strength and frequency, present significant risks to residential housing, particularly in the areas with high population densities, and informal settlements. Wildfires also present significant risk to residential properties and public infrastructure facilities, including a significant proportion of middle to high income housing developments built in or adjacent to wilderness areas.

As previously discussed, low-income areas are less resilient for a number of reasons and are thus more socially vulnerable to climate-related hazards, signalling the importance of prioritising these areas in terms of investing in resilience. However, the nature of re-distributional taxation in South Africa provides an argument for protecting high value properties from the impacts of climate change. Household municipal rates are based on property value, and a proportion of rates paid to CCT is used to cross-subsidise low-income areas, thus contributing directly to their resilience. Thus, if climate-related shocks and stressors pose a threat to high value properties, these may negatively influence property values and reduce the cross-subsidisation that contributes to resilience in low-income areas. While this argument has merit, it must be balanced with the increasing need to invest in areas of low resilience, noting that reducing resilience inequalities may reduce the pressure on cross subsidisation from property rates over time.

Figure 27 demonstrates the areas at highest risk of inundation from future sea-level rise in Cape Town. Darker red shows the areas that are the most exposed to sea-level rise. Although the direct impacts of sea-level rise are likely going to occur slowly over many years, associated effects on changes in coastal erosion and coastal flooding may exacerbate risks to coastal infrastructure in these areas. Risks particularly to public infrastructure are important because of the resultant knock-on effects and interrelationships with social and economic vulnerabilities. For example, damaged roads or rail infrastructure limits human mobility in time of crisis (for example to reach a hospital, etc.), and access to economic opportunities, which result in lower overall resilience. Furthermore, risks of sea-level rise and coastal flooding to high value property, for example in the low-lying Green Point and Milnerton areas, and continuous erosion of the Sea Point seawall, will have knock-on impacts for tourism and the broader economy.

Figure 27: Sea-level rise inundation risk in Cape Town



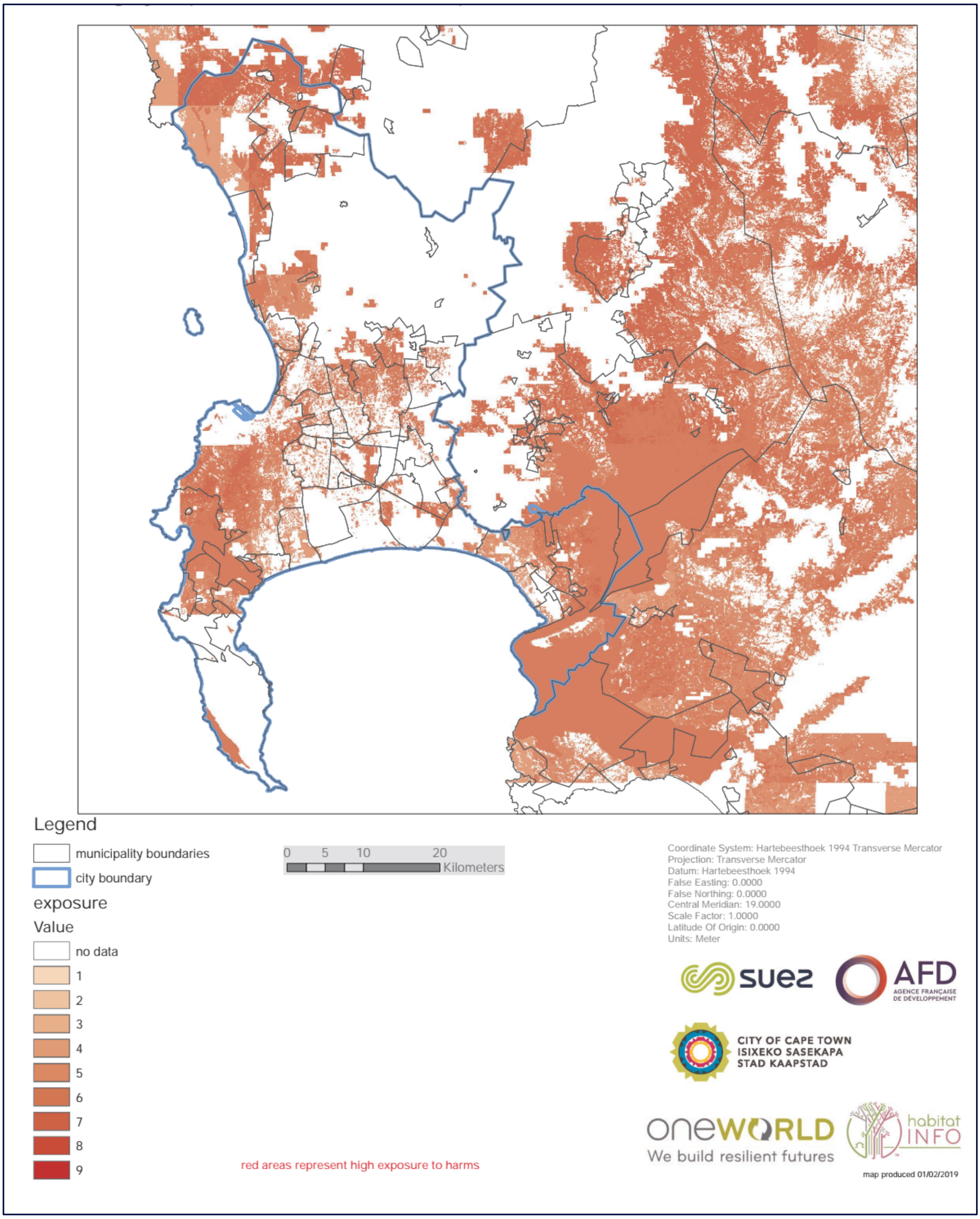
D.5 Disaster Risk

Disaster risk response and preparedness, both important adaptation responses, contribute directly to relative levels of vulnerability throughout the City. The obvious relationships are directly related to resilience, for example a residential area with a shorter travel time to and from a fire station, a hospital, police station or freshwater spring is likely to be more resilient to climate-related shocks than one further away from such amenities. However, disaster risks manifest through different pathways, many of which will have cumulative impacts and will result in increasing vulnerability to future climate-related hazards. As such, disaster risk, although articulated as a fourth cross cutting theme, is also a direct threat to livelihoods, poverty and inequality and the built environment.

Figure 28 demonstrates future high fire risk areas in and around Cape Town. The darker red areas show areas at highest risk of fire in the future because of changes in climatic conditions. The risks associated with high fire danger are extensive, and include human, social, environmental and infrastructural risks. In relation to risks to human life and health, densely populated areas in informal areas that have limited access to municipal disaster response services will experience the greatest risk from fire disasters. Other related impacts include deterioration in in-situ and down-wind air quality as a result of higher numbers of fires. Furthermore, the risk from fire for natural areas with high biodiversity and those yielding high-value ecosystem services, represents considerable risks to society, as loss of these areas has a variety of ripple effects for different sectors such as tourism, agriculture and water.

Fire disaster risk is closely interwoven with water security risks for Cape Town, partly because of the biophysical impacts of alien invasive species. The Status of Biological Invasions and their Management in South Africa Report (SANBI, 2017) highlights that alien plants use up to 30% of the water supply in major cities such as Cape Town. Moreover, alien species change the structure and biomass of vegetation, adding fuel and increasing the severity of wildfires, making them more difficult to control and more destructive.

Figure 28: Future fire risk areas in Cape Town region



E. The Way Forward

Although the findings presented in this report will be subject to continued development and refinement through participatory analysis, this marks the end of Phase 2 of the project. From here on out, the project team is carrying out the Economic Risk Assessment and prioritisation of adaptation investments in parallel. The increasingly nuanced R&V assessment continues to add nuance. Additionally, Phase 3 of the project will incorporate a variety of in-depth engagement activities to create the platform for the final Phase: Communication of Findings. Specifically, upcoming engagement activities are envisioned to include:

- Focus Group Discussions with key participants of the reference group and key informants within CCT;
- The second participatory analysis workshop once preliminary findings from the Economic Risk Analysis and Adaptation Options Assessment have been collated;
- Project presentations to key CCT corporate structures such as the relevant portfolio committee and selected Executive Directors.
- Attendance of workshop/s for the AFD funded 'low-income household energy study' being undertaken by OneWorld, which has various synergies with this project, and are currently being explored.

In addition, and to further inform the Economic Risk Assessment, while also deepening the R&V analysis contained in this report, the following 'deep dive' assessments are about to commence:

- Rainfall and flooding assessment to validate and refine the findings contained in this report;
- Land use assessment, integrating and deepening the associated risks across the four themes discussed in the previous section;
- Fire risk assessment, detailing the interactions between increased fire risk, common drivers of fires in informal settlements, risks for property investments and for land uses in general;
- Coastal risk dynamics assessment to deepen the understanding of the extent of the risks of coastal erosion and the interactions with wind and storm surges.

Based on the outcomes of this report and the above assessments, the Economic Risk Assessment will be focused on assessing the economic risks associated with both immediate climate shocks and more gradual climate stressors through a broad 'capital theory' approach. The logic follows that different forms of capital provide different flows of benefits (or services) to society such as human capital, social capital, natural capital, intellectual capital and manufactured capital. Baseline indicators for these various forms of capital will be drawn from the R&V assessment and other relevant data sources. Thereafter, the project team will carry out a systematic cost-benefit analysis for priority adaptation investment options, which have been scrutinised and verified through multiple stakeholder engagements.

This overarching approach to understanding broader economic risks is consistent with the notion of risk manifesting through multiple pathways and is centred around managing the trade-offs within complex socio-economic and biophysical systems.

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Appendix 1: Seasonality of fire risk

Winter rainfall, and well as the frontal rain that occurs during the transition seasons of autumn and spring, are projected to decrease significantly under enhanced anthropogenic forcing. This is due to the strengthening of the subtropical high-pressure belt over the southern African region and the southward displacement of the westerly wind regime (and cold fronts) under climate change (Christensen et al., 2007; Engelbrecht et al., 2009). Moreover, temperatures are projected to increase over the southwestern Cape across all seasons. This implies that fire risk is to increase across all seasons in the southwestern Cape. Of particular importance is the potential of more frequent occurrence of fires during winters that are projected to increasingly become drier and warmer, upsetting the natural seasonal cycle of fire in the Fynbos Kingdom and posing severe threats to biodiversity. Also important is the potential for more frequent mega-fires to occur within the longer burning season, with implications for biodiversity and disaster events impacting on human mortality and property. Figures 29 to 32 show the projected changes in the seasonal cycle of the number of high fire-danger days for two cases of Cederberg and Vermaaklikheid (along the Cape south coast).

Cederberg

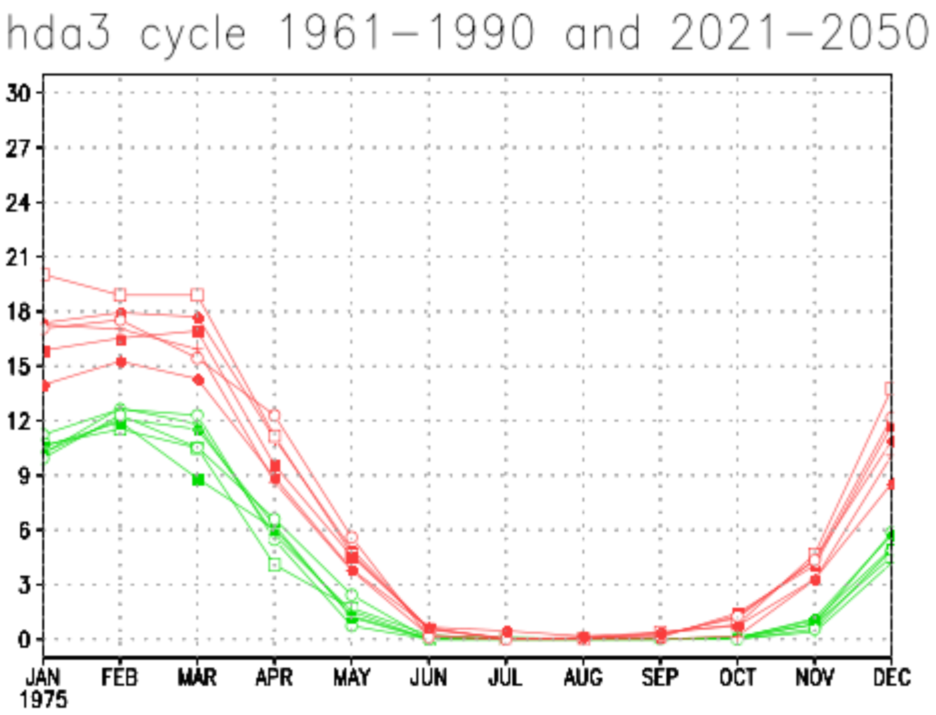
Model-projected changes in the annual cycle of the number of days pear month when the FFDI value is rated as high, very high or extreme (FFDI > 12) is shown in Figure 29 (top panel), for the future time period 2021-2100 and the baseline period 1961-1990, for the Cederberg region (32.5 °S and 19.25 °E). For each time period, the simulated cycles for all six ensemble members are shown. The projected changes in the annual cycle of high fire danger days are shown in Figure 29 (lower panel). The same quantities are displayed in Figure 30 but for the period 2070-2099 relative to 1961-1990. The present day (1961-1990) annual cycle in the number of high fire danger days shows a distinct peak in the late summer (January to March), which forms part of the dry season over the region. During this time of the year, about 10-12 days per month are associated with a high fire risk according to the FFDI.

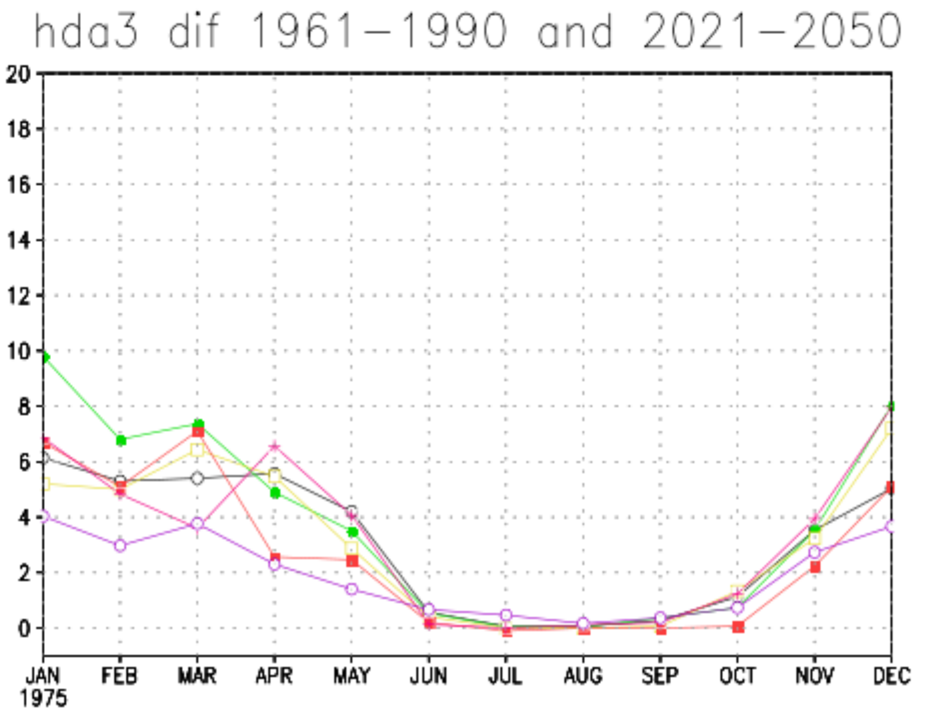
For the far-future period of 2070-2099, the projected increases in days with high fire risk are drastic for late spring to autumn – increases range between 8 and 18 days per month (Figure 30). High fire danger days are also projected to occur regularly during the winter months (very low fire risk is simulated for the region for the present-day climate in winter). The projected increases in high fire-risk are also substantial for the mid-future period of 2021-2050, with increases for the late spring autumn period projected to range between 2 and 10 days per month. These results suggest the potential of a future expansion of the length of the fire season over the Cederberg region, with a significant increase in risk during an important part of the fire season, namely the late summer.

Vermaaklikheid

At Vermaaklikheid along the Cape South coast region, the FFDI is indicative of relatively smaller fire risk than over the Cederberg to the north. Over this region the number of high fire-danger days is simulated to range between 2 and 4 days per month during the late spring to autumn period (Figure 31, top panel). Increases are projected to range between 0 and 1 days by the mid-future period of 2021-2050 (Figure 31, lower panel), and by 4-8 days by the far-future period of 2070-2099 (Figure 32, lower panel).

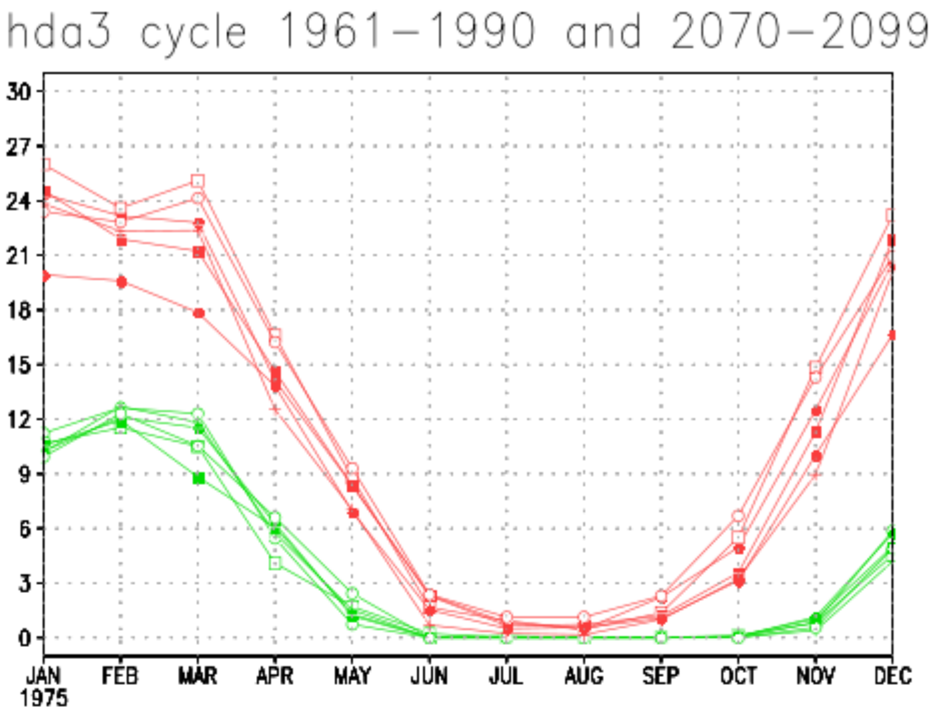
Figure 29: Projected changes in the number of high fire-danger days per month: Cederberg

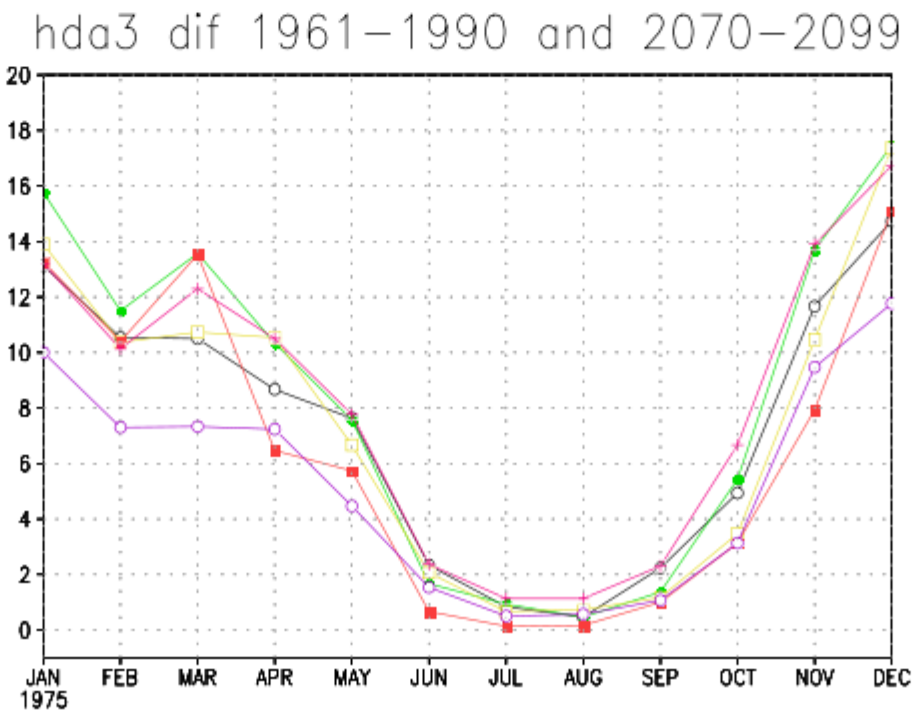




Projected changes in the annual cycle of the number of days per month when the FFDI value is rated as high, very high or extreme (FFDI > 12) over the Cederberg region, for the future time period 2021-2050 and the baseline period 1961-1990. For each time period, the simulated cycles are shown (top panel) for ***present-day climate (green lines) and far-future climate (red lines)****. The bottom panel shows the projected monthly differences in the number of high fire danger days for 2021-2050 relative to 1961-1990.*

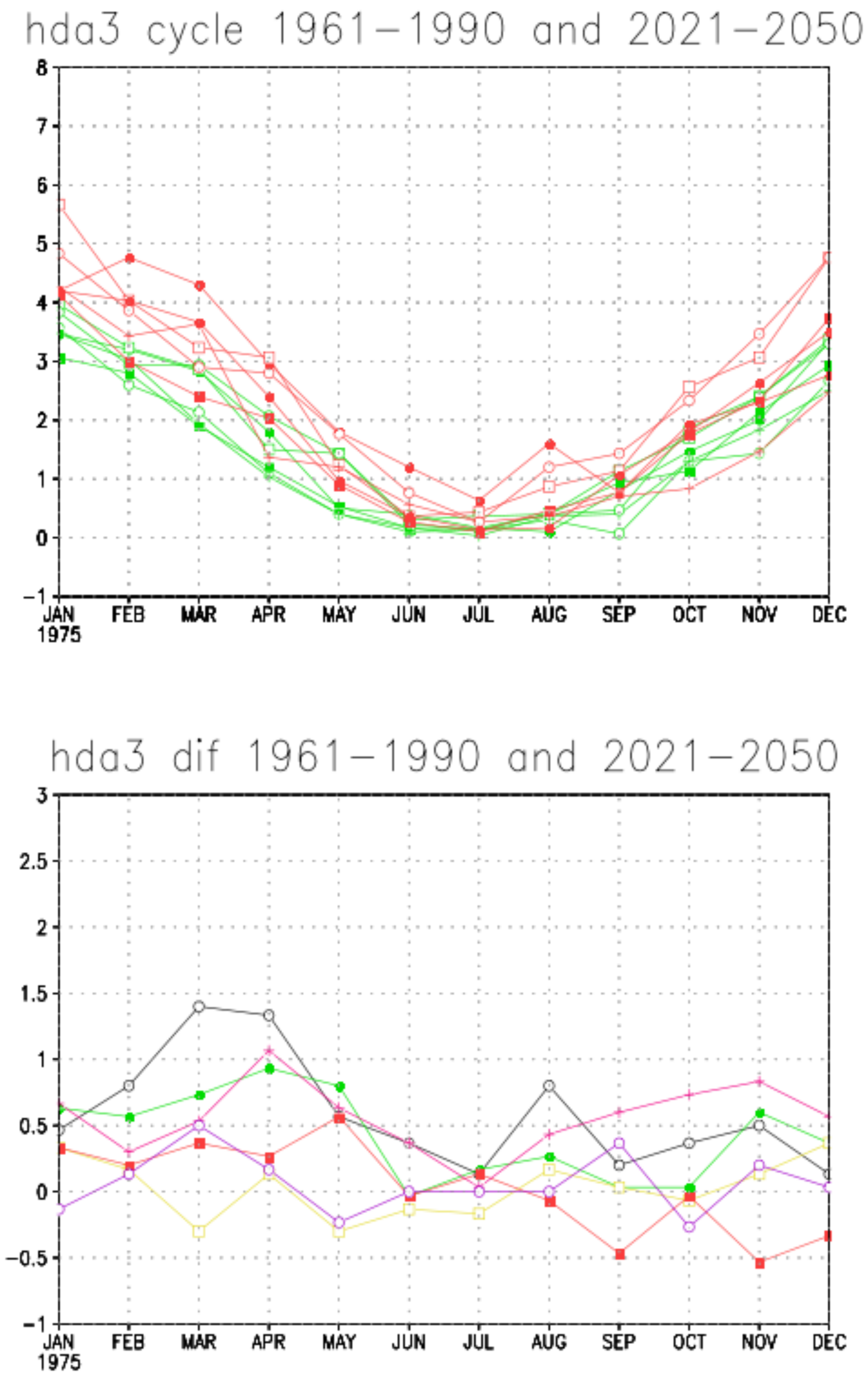
Figure 30: Projected changes in the number of high fire-danger days per month: Cederberg





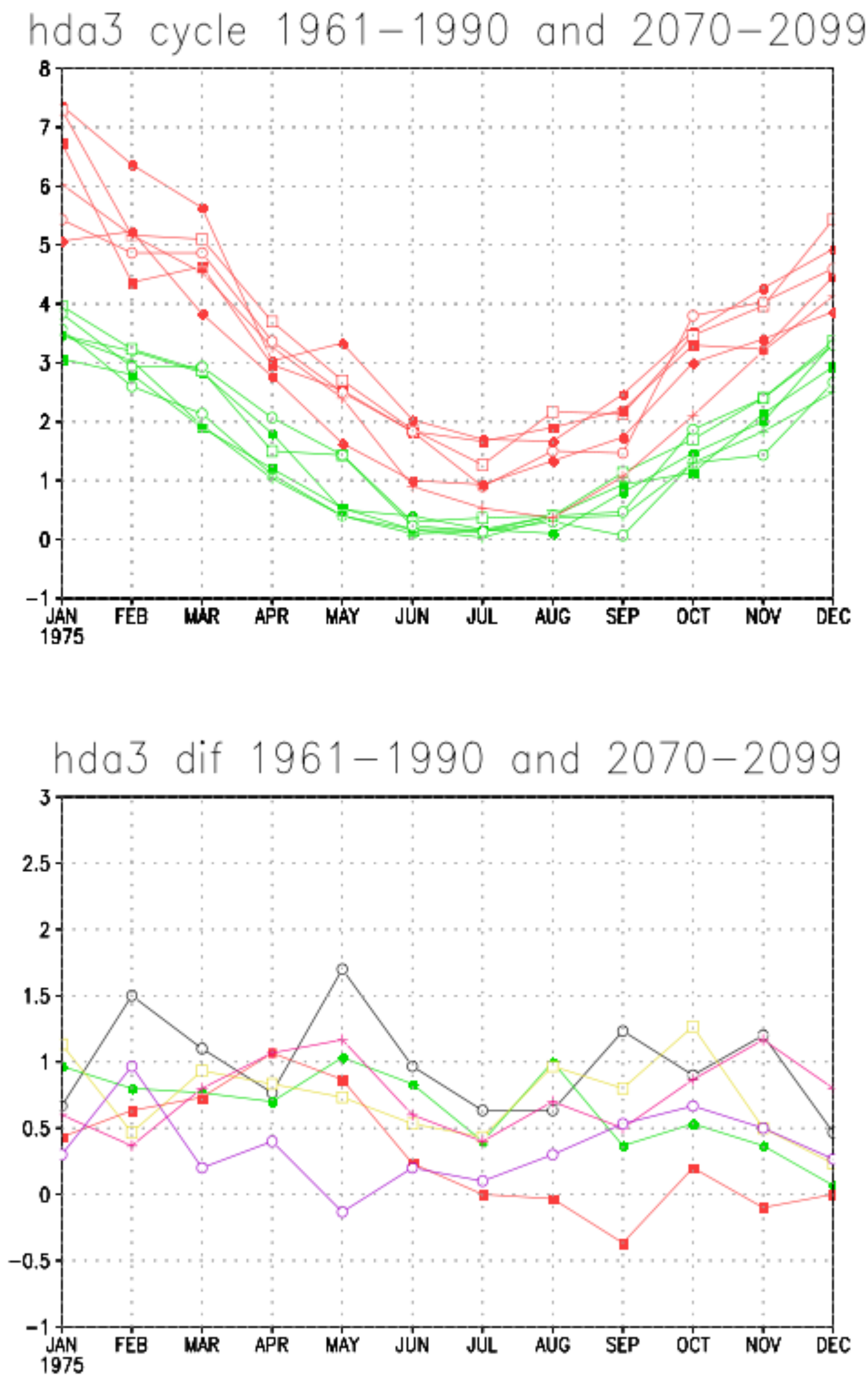
Projected changes in the annual cycle of the number of days per month when the FFDI value is rated as high, very high or extreme (FFDI > 12) over the Cederberg region, for the future time period 2070-2099 and the baseline period 1961-1990. For each time period, the simulated cycles are shown (top panel) for ***present-day climate (green lines)*** *and* ***far-future climate (red lines).*** *The bottom panel shows the projected monthly differences in the number of high fire danger days for 2070-2099 relative to 1961-1990.*

Figure 31: Projected changes in the number of high fire-danger days per month: Vermaaklikheid



Projected changes in the annual cycle of the number of days per month when the FFDI value is rated as high, very high or extreme (FFDI > 12) at Vermaaklikheid along the Cape south coast, for the future time period 2021-2050 and the baseline period 1961-1990. For each time period, the simulated cycles are shown ***(top panel) for present-day climate (green lines) and far-future climate (red lines)****. The bottom panel shows the projected monthly differences in the number of high fire danger days for 2021-2050 relative to 1961-1990.*

Figure 32: Projected changes in the number of high fire-danger days per month: Vermaaklikheid



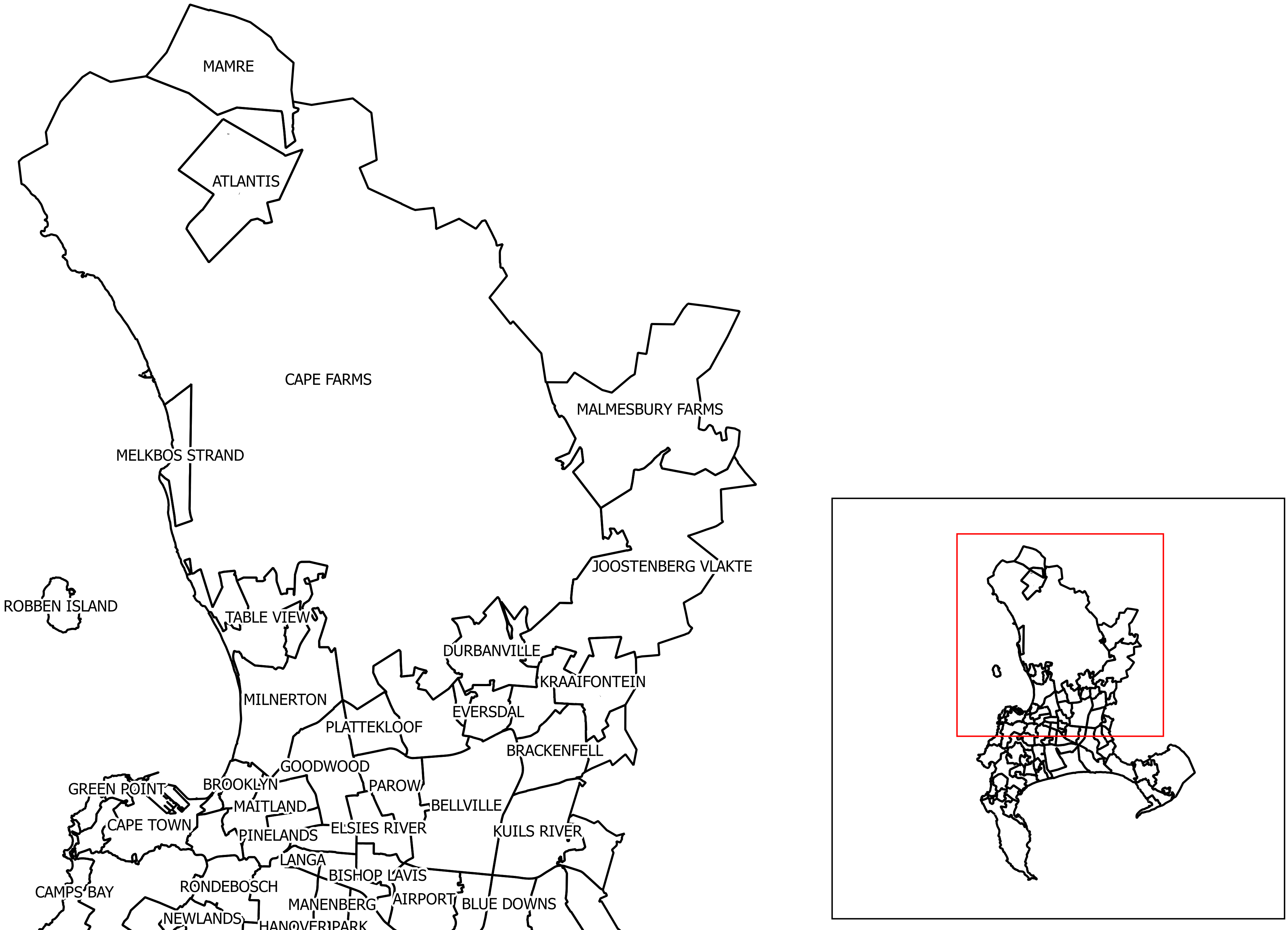
Projected changes in the annual cycle of the number of days per month when the FFDI value is rated as high, very high or extreme (FFDI > 12) at Vermaaklikheid along the Cape south coast, for the future time period 2070-2099 and the baseline period 1961-1990. For each time period, the simulated cycles are shown ***(top panel) for present-day climate (green lines) and far-future climate (red lines)****. The bottom panel shows the projected monthly differences in the number of high fire danger days for 2070-2099 relative to 1961-1990.*

Appendix 2: Maps of Major Suburbs of Cape Town

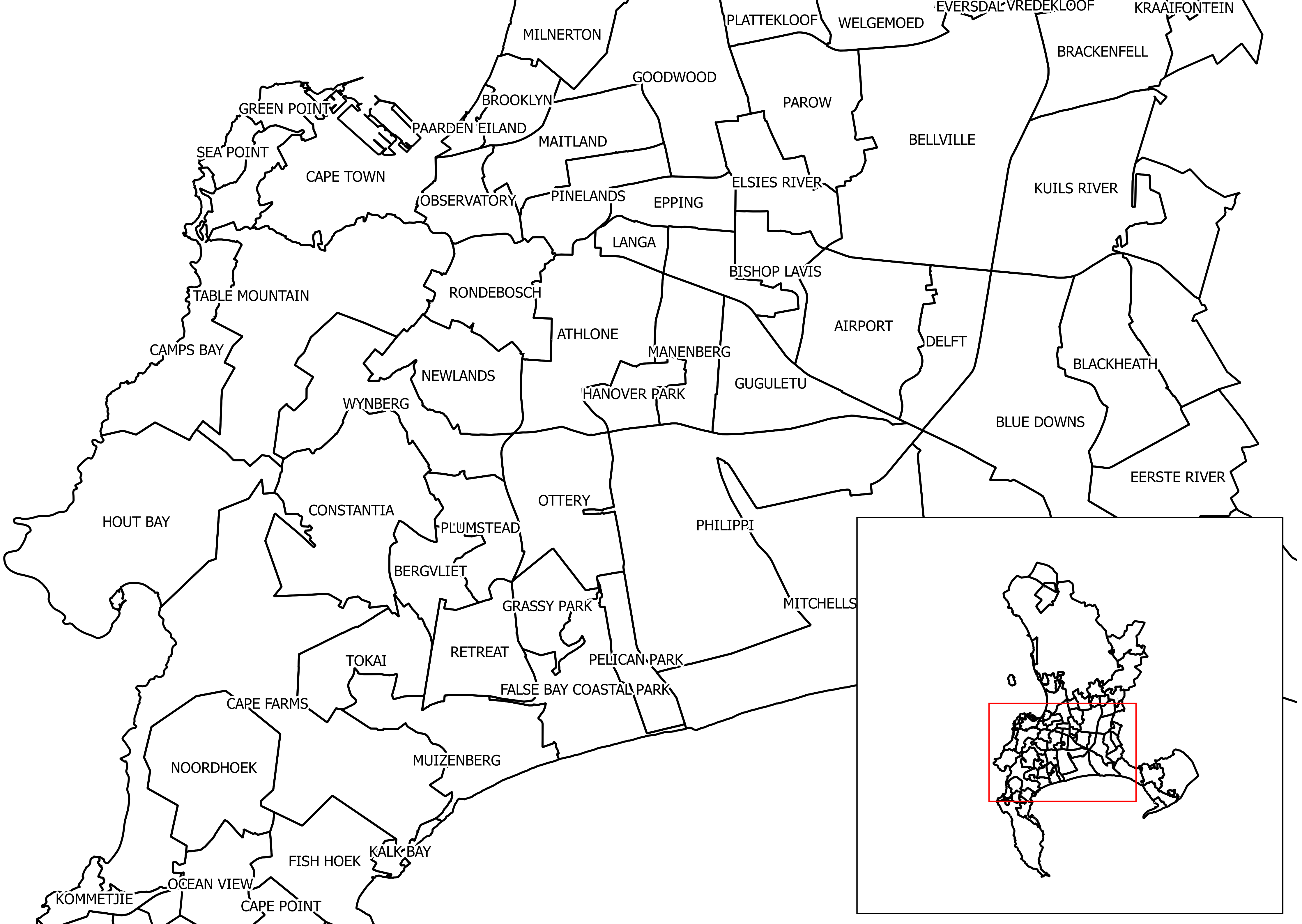
Appendix 3: Risk and Vulnerability Assessment Summary Maps

Appendix 4: Exposure Input Indicator Maps

Appendix 5: Resilience Input Indicator Maps


MAMRE
ATLANTIS
CAPE FARMS
MALMESBURY FARMS
MELKBOS STRAND
JOOSTENBERG VLAKTE
ROBBEN ISLAND
TABLE VIEW
DURBANVILLE
KRAAIFONTEIN
MILNERTON
EVERSDAL
PLATTEKLOOF
BRACKENFELL
GOODWOOD
GREEN POINT
BROOKLYN
PAROW
MAITLAND
BELLVILLE
CAPE TOWN
ELSIES RIVER
KUILS RIVER
PINELANDS
LANGA
BISHOP LAVIS
CAMPS BAY
RONDEBOSCH
MANENBERG
AIRPORT
BLUE DOWNS
NEWLANDS
HANOVER PARK


MILNERTON
PLATTEKLOOF
EVERSDAL
KRAAIFONTEIN
BRACKENFELL
GOODWOOD
GREEN POINT
BROOKLYN
PAROW
MAITLAND
BELLVILLE
CAPE TOWN
ELSIES RIVER
KUILS RIVER
PINELANDS
LANGA
BISHOP LAVIS
TABLE MOUNTAIN
AIRPORT
ATHLONE
CAMPS BAY
BLACKHEATH
GUGULETU
WYNBERG
BLUE DOWNS
EERSTE RIVER
OTTERY
CONSTANTIA
HOUT BAY
PHILIPPI
BERGVLIET
GRASSY PARK
MITCHELLS PLAIN
MACASSAR
STELLENBOSCH FARMS
RETREAT
TOKAI
SOMERSET WEST
FALSE BAY COASTAL PARK
CAPE FARMS
MUIZENBERG
NOORDHOEK
STRAND
FISH HOEK
KOMMETJIE
GORDONS BAY
SIMONS TOWN
CAPE POINT


MILNERTON
PLATTEKLOOF
WELGEMOED
EVERSDAL
VREDEKLOOF
KRAAIFONTEIN
BRACKENFELL
GOODWOOD
PAROW
BROOKLYN
GREEN POINT
PAARDEN EILAND
MAITLAND
BELLVILLE
SEA POINT
CAPE TOWN
ELSIES RIVER
KUILS RIVER
OBSERVATORY
PINELANDS
EPPING
LANGA
BISHOP LAVIS
RONDEBOSCH
TABLE MOUNTAIN
ATHLONE
AIRPORT
DELFT
CAMPS BAY
MANENBERG
BLACKHEATH
NEWLANDS
HANOVER PARK
GUGULETU
WYNBERG
BLUE DOWNS
EERSTE RIVER
OTTERY
CONSTANTIA
HOUT BAY
PLUMSTEAD
PHILIPPI
BERGVLIET
GRASSY PARK
MITCHELLS
RETREAT
TOKAI
PELICAN PARK
FALSE BAY COASTAL PARK
CAPE FARMS
NOORDHOEK
MUIZENBERG
FISH HOEK
KALK BAY
OCEAN VIEW
KOMMETJIE
CAPE POINT

map 1

dataset reference: a_airquality

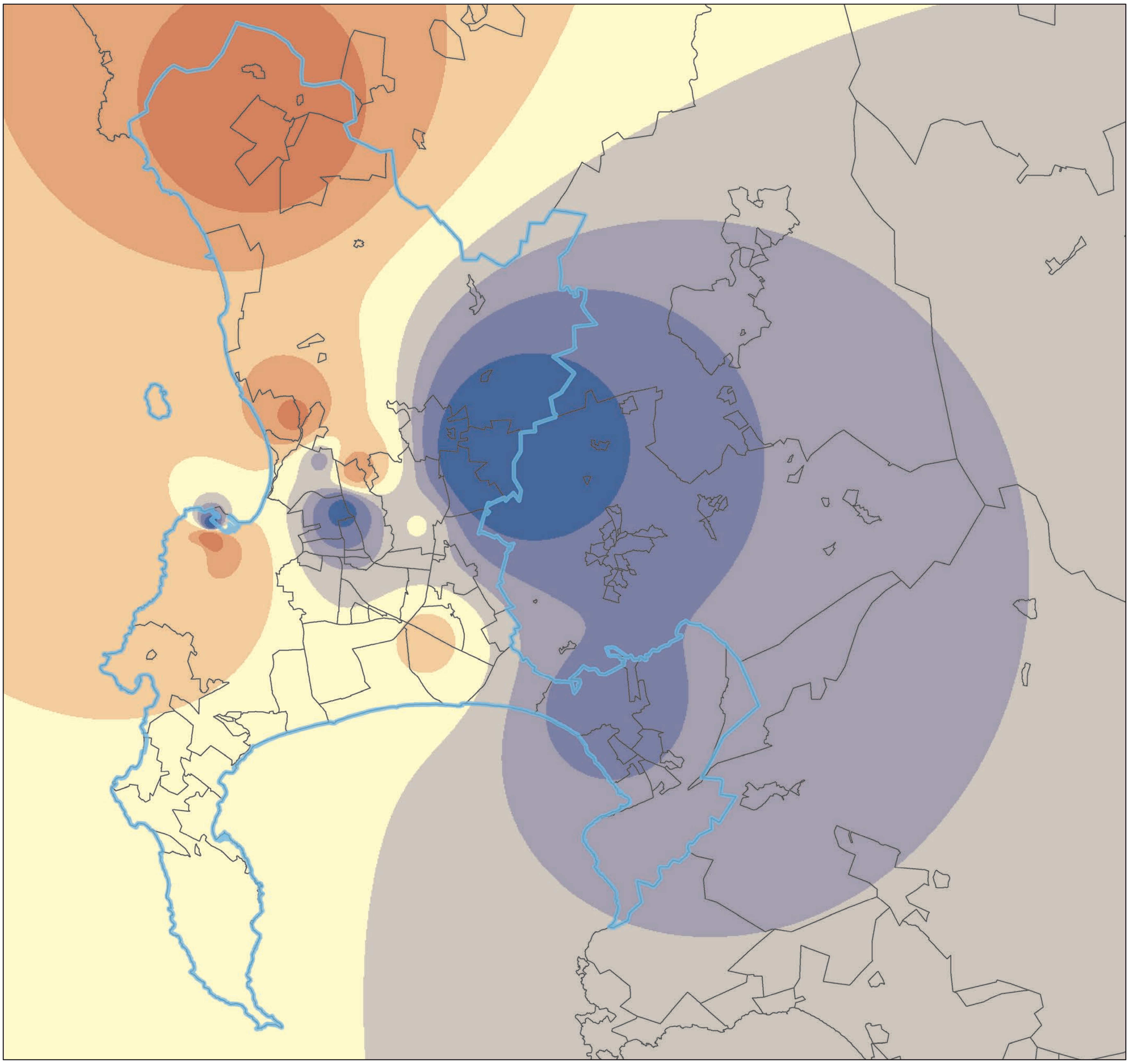
City of Cape Town Risk & Vulnerability Analysis

Air Quality

category: resilience

time period: current conditions

weighting 3



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Air quality (2016). Raw values of Nitrogen oxide, Ozone, Sulphur dioxide, Carbon monoxide and particulate matter (PM10 and PM2.5) were combined. Air quality monitoring station locations sourced from CoCT. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: n/a. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

suez

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habitat INFO

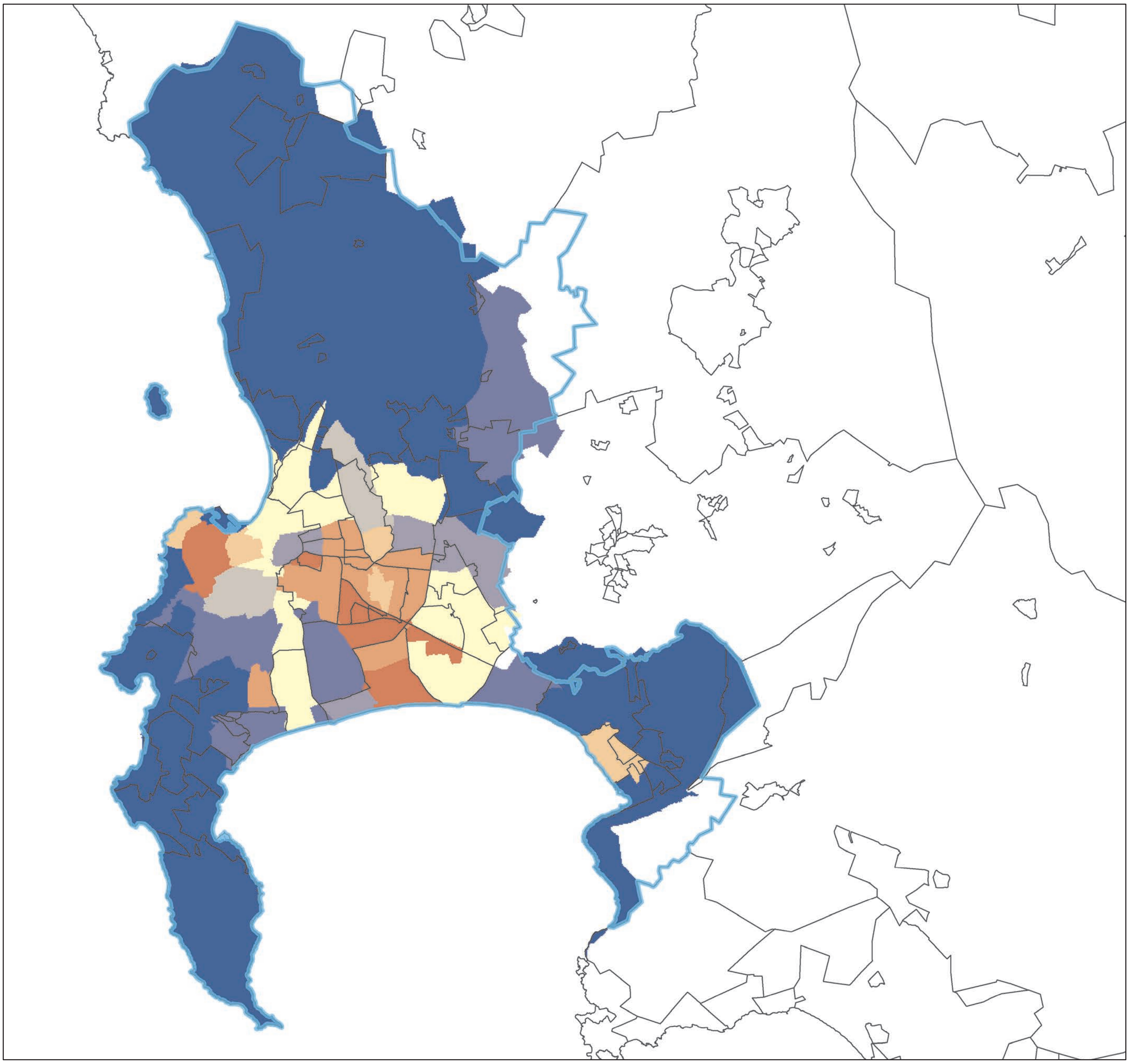
map produced 29/04/2019

map 2

dataset reference: A_crimes

Crime Rate

category: resilience **time period: current conditions** weighting 5



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Total crimes per square km (April 2017-March 2018). Calculated by dividing Total Crimes by area (km). The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Police Bound. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

map produced 29/04/2019

map 3

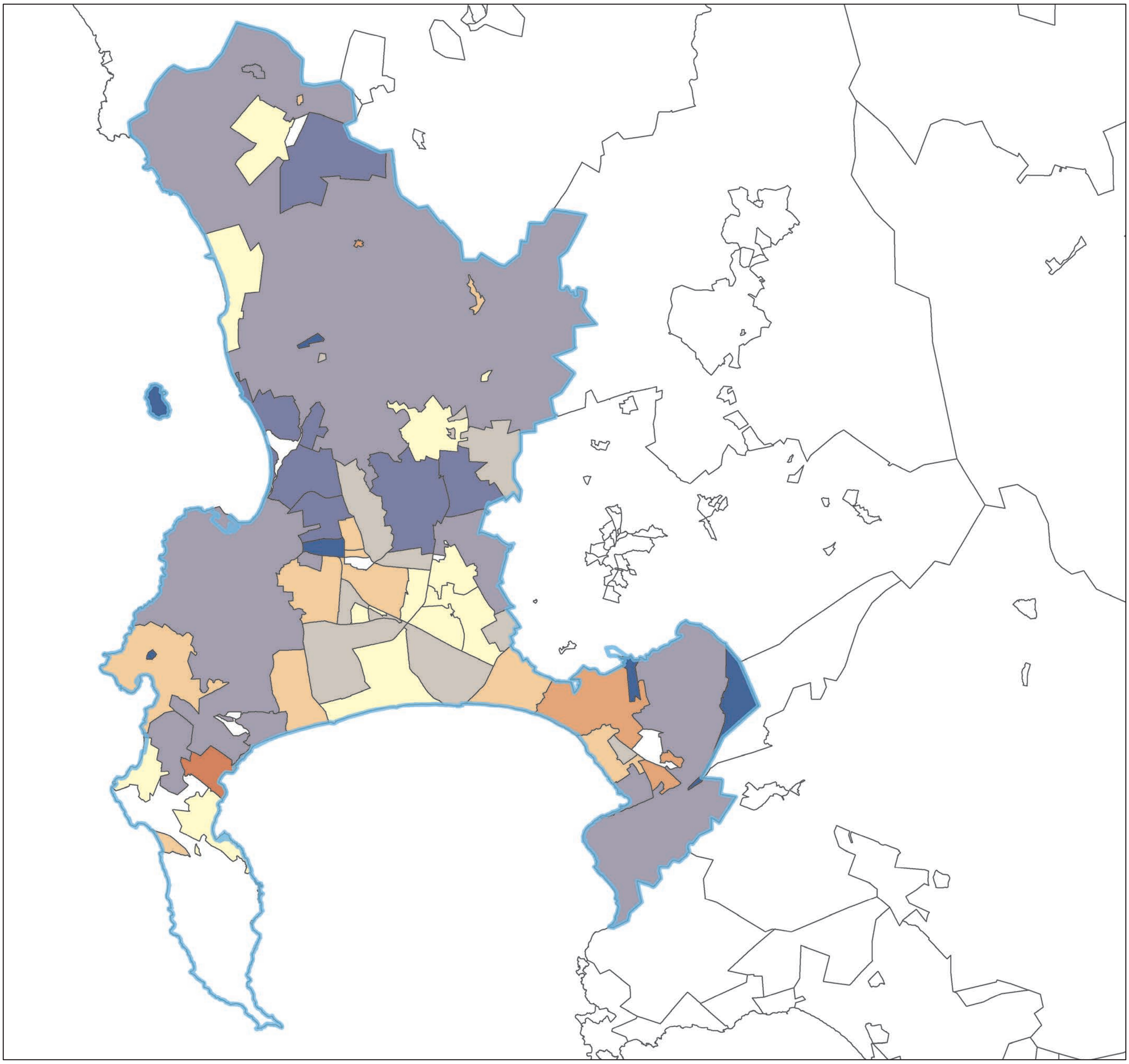
dataset reference: a_dependancy

Dependency

category: resilience

time period: current conditions

weighting 4



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Dependancy ratio (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Main Place. Credits: City of Cape Town

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

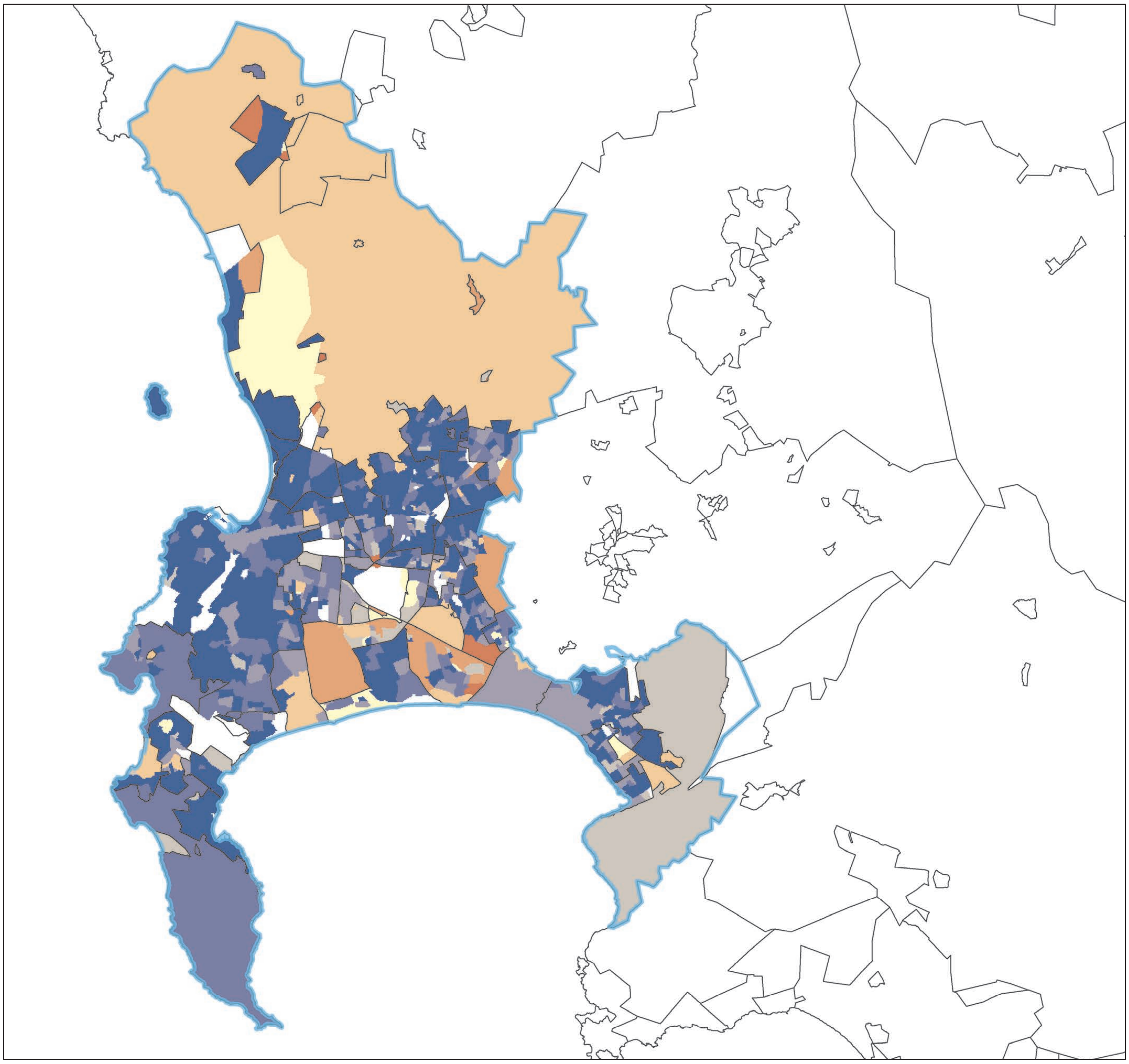
blue areas represent high resilience

map produced 29/04/2019

dataset reference: A_electricityforlighting

Electricity for Lighting

category: resilience **time period: current conditions** weighting 4



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Percentage of households with electricity for lighting (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. Cells with no data were assigned a value of 0. Original resolution: SP. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

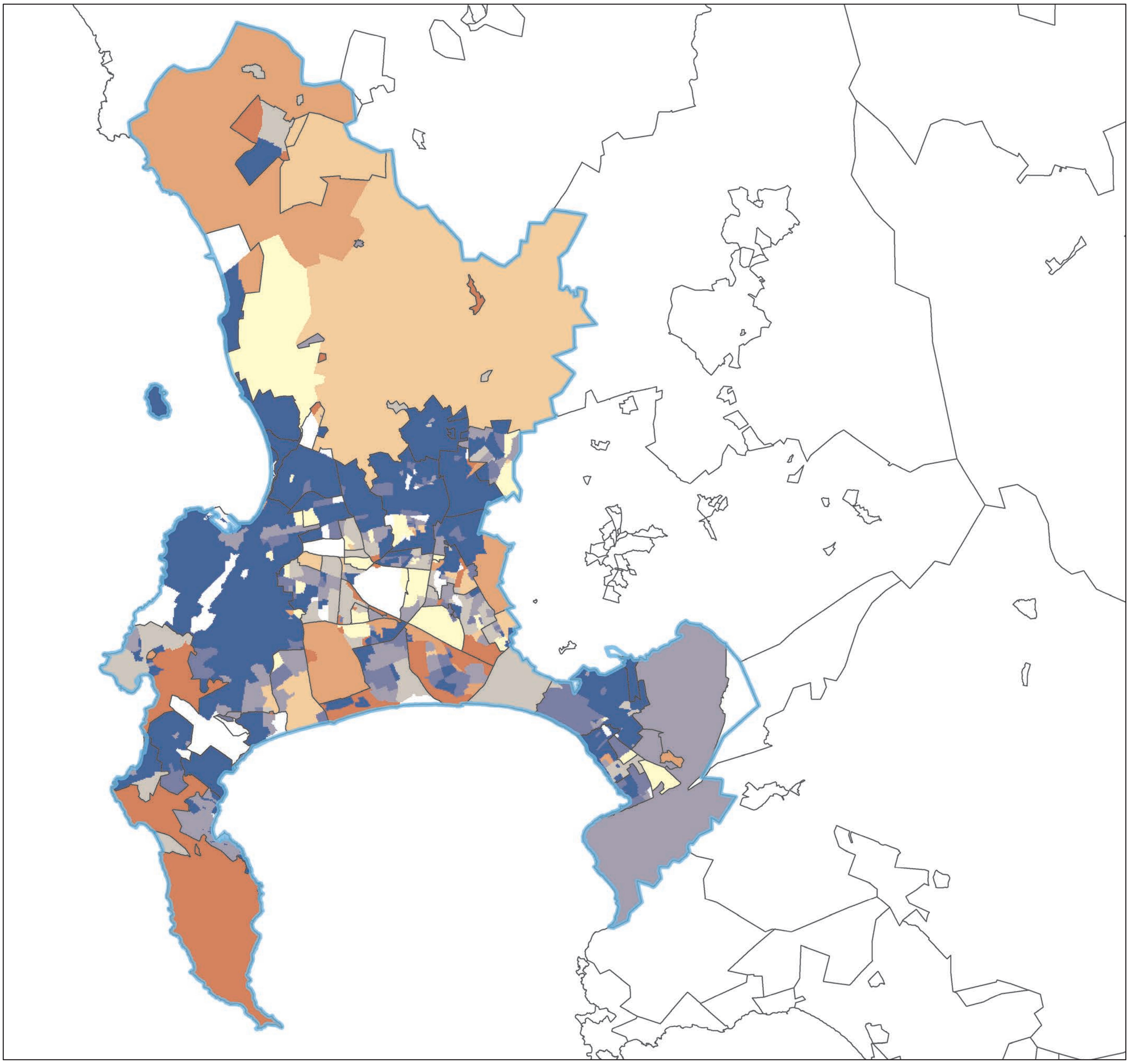
map produced 29/04/2019

City of Cape Town Risk & Vulnerability Analysis

dataset reference: A_flushtoilet

Flushing Toilets

category: resilience **time period: current conditions** weighting 4



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Percentage of households with a flush toilet (2011). Includes toilets which are both connected to main sewers and to septic tanks. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. Cells with no data were assigned a value of 0. Original resolution: SP. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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habitat INFO

map produced 29/04/2019

map 6

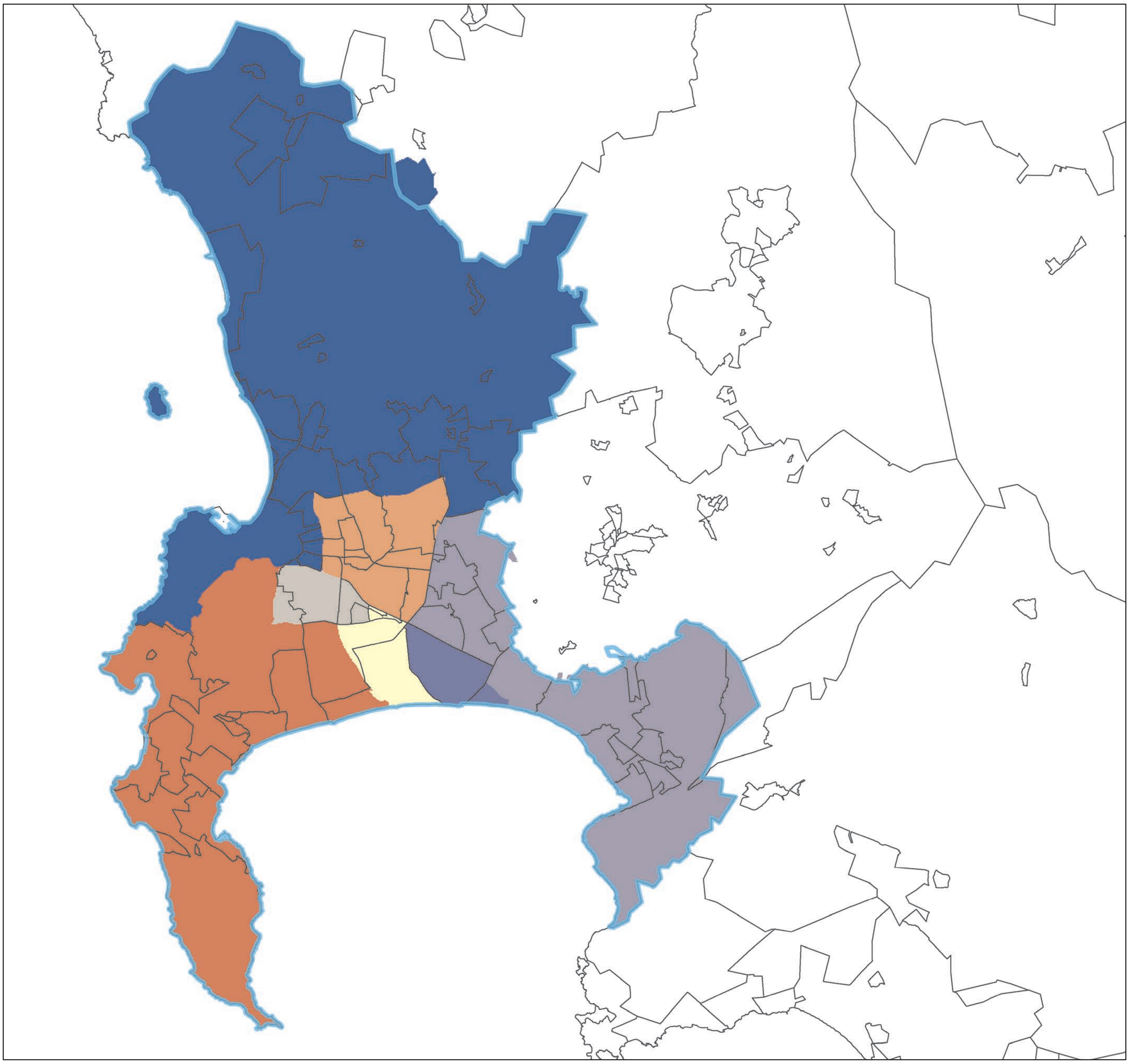
dataset reference: a_hepatitisA_incidence

Hepatitis Rate

category: resilience

time period: current conditions

weighting 2



Legend

- city_boundary
- municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Number of people infected with Hepatitis A (2017). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method with some manual input. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Health regions. Credits: City of Cape Town

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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habitat INFO

blue areas represent high resilience

map produced 29/04/2019

map 7

dataset reference: A_hhincome

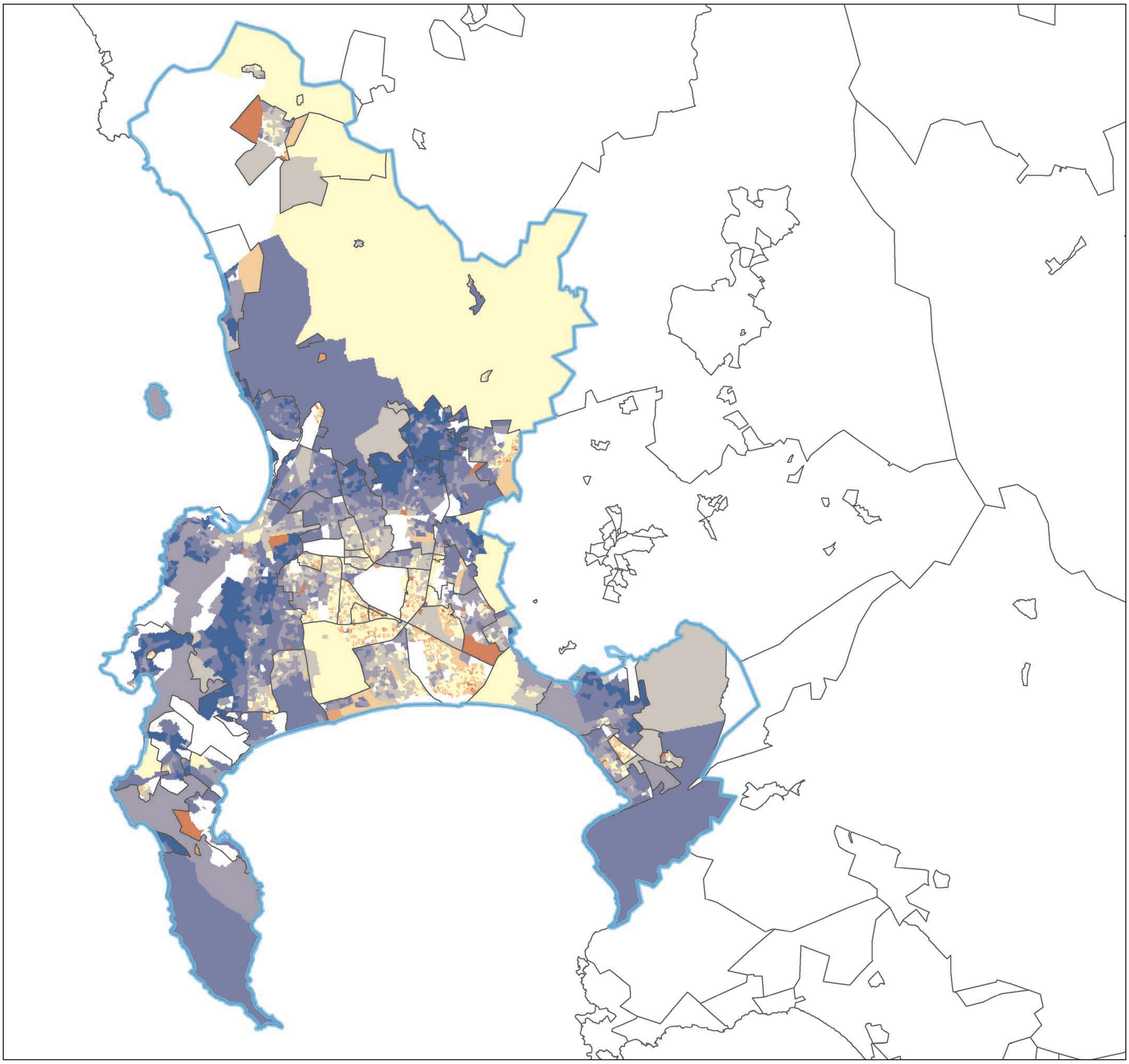
City of Cape Town Risk & Vulnerability Analysis

Median Household Income

category: resilience

time period: current conditions

weighting 5



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Median household income (2011). 0-10 values in raw data used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. Cells with no data were assigned a value of 0. Original resolution: SAL. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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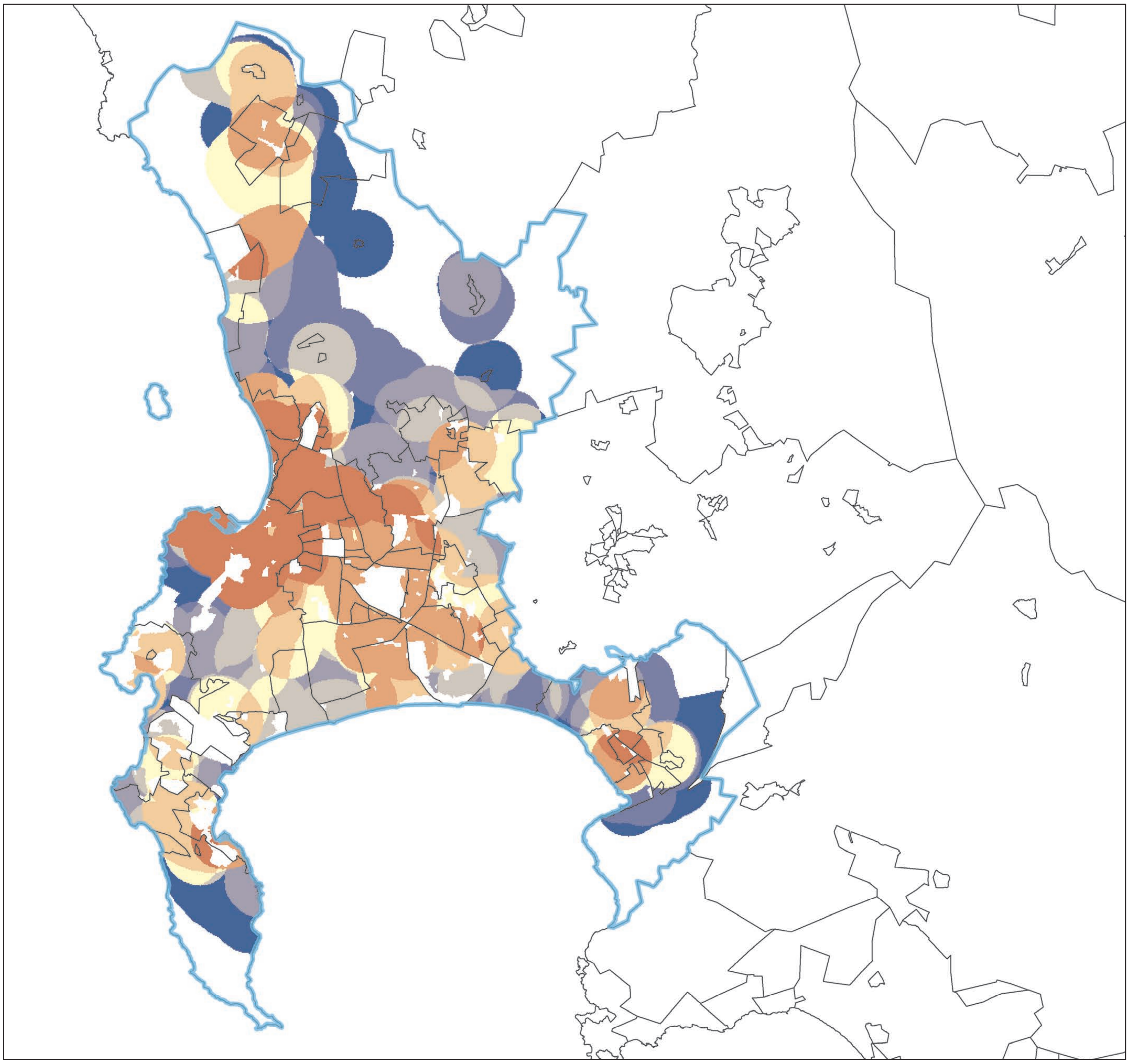
map produced 29/04/2019

dataset reference: A_hhincomerange_3km

Range of Household Income within 3km

category: resilience **time period: current conditions** weighting 4



Legend

- city_boundary
- municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

We ran focal statistics (ArcGIS Spatial Analyst: neighbourhood toolset) to measure the range (minimum to maximum value) of Median Household Income (2011) encountered within a 3km radius of each grid cell. This method is designed to contrast areas of high income disparity where crime may be more prevalent with areas where incomes are more equitable. Credits: City of Cape Town.

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

blue areas represent high resilience

map produced 29/04/2019

map 9

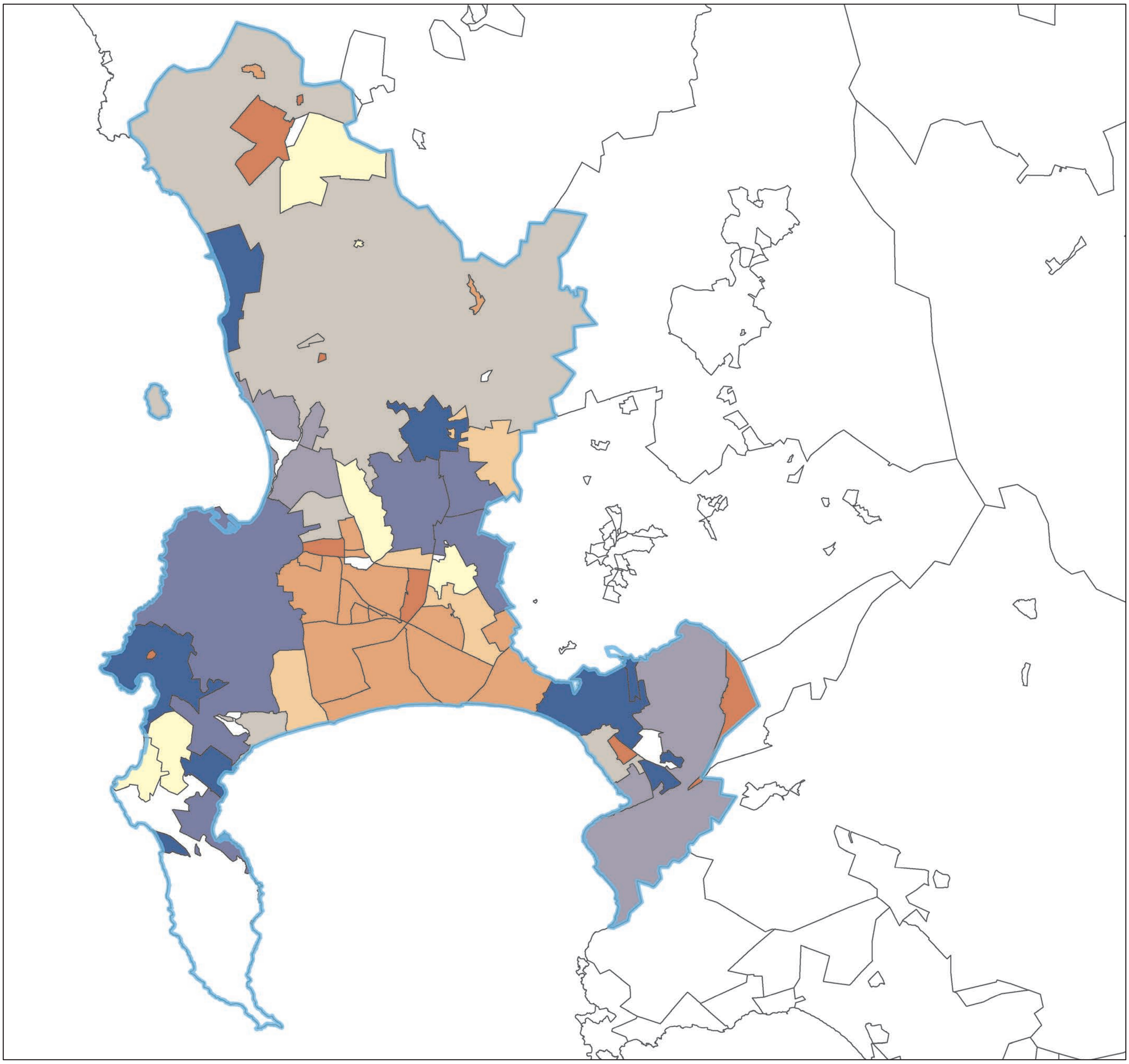
dataset reference: A_highereducation

Higher Education

category: resilience

time period: current conditions

weighting 4



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Percentage aged 20+ years-old with higher education (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using an equal interval method. Cells with no data were assigned a value of 0. Original resolution: Main Place. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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map produced 29/04/2019

map 10

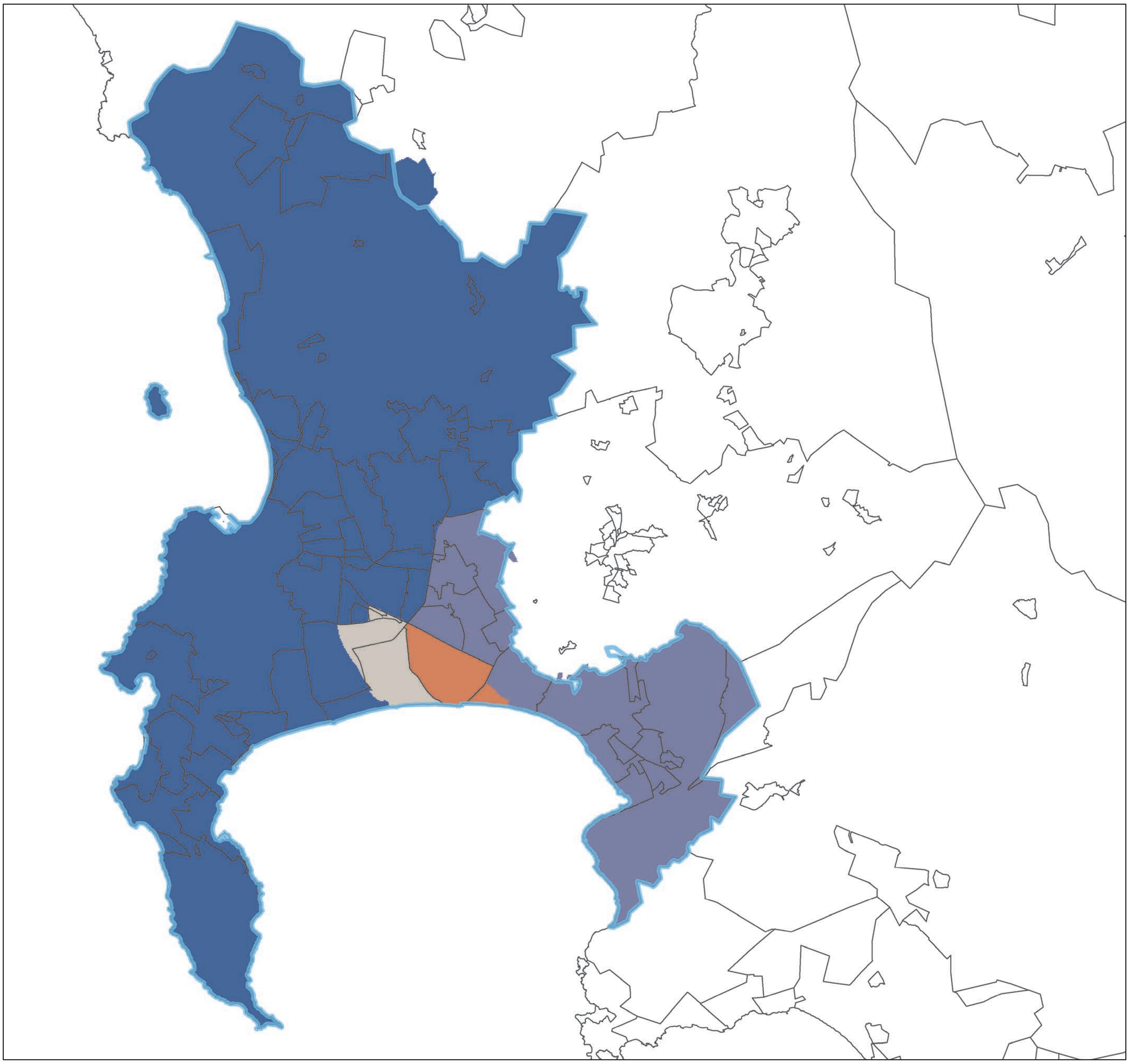
dataset reference: a_HIVuninsuredpopulation_incidence

HIV Rate

category: resilience

time period: current conditions

weighting 3



Legend

city_boundary

municipality boundaries

resilience

Value

no data
1 = low
2
3
4
5
6
7
8
9 = high

0 5 10 20 Kilometers

Estimated number of the uninsured population infected with HIV (2018). Original raw data values used. The data were reclassifed to 1-9 using an equal intervals method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Health regions. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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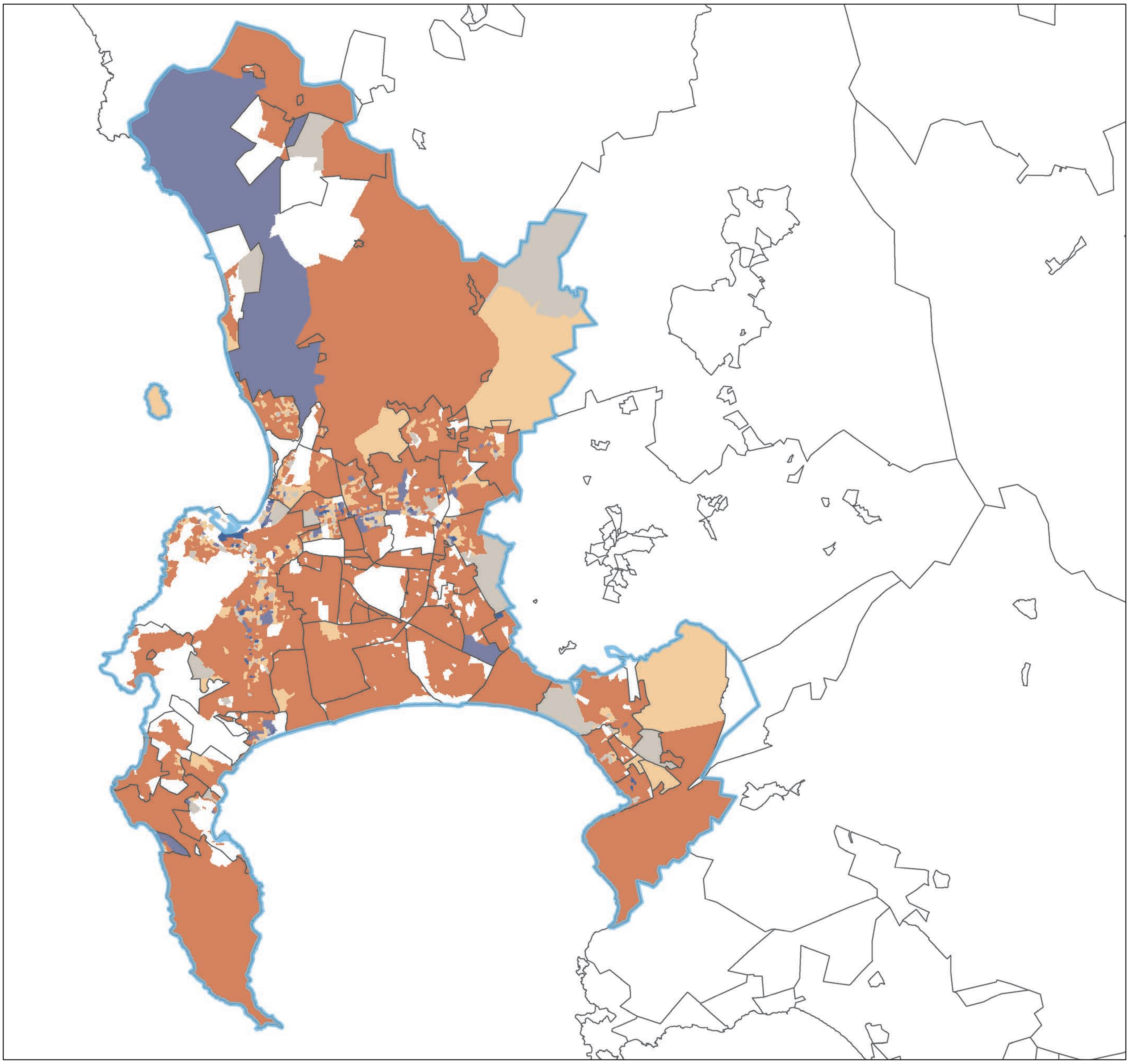
map produced 29/04/2019

dataset reference: A_integration

Social Integration

category: resilience **time period: current conditions** weighting 3



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Integration Score (2011). CoCT data representing the % of three population groups (Black African, Coloured, White) in each SAL were used (Non-residential areas=0, <10% of each population group=1, >10% of each population group=2, >15% of each population group=3, >20% of each population group=4, >25% of each population group=5). The data were converted to raster and then reclassifed to 1-9 using a manual method (0=0, 1=1, 2=3, 3=5, 4=7, 5=9). Cells with no data were assigned a value of 0. Original resolution: SAL. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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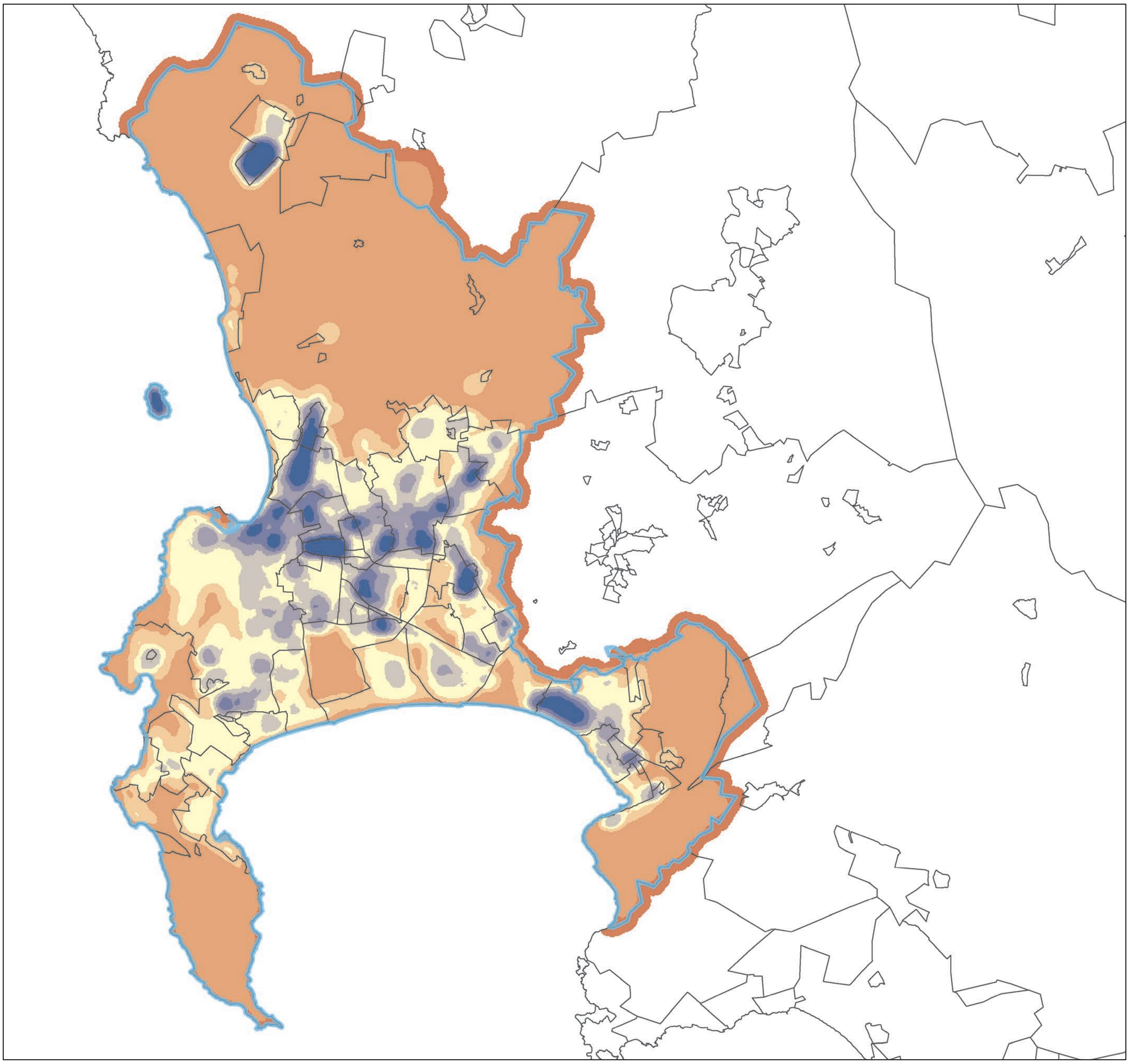
map 12

dataset reference: A_jobs_freq

Employment opportunities within 1km

category: resilience **time period: current conditions** **weighting 4**



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

An indication of job opportunities within 1km was obtained through use of the integrated zoning layer which shows land use classes at high resolution. Each class was given a ranking score from 1 (poor job opportunities) to 9 (very good job opportunities). We ran a focal statistics to sum all of these scores within a 1km radius (raster resolution 100mx100m)

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

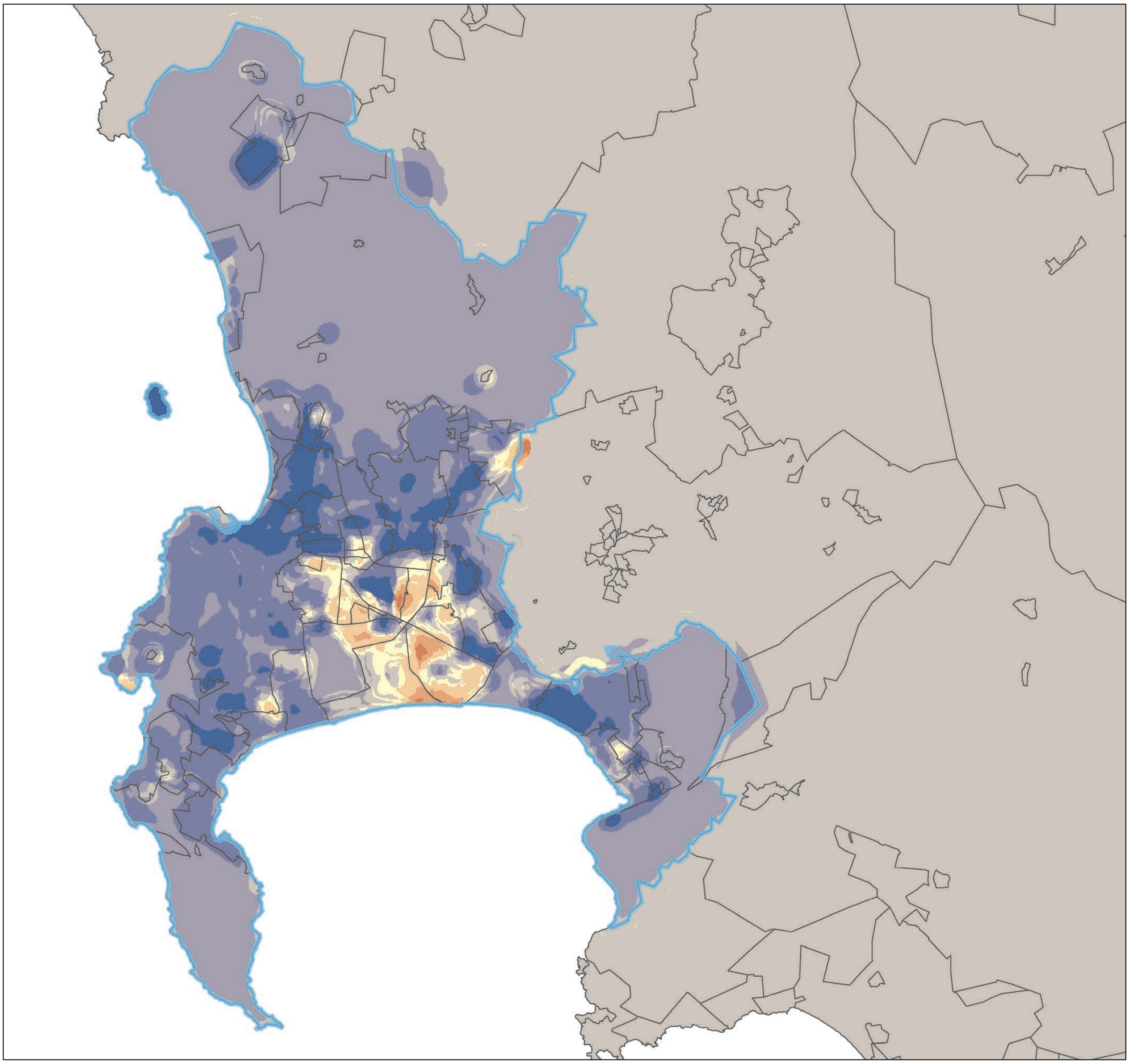
map produced 29/04/2019

map 13

dataset reference: A_jobs_pop_balance

Jobs : Population Balance

category: resilience **time period: current conditions** weighting 5



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

We used two inputs: indicator of population density within 1km radius and indicator of job opportunities within 1km. The latter was obtained by ranking each land use class from COCT integrated zoning layer. Both were scaled 1-9. To arrive at a comparison of where people live in relation to where the jobs are we simply subtracted the local population indicator from the local job indicator so high values in blue represent lots of jobs in the neighbourhood, not many people and low values in red represent not many jobs in the neighbourhood, lots of people competing for them. Reclassified scale from -9 to +8, to 1 to 9.

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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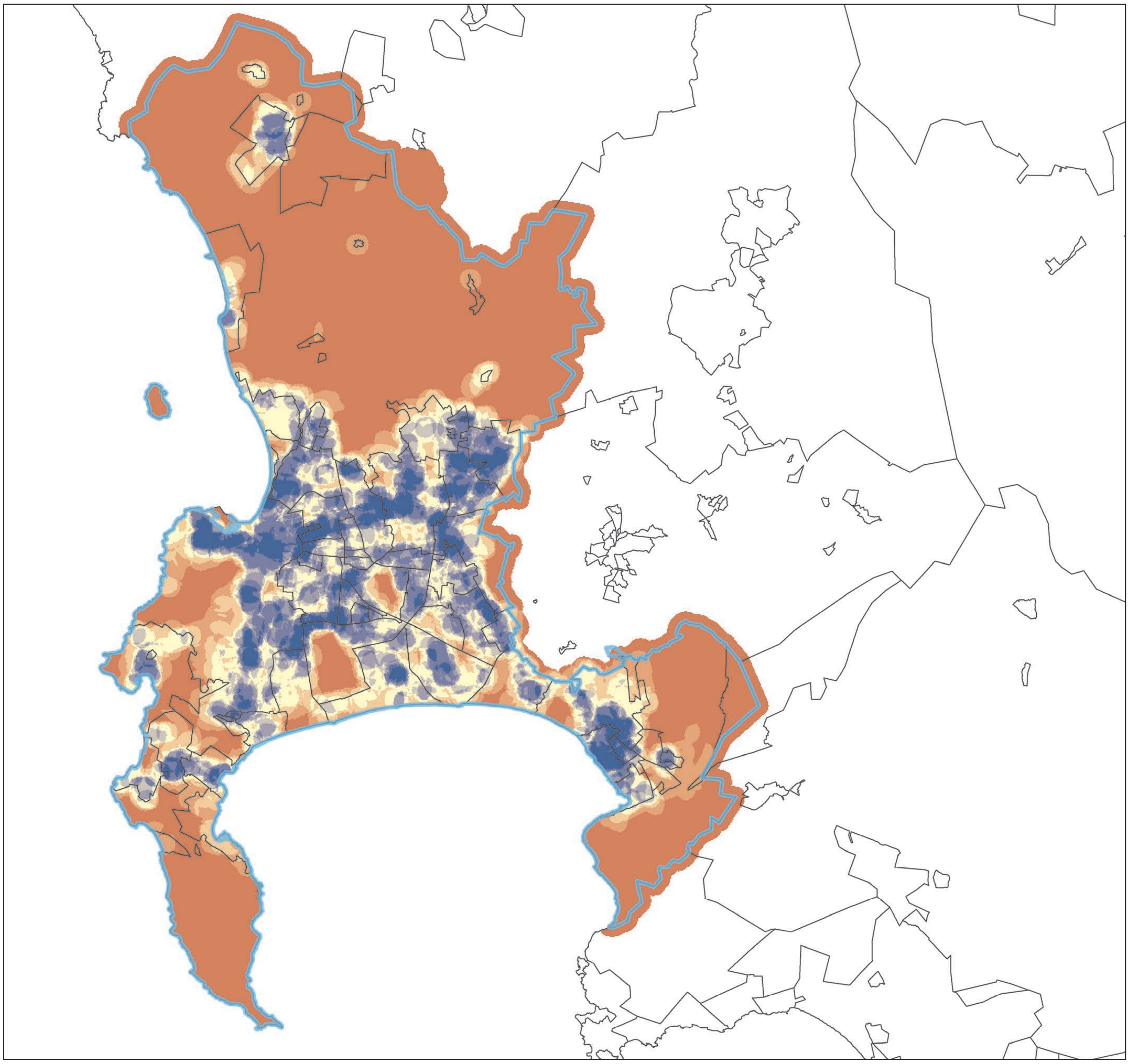
map 14

dataset reference: A_jobs_variety

City of Cape Town Risk & Vulnerability Analysis

Employment variety within 1km

category: resilience   time period: current conditions   weighting 3



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

An indication of job diversity within 1km was obtained through use of the integrated zoning layer which shows land use classes at high resolution. We ran a focal statistics to measure the variety of classes within a 1km radius (raster resolution 100mx100m)

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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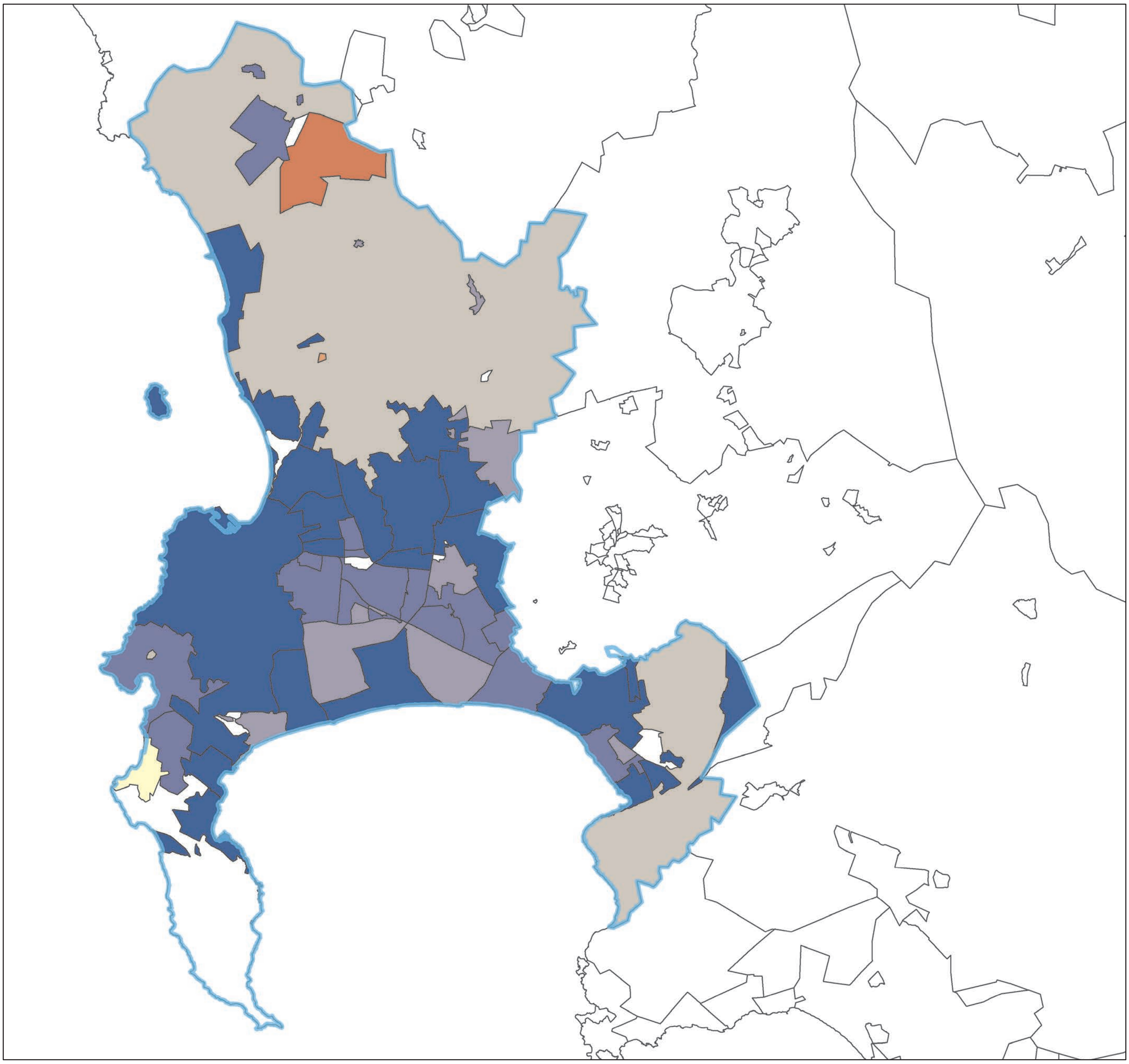
map produced 29/04/2019

dataset reference: A_noeducation

Education (no education)

category: resilience **time period: current conditions** weighting 5



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Percentage aged 20+ years-old with no education (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using an equal interval method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Main Place. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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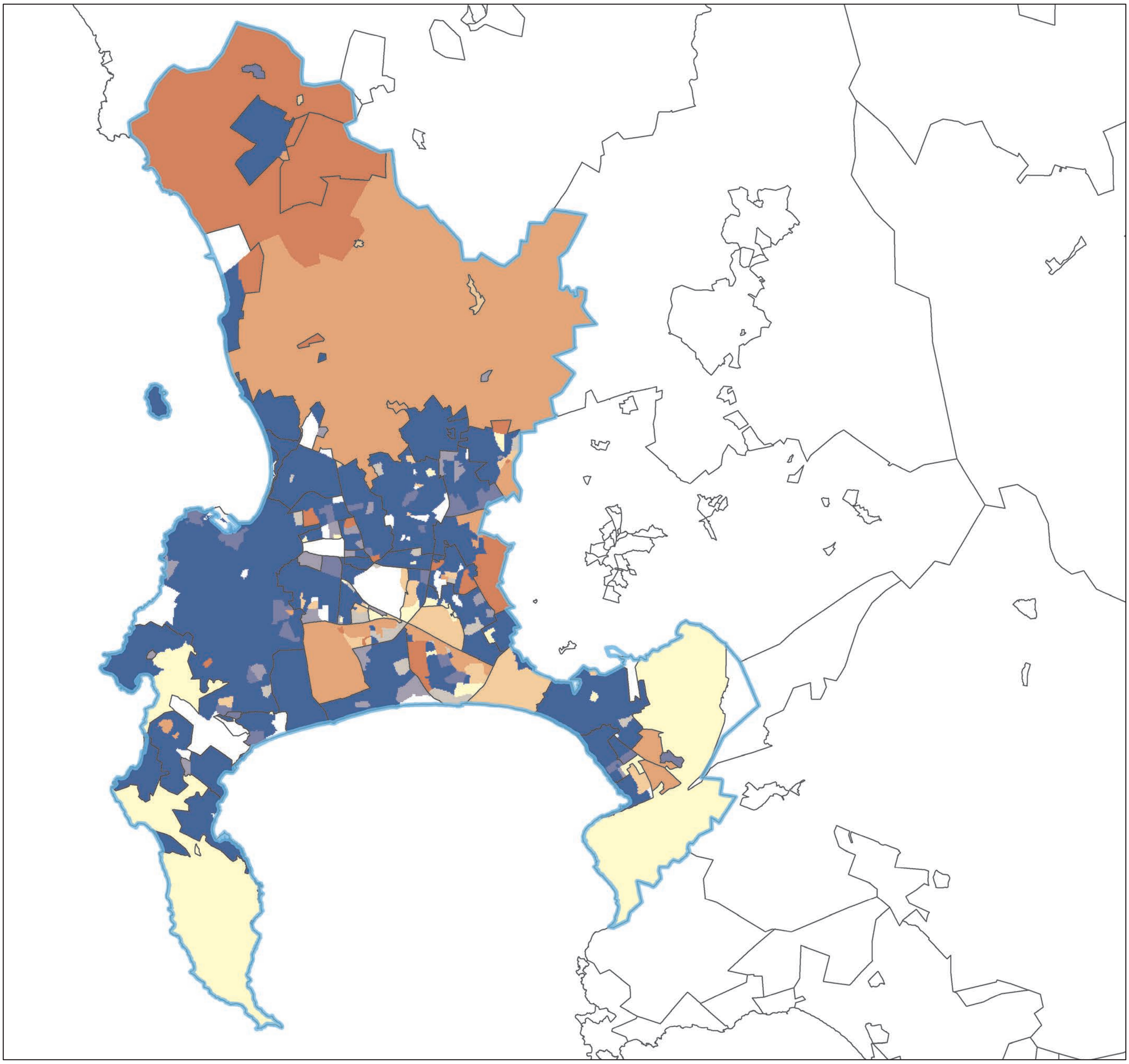
habitat INFO

map produced 29/04/2019

dataset reference: A_norubbishcollection

Refuse Collection

category: resilience | time period: current conditions | weighting 3



Legend

- city_boundary
- municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Percentage of households with no rubbish collections (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: SP. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

map produced 29/04/2019

dataset reference: A_notapwater

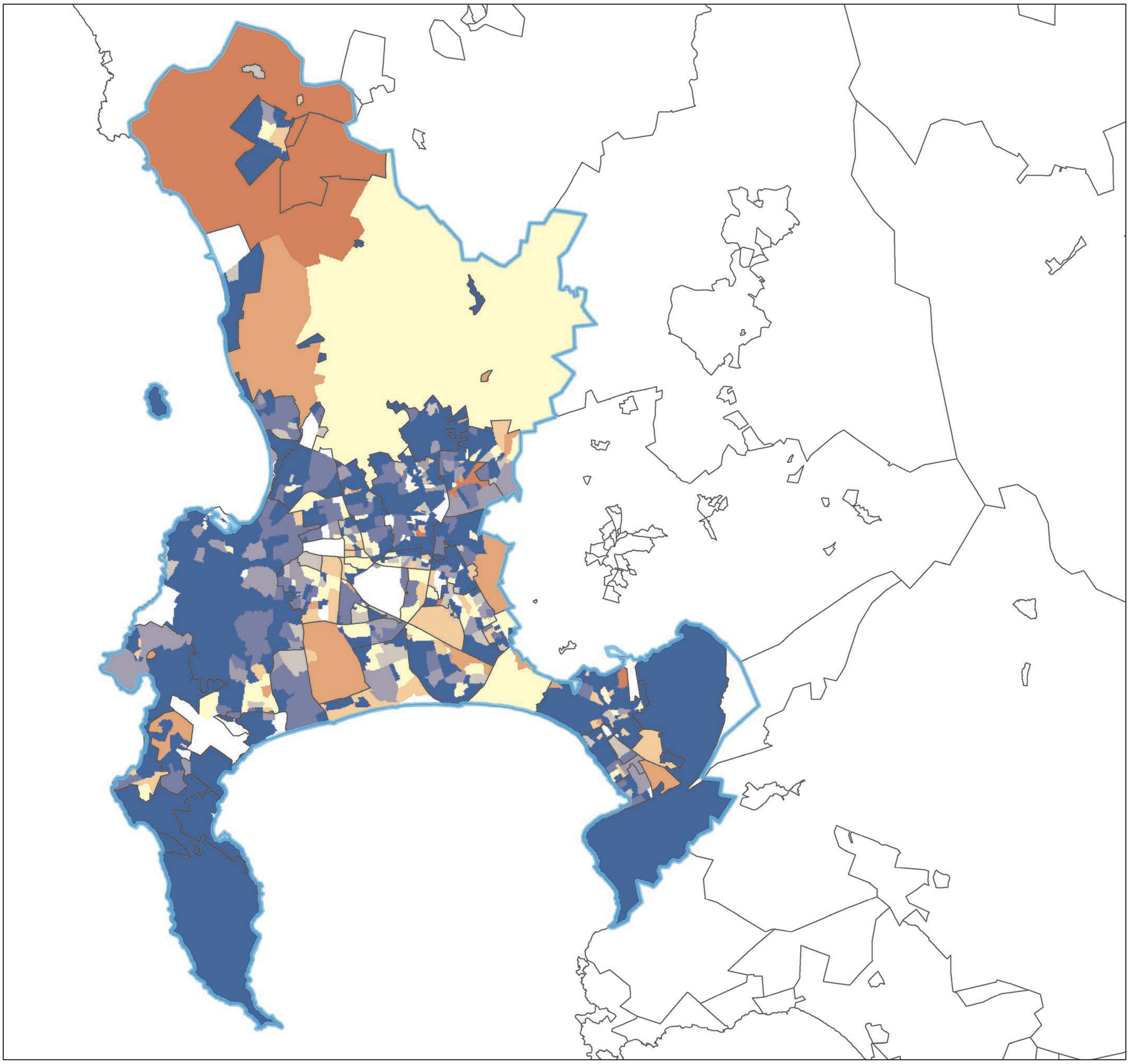
City of Cape Town Risk & Vulnerability Analysis

Tap Water

category: resilience

time period: current conditions

weighting 5



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Percentage of households with no tap water (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: SP. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

map produced 29/04/2019

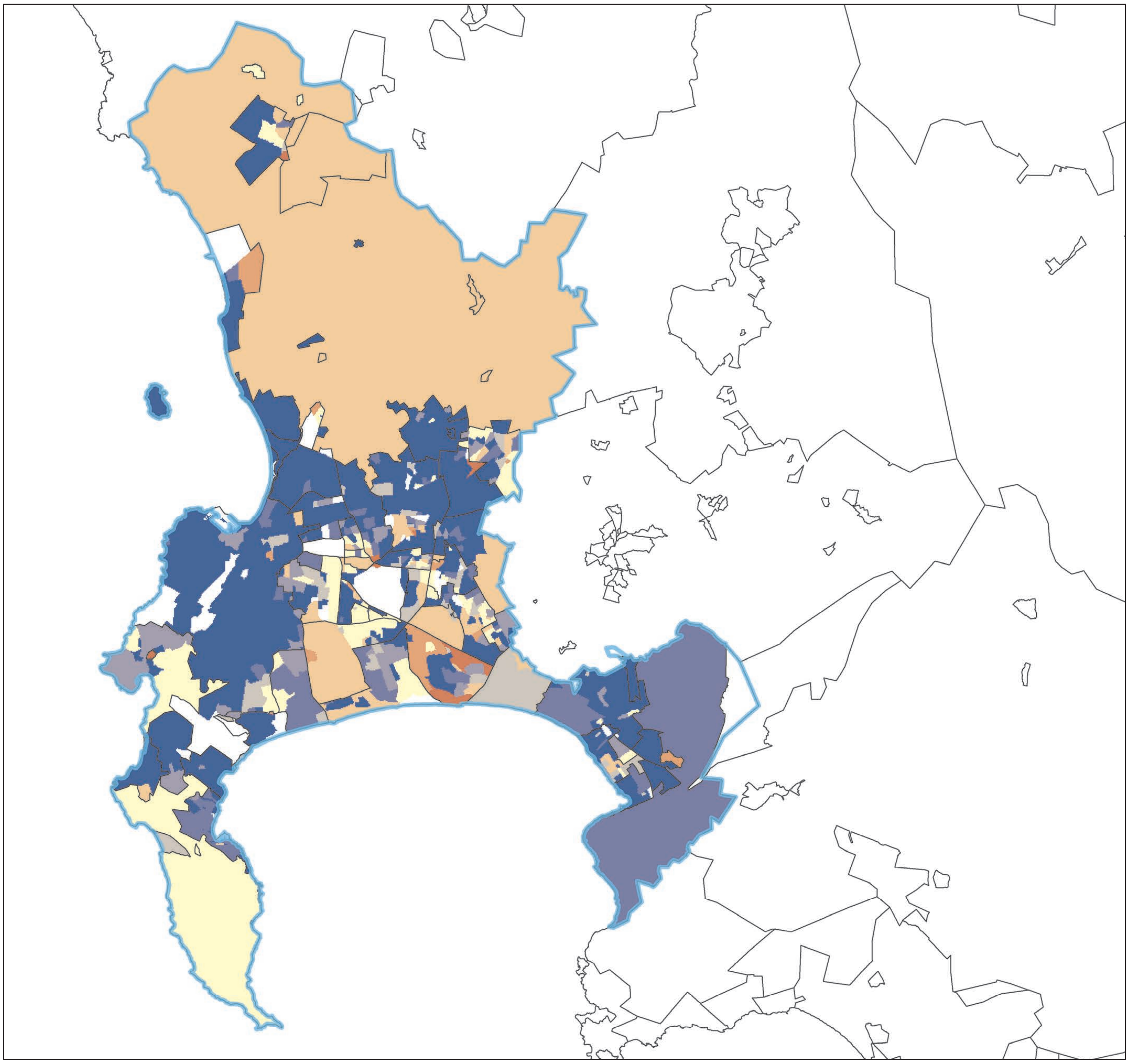
map 18

dataset reference: A_notoilet

City of Cape Town Risk & Vulnerability Analysis

Toilet Facilities

category: resilience **time period: current conditions** weighting 5



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Percentage of households without any toilet (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: SP. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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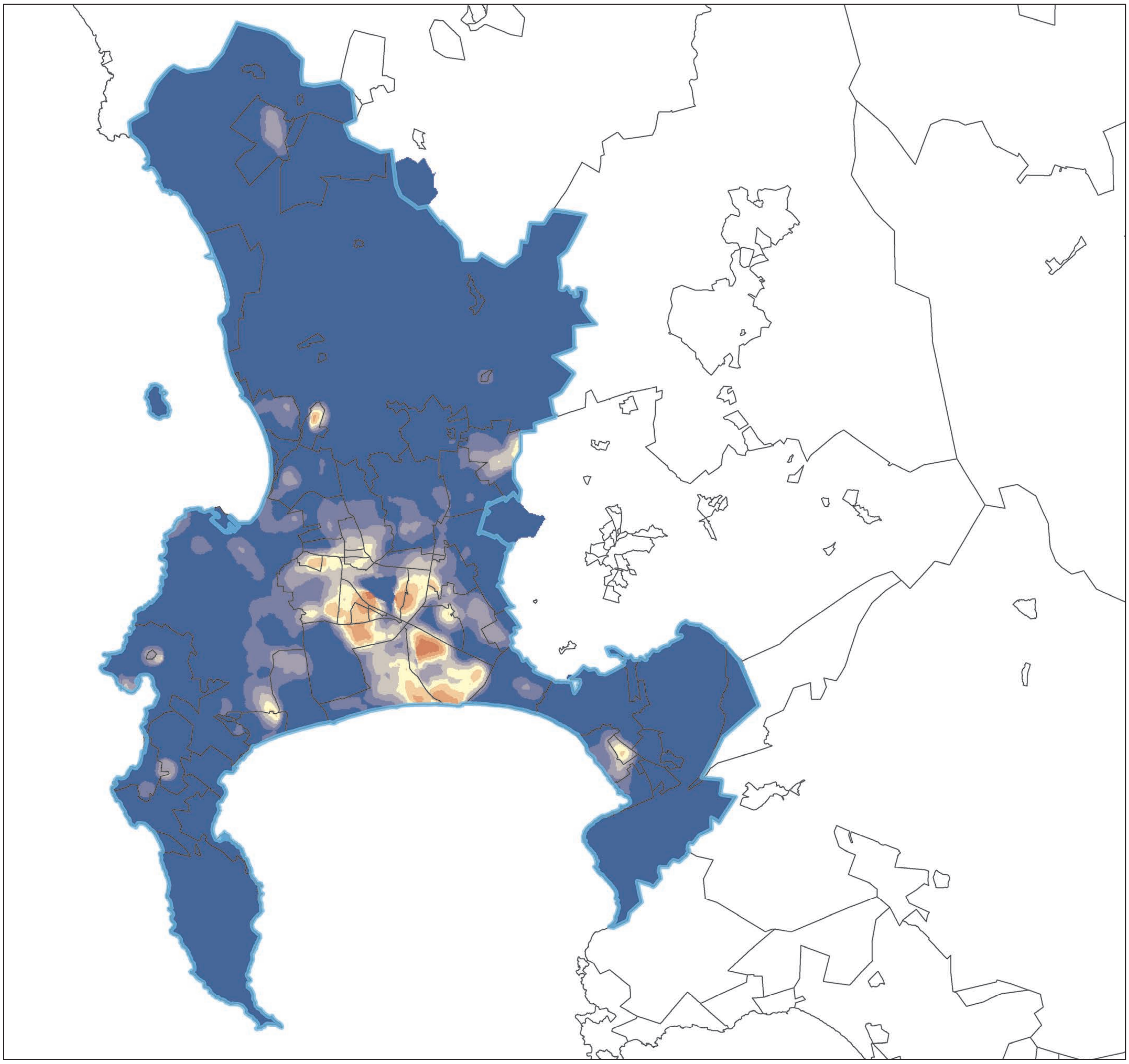
map 19

dataset reference: A_pop_density

Population Density

category: resilience **time period: current conditions** weighting 5



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Data on population density (people per km2) were obtained from the 2011 Census at ward district resolution. We converted polygon values to a raster of 100m resolution, inverted and reclassified values on a scale 1 to 9 such that high values of resilience corresponded to low values of population density. Credits: City of Cape Town.

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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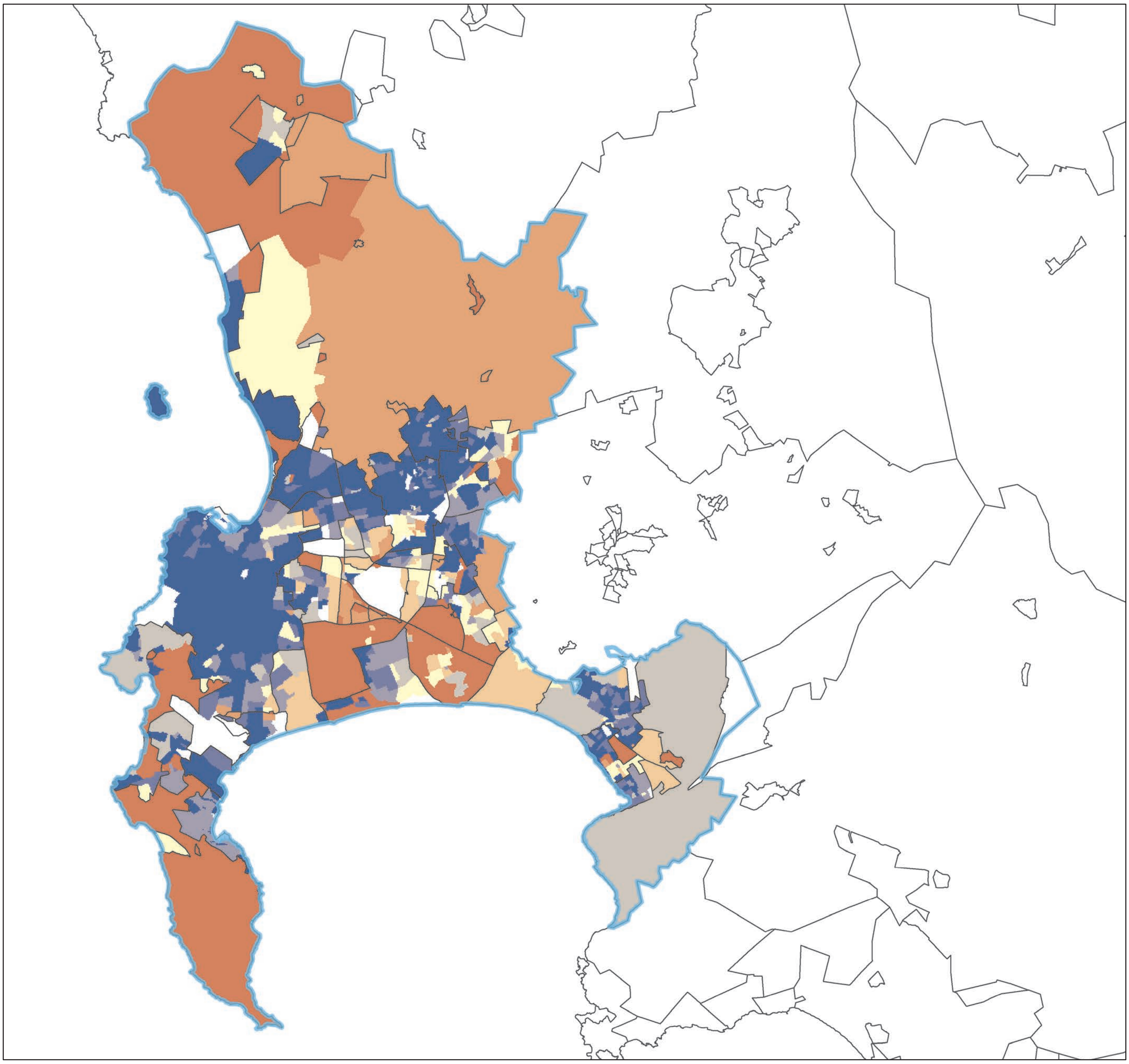
map produced 29/04/2019

Tap Water Inside Houses

category: resilience **time period: current conditions** weighting 4



Legend

city_boundary
municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Percentage of households with tap water inside (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. Cells with no data were assigned a value of 0. Original resolution: SP. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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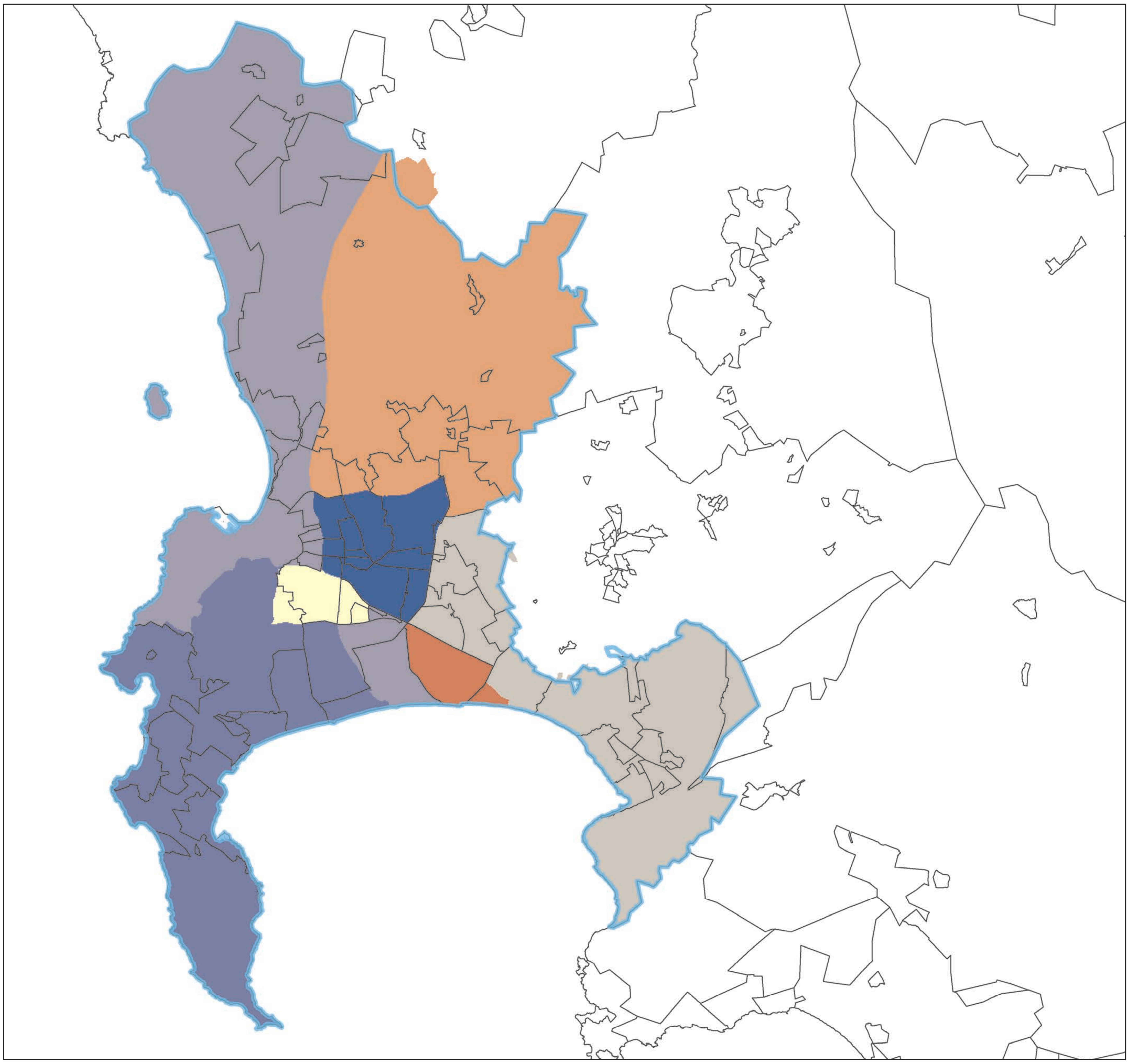
map produced 29/04/2019

map 21

dataset reference: a_TBtestspositive_pcent

TB Rate

category: resilience **time period: current conditions** weighting 2



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

% of people tested for TB who are infected (unknown year). Calculated as the proportion of the people who have been tested who are infected. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method with some manual input. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Health regions. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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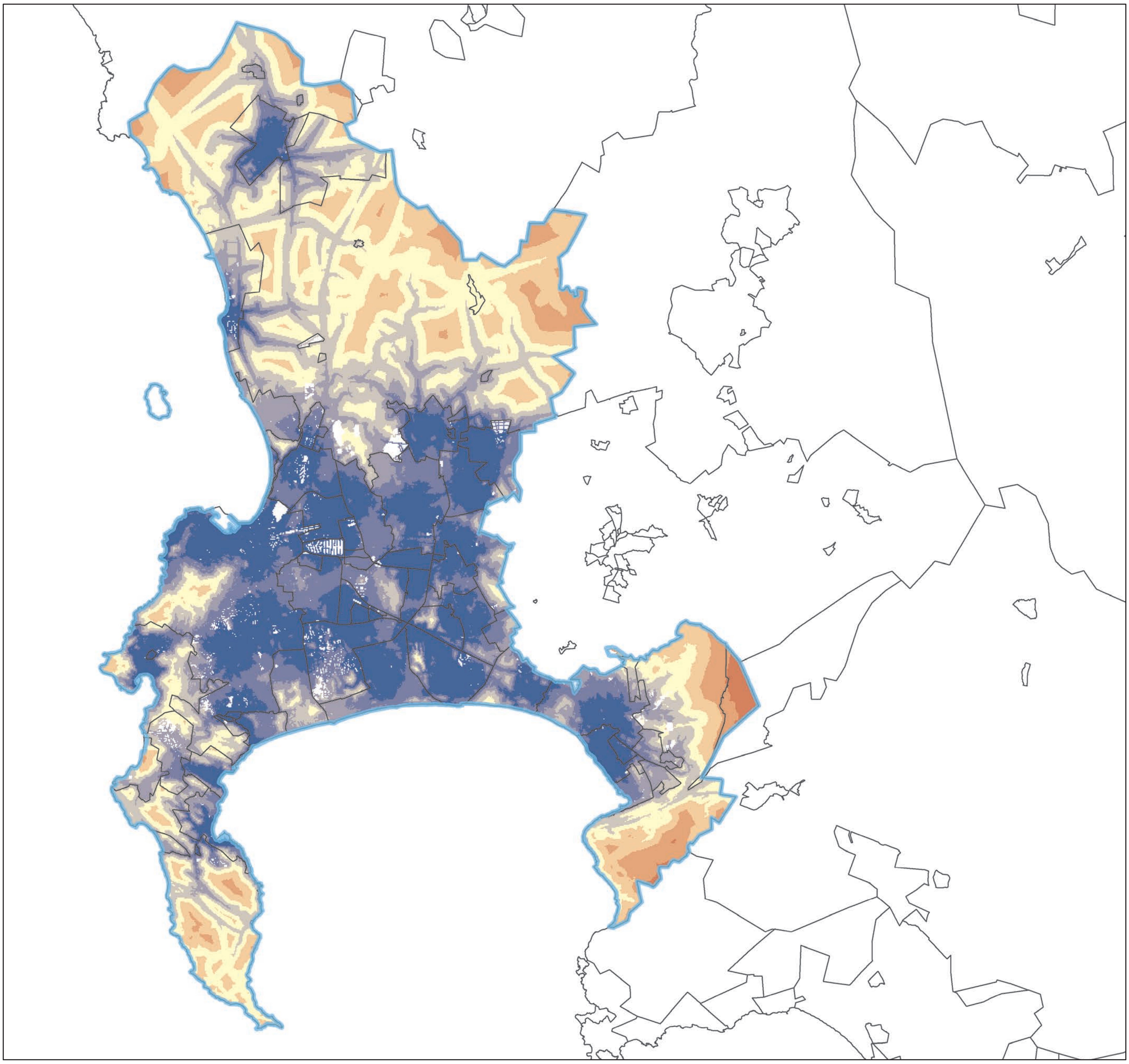
City of Cape Town Risk & Vulnerability Analysis

dataset reference: a_traveltime_city_fire_norail

Access to Fire Stations

category: resilience **time period: current conditions** weighting 4



Legend

city_boundary

municipality boundaries

0 5 10 20 Kilometers

resilience

Value

no data
1 = low
2
3
4
5
6
7
8
9 = high

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

Travel time within the city to fire stations via road and foot (2019). OpenStreetMap (OSM) landuse and roads categories were accessed and speeds attributed to each sub-category of these. These were combined into a friction layer from which travel time was calculated from each cell for. Fire station locations provided by CoCT. The data were reclassifed to 1-9 using a geometrical intervals method. The reclassified values were inverted such that high values represented high Resilience. Original resolution: n/a. Credits: habitat INFO, OSM, CoCT

blue areas represent high resilience

map produced 29/04/2019

map 23

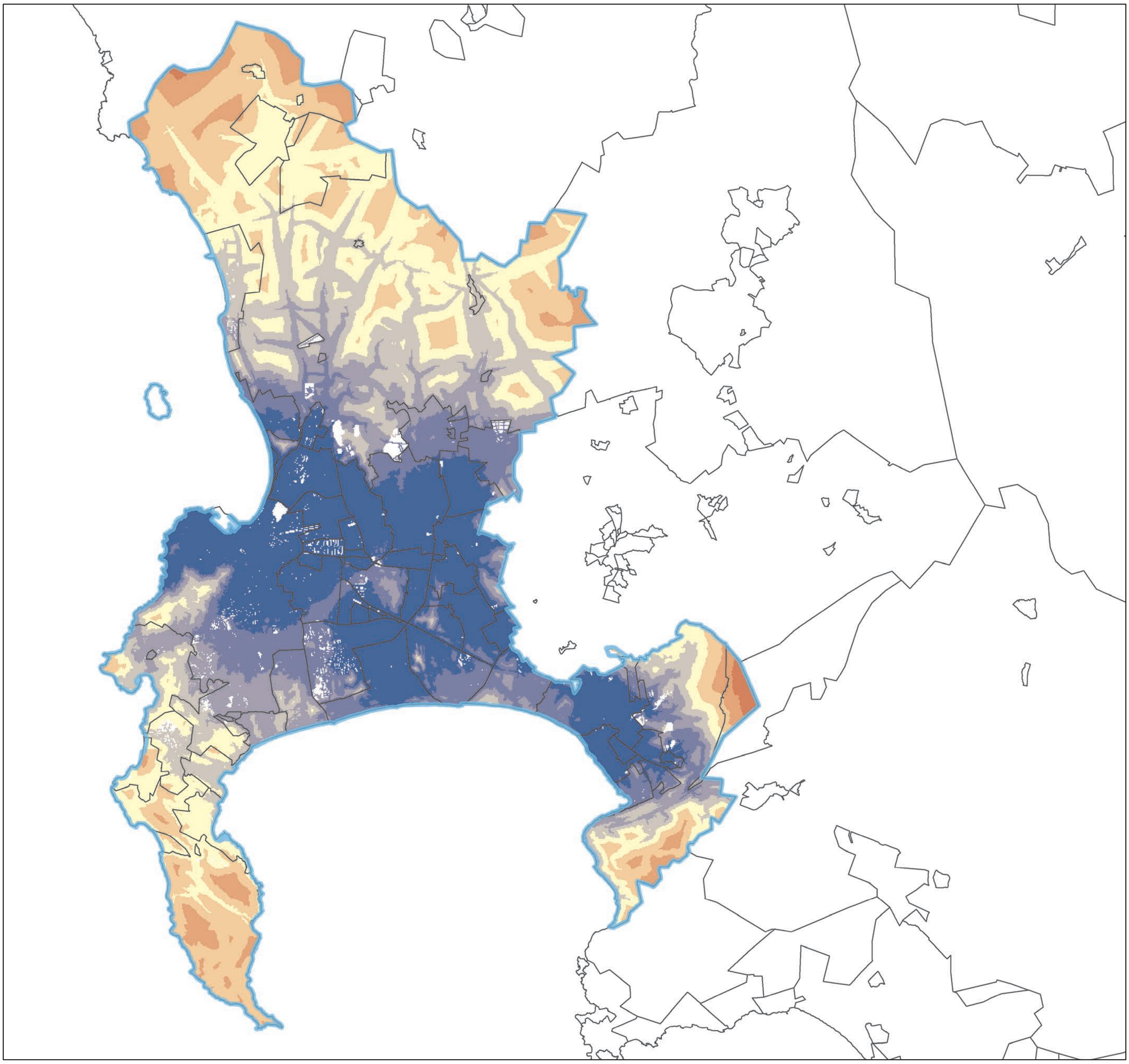
dataset reference: a_traveltime_city_hospital_withrail

Access to Hospitals

category: resilience

time period: current conditions

weighting 4



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Travel time within the city to hospitals via road, rail and foot (2019). OpenStreetMap (OSM) landuse, roads and railways categories were accessed and speeds attributed to each sub-category of these. These were combined into a friction layer from which travel time was calculated from each cell for. This travel time analysis includes railways, but does not account for ability to only access railways at defined points (i.e. stations). Hospital locations sourced from OSM buildings category. The data were reclassifed to 1-9 using a geometrical intervals method. The reclassified values were inverted such that high values represented high Resilience. Original resolution: n/a. Credits: habitat INFO, OSM, CoCT

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

map produced 29/04/2019

map 24

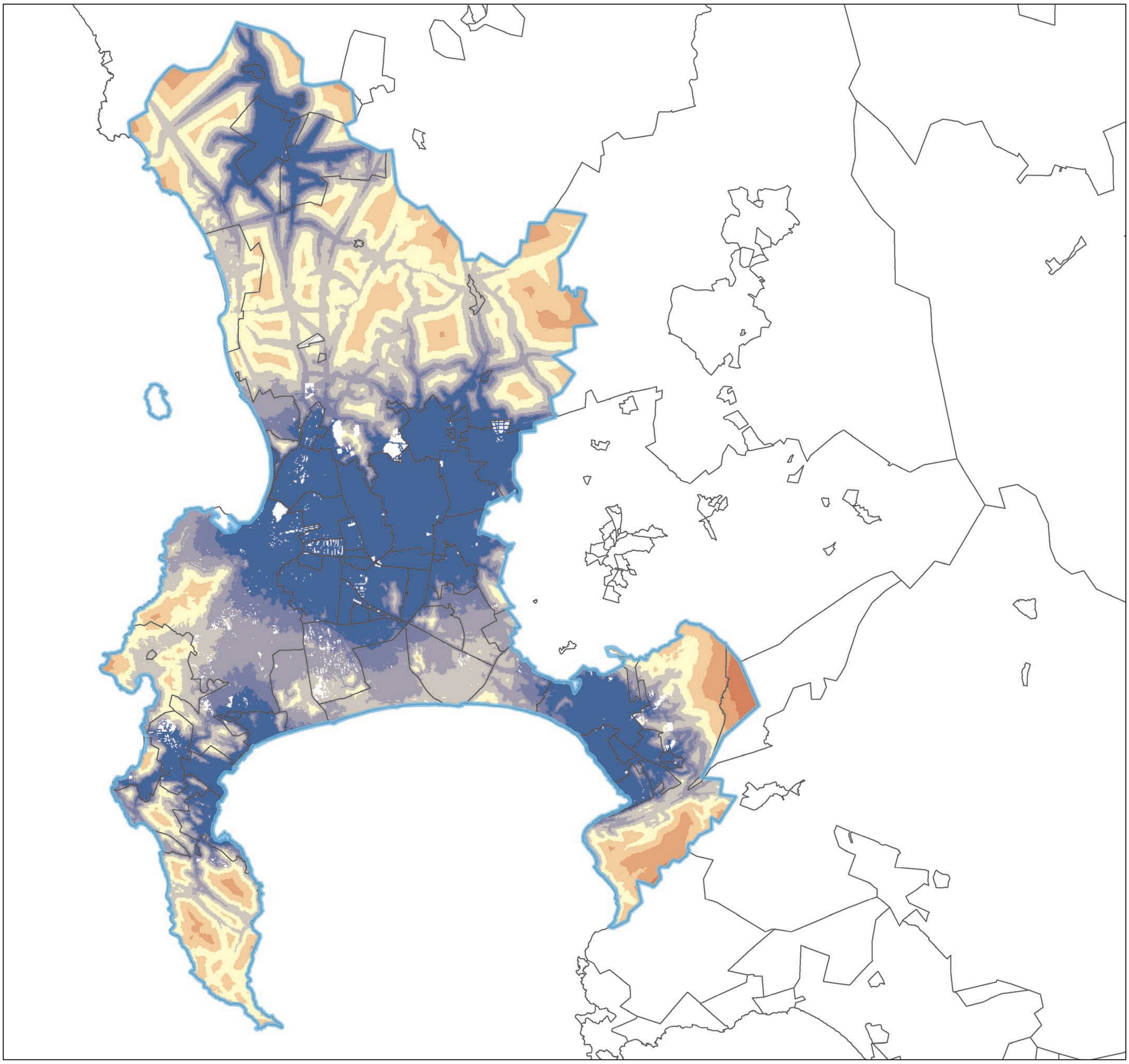
dataset reference: a_traveltime_city_otherCBDs_withrail

Access to all CBDs

category: resilience

time period: current conditions

weighting 3



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Travel time within the city to other CBDs via road, rail and foot (2019). OpenStreetMap (OSM) landuse, roads and railways categories were accessed and speeds attributed to each sub-category of these. These were combined into a friction layer from which travel time was calculated from each cell for. This travel time analysis includes railways, but does not account for ability to only access railways at defined points (i.e. stations). CBD locations identified from the CoCT intergrated zoning data. The data were reclassifed to 1-9 using a geometrical intervals method. The reclassified values were inverted such that high values represented high Resilience. Original resolution: n/a. Credits: habitat INFO, OSM, CoCT

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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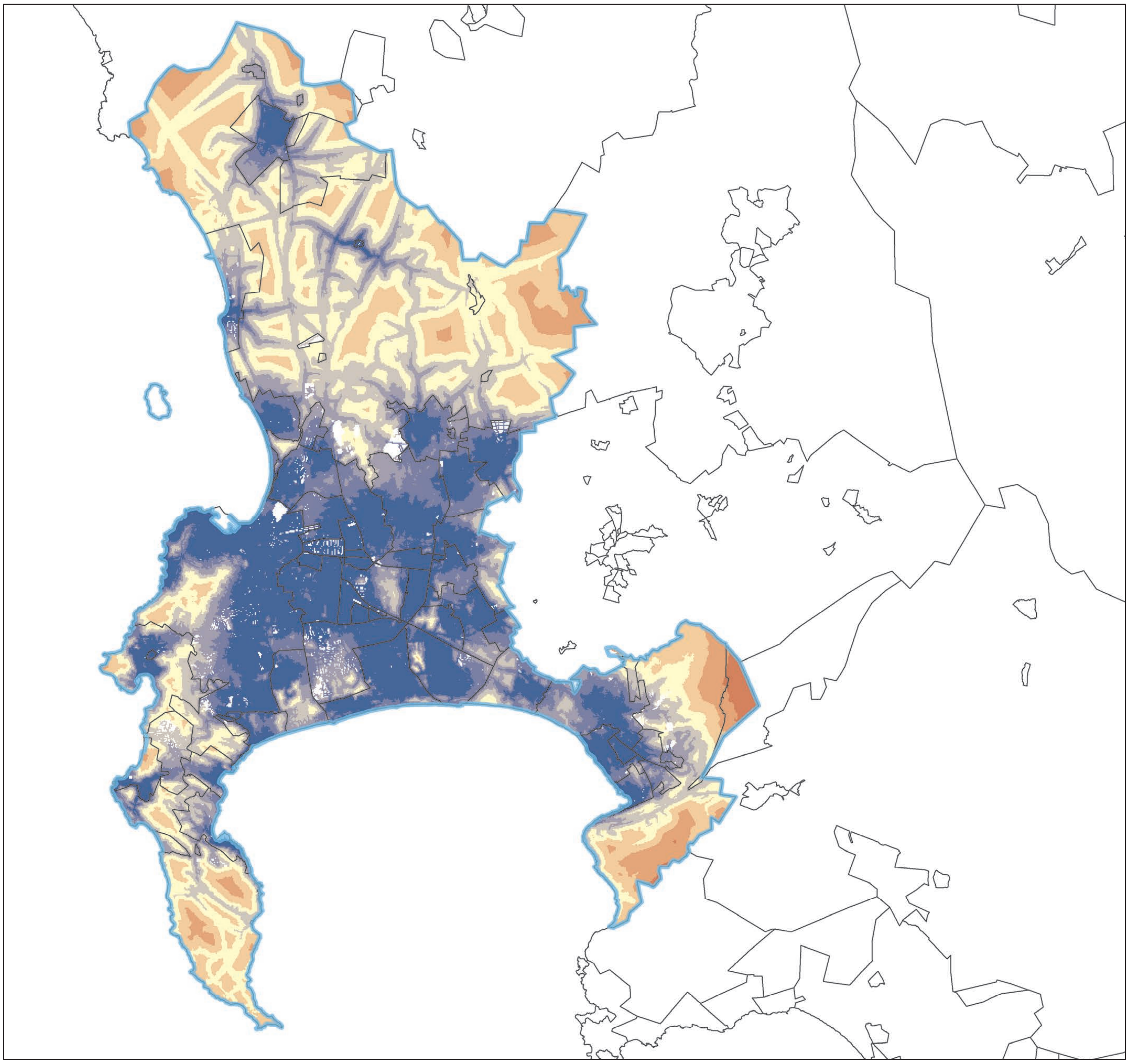
oneWORLD We build resilient futures habitat INFO

map produced 29/04/2019

Access to Police Stations

category: resilience **time period: current conditions** weighting 3



Legend

city_boundary
municipality boundaries

resilience

Value

no data
1 = low
2
3
4
5
6
7
8
9 = high

0 5 10 20 Kilometers

Travel time within the city to police stations via road, rail and foot (2019). OpenStreetMap (OSM) landuse, roads and railways categories were accessed and speeds attributed to each sub-category of these. These were combined into a friction layer from which travel time was calculated from each cell for. This travel time analysis includes railways, but does not account for ability to only access railways at defined points (i.e. stations). Police station locations provided by CoCT. The data were reclassifed to 1-9 using a geometrical intervals method. The reclassified values were inverted such that high values represented high Resilience. Original resolution: n/a. Credits: habitat INFO, OSM, CoCT

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
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Latitude Of Origin: 0.0000
Units: Meter

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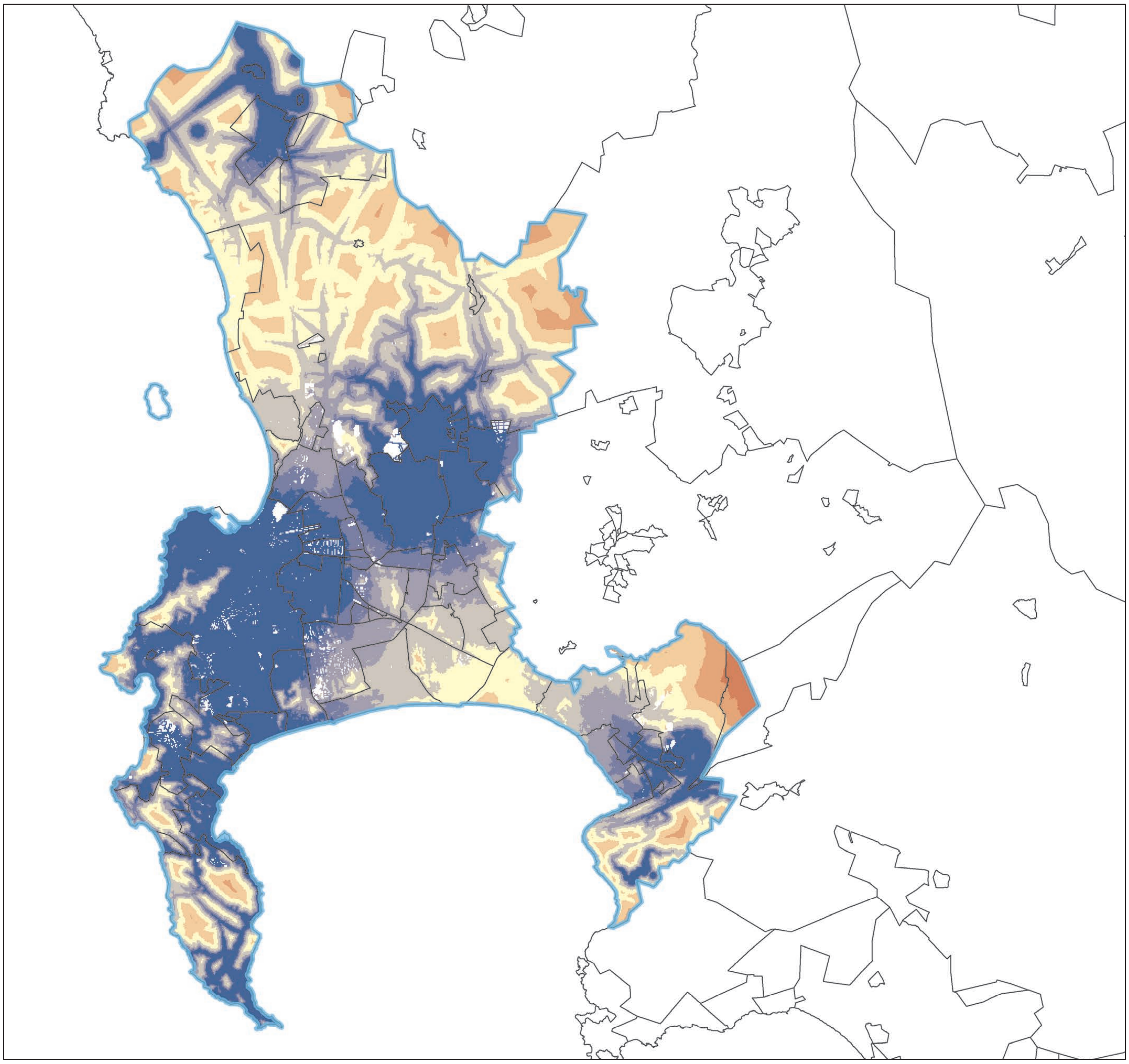
map produced 29/04/2019

Access to Freshwater Springs

category: resilience **time period: current conditions** weighting 1



Legend

city_boundary
municipality boundaries

resilience

Value

no data
1 = low
2
3
4
5
6
7
8
9 = high

0 5 10 20 Kilometers

Travel time within the city to springs via road, rail and foot (2019). OpenStreetMap (OSM) landuse, roads and railways categories were accessed and speeds attributed to each sub-category of these. These were combined into a friction layer from which travel time was calculated from each cell for. This travel time analysis includes railways, but does not account for ability to only access railways at defined points (i.e. stations). Spring locations provided by CoCT. The data were reclassifed to 1-9 using a geometrical intervals method. The reclassified values were inverted such that high values represented high Resilience. Original resolution: n/a. Credits: habitat INFO, OSM, CoCT

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
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Latitude Of Origin: 0.0000
Units: Meter

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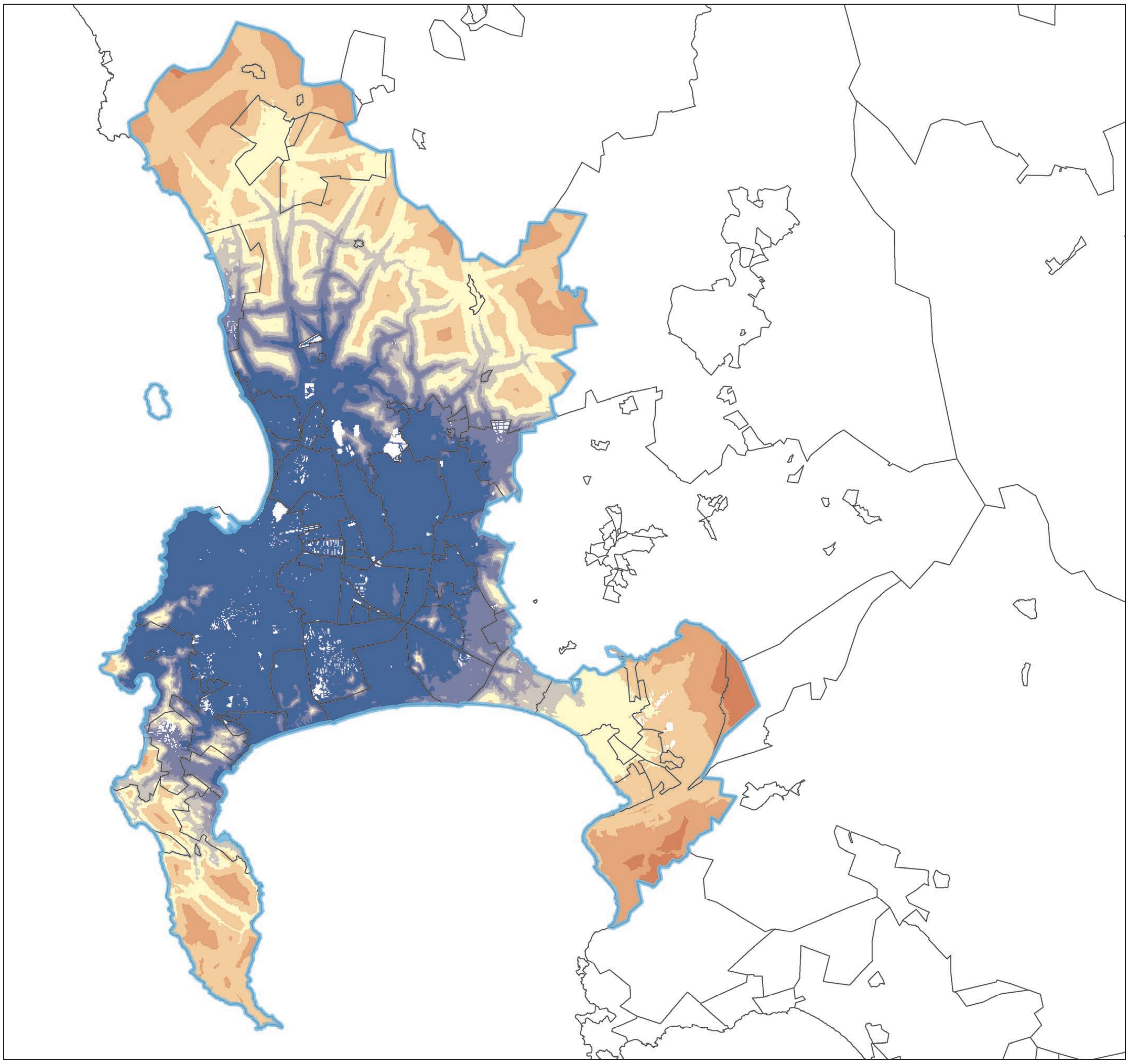
map produced 29/04/2019

map 27

dataset reference: a_traveltime_city_withrail

Access to Cape Town CBD

category: resilience **time period: current conditions** weighting 4



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Travel time within the city to the CBD via road, rail and foot (2019). OpenStreetMap (OSM) landuse, roads and railways categories were accessed and speeds attributed to each sub-category of these. These were combined into a friction layer from which travel time was calculated from each cell for. This travel time analysis includes railways, but does not account for ability to only access railways at defined points (i.e. stations). CBD location provided by CoCT. The data were reclassifed to 1-9 using a geometrical intervals method. The reclassified values were inverted such that high values represented high Resilience. Original resolution: n/a. Credits: habitat INFO, OSM, CoCT

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

map produced 29/04/2019

City of Cape Town Risk & Vulnerability Analysis

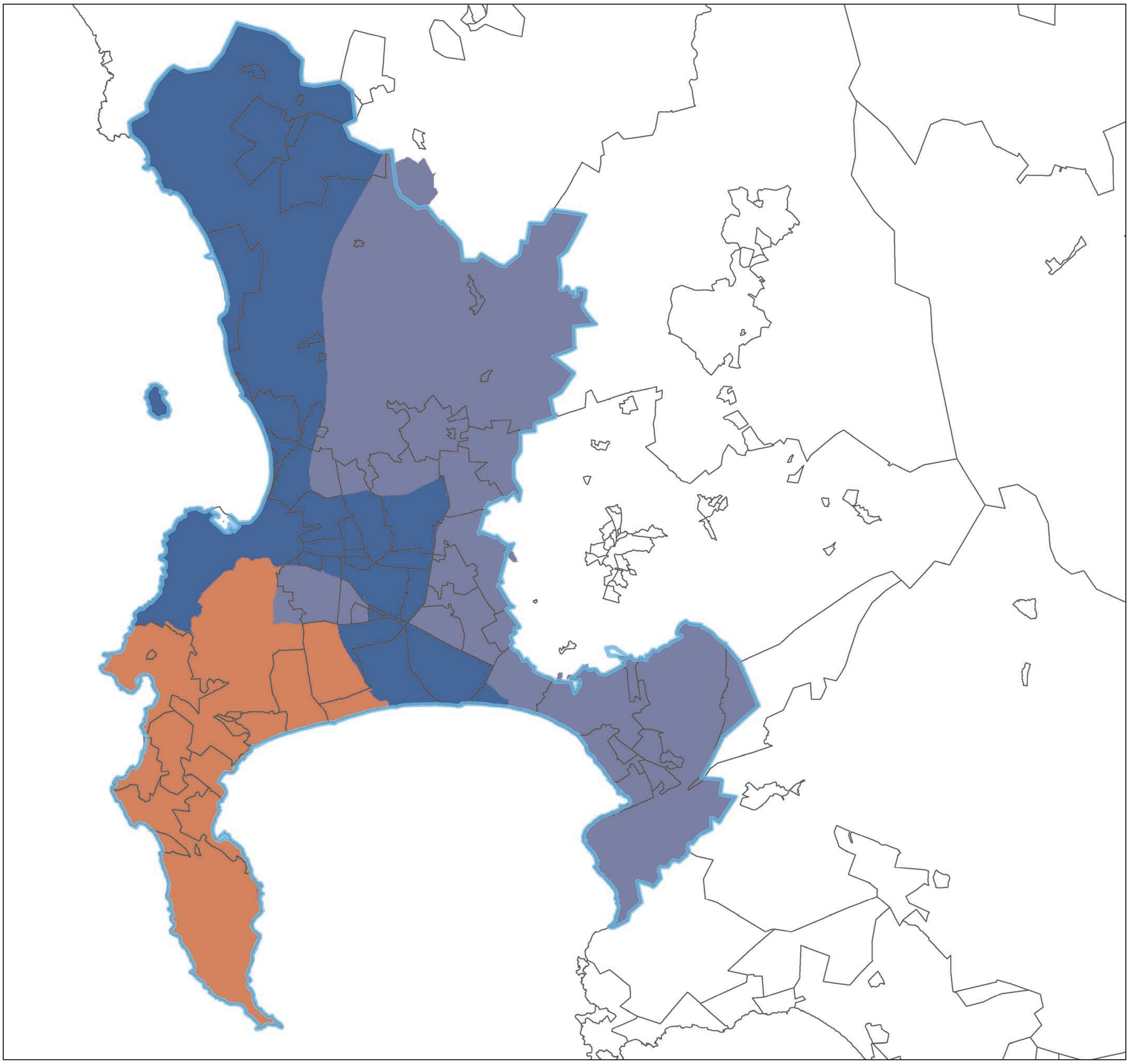
dataset reference: a_typhoid_incidence

Typhoid Rate

category: resilience

time period: current conditions

weighting 2



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Number of people infected with Typhoid (2017). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using an equal intervals method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Health regions. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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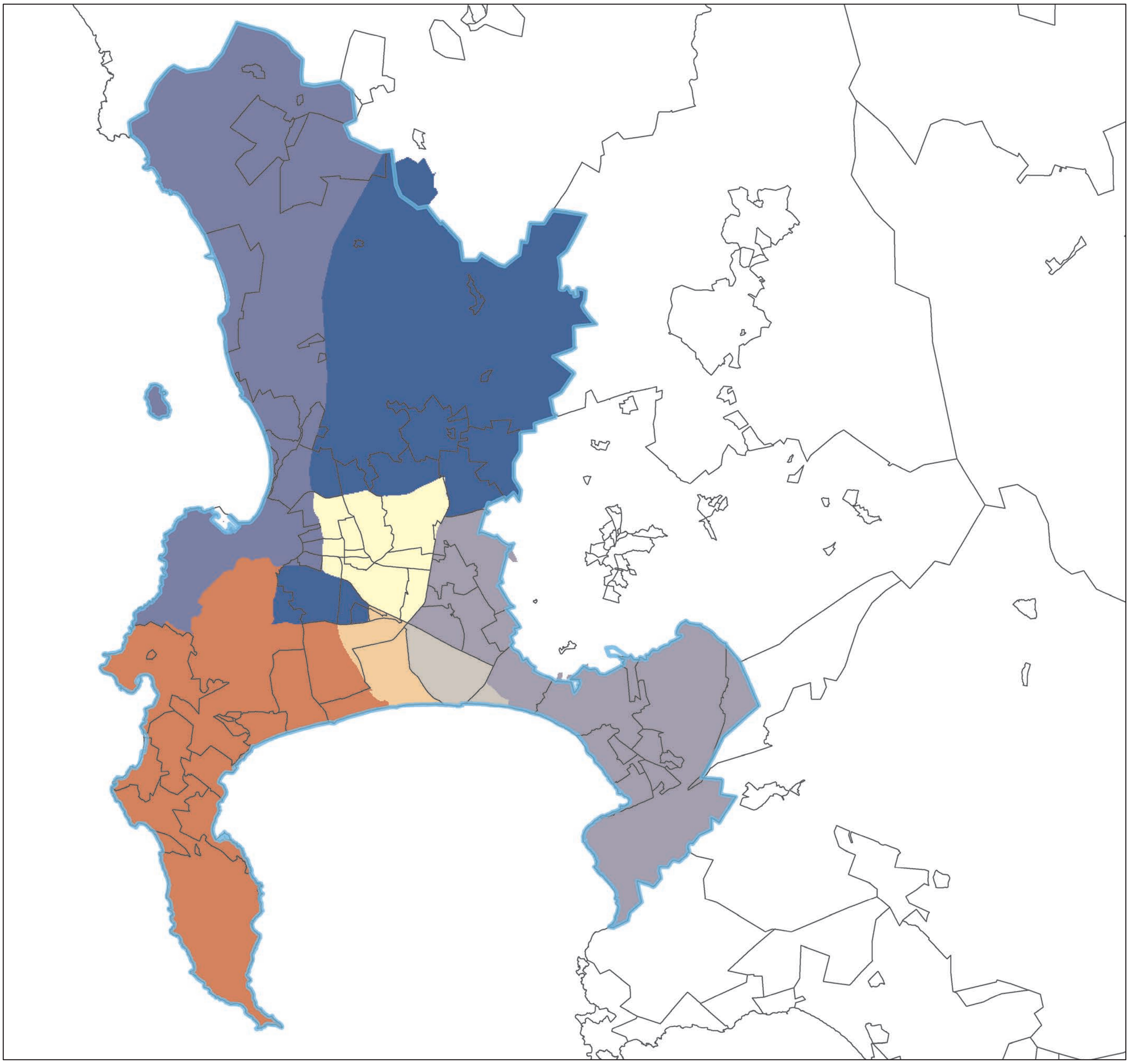
map 29

dataset reference: a_under5malnutrition_incidence

Malnourishment Rate (Children under 5y)

category: resilience **time period: current conditions** weighting 3



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

Number of malnourished children aged under 5 years-old (unknown year). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method with some manual input. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Health regions. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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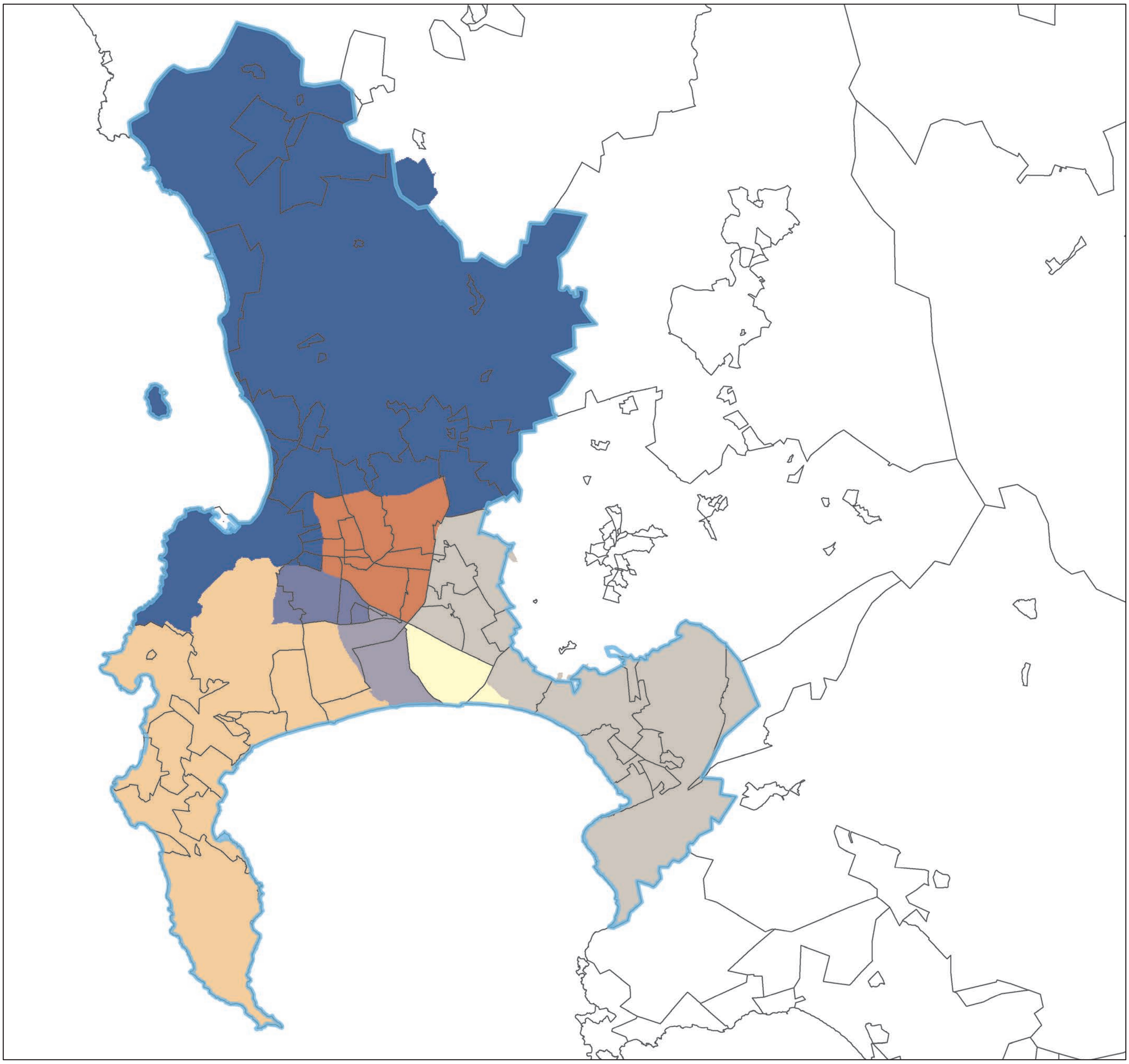
dataset reference: a_under5pneumonia_incidence

Pneumonia Rate (Children under 5y)

category: resilience **time period: current conditions** weighting 2



Legend

city_boundary
municipality boundaries

resilience

Value

no data
1 = low
2
3
4
5
6
7
8
9 = high

0 5 10 20 Kilometers

Number of children aged under 5 years-old with Pneumonia (unknown year). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method with some manual input. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Health regions. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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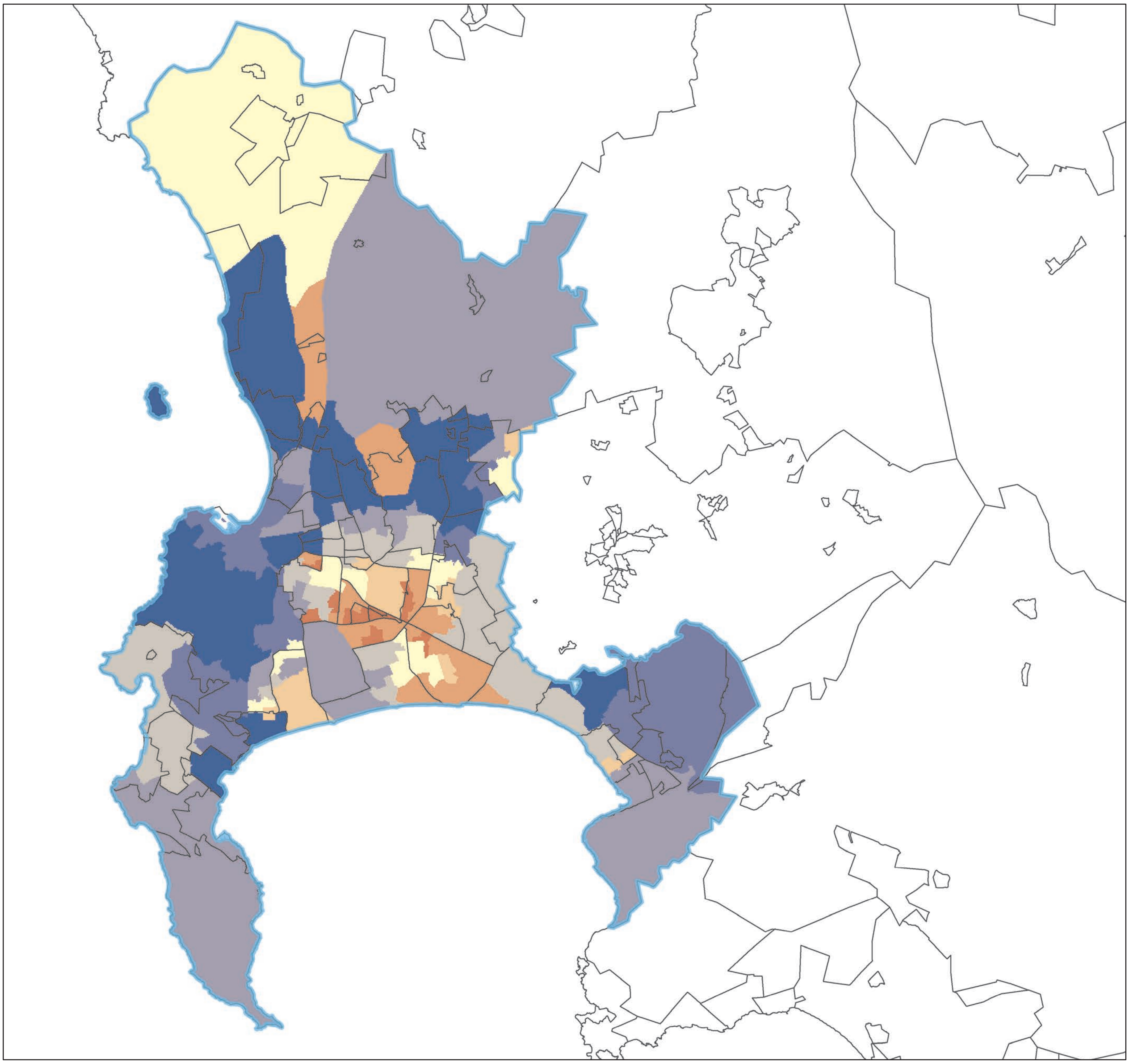
dataset reference: A_unemployed

City of Cape Town Risk & Vulnerability Analysis

Employment Rate

category: resilience **time period: current conditions** weighting 4



Legend

city_boundary

municipality boundaries

resilience

Value

no data

1 = low

2

3

4

5

6

7

8

9 = high

0 5 10 20 Kilometers

Percentage of the labour force unemployed (2011). Calculated as the proportion of the total labour force who are unemployed. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. The reclassified values were inverted such that high values represented high Resilience. Cells with no data were assigned a value of 0. Original resolution: Ward. Credits: City of Cape Town

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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map 32

dataset reference: A_weeklyrubbishcollection

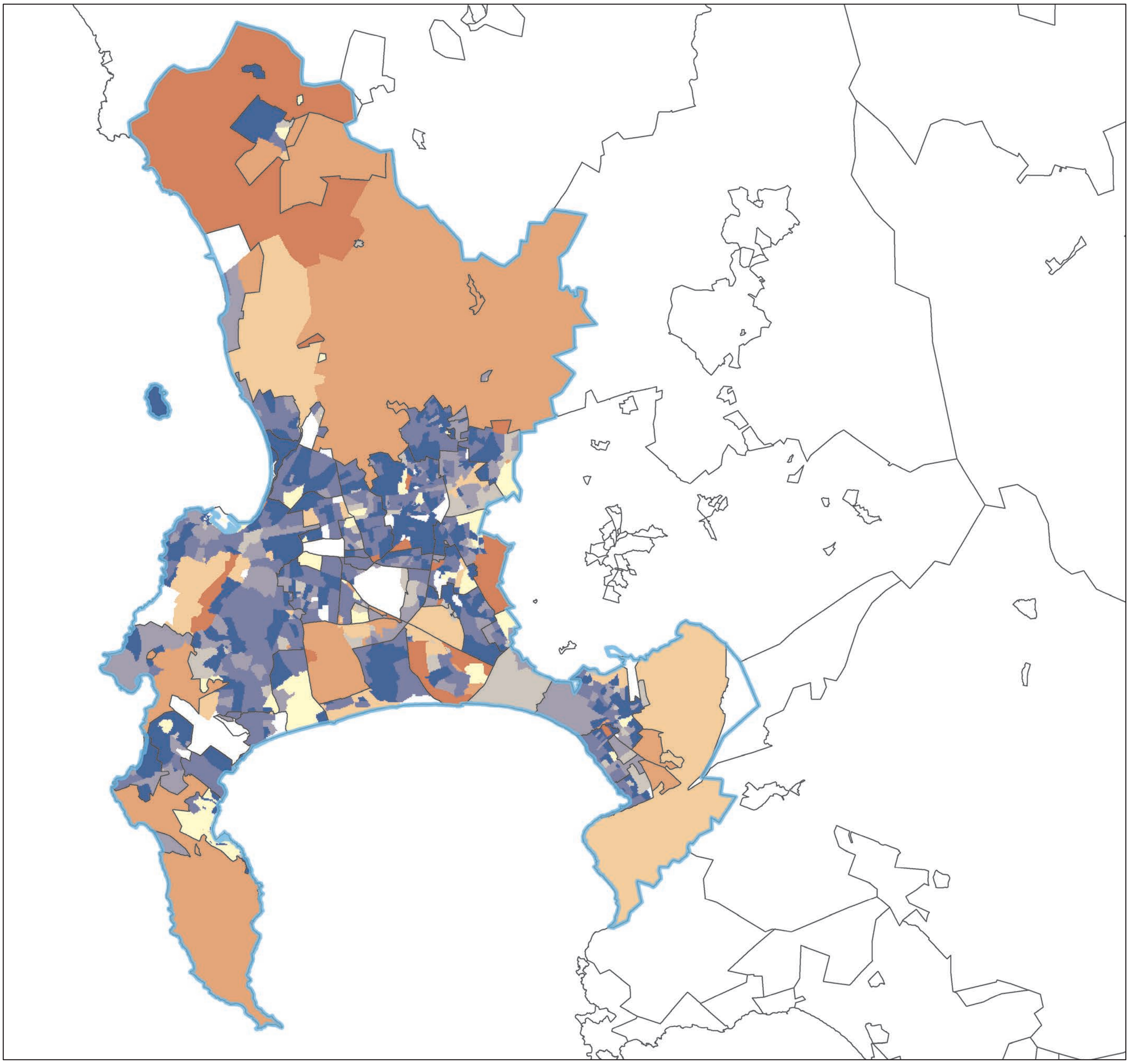
City of Cape Town Risk & Vulnerability Analysis

Weekly Rubbish Collection

category: resilience

time period: current conditions

weighting 3



Legend

city_boundary

municipality boundaries

0 5 10 20 Kilometers

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

Percentage of households with weekly rubbish collections (2011). Original raw data values used. The data were converted to raster and then reclassifed to 1-9 using a natural breaks method. Cells with no data were assigned a value of 0. Original resolution: SP. Credits: City of Cape Town

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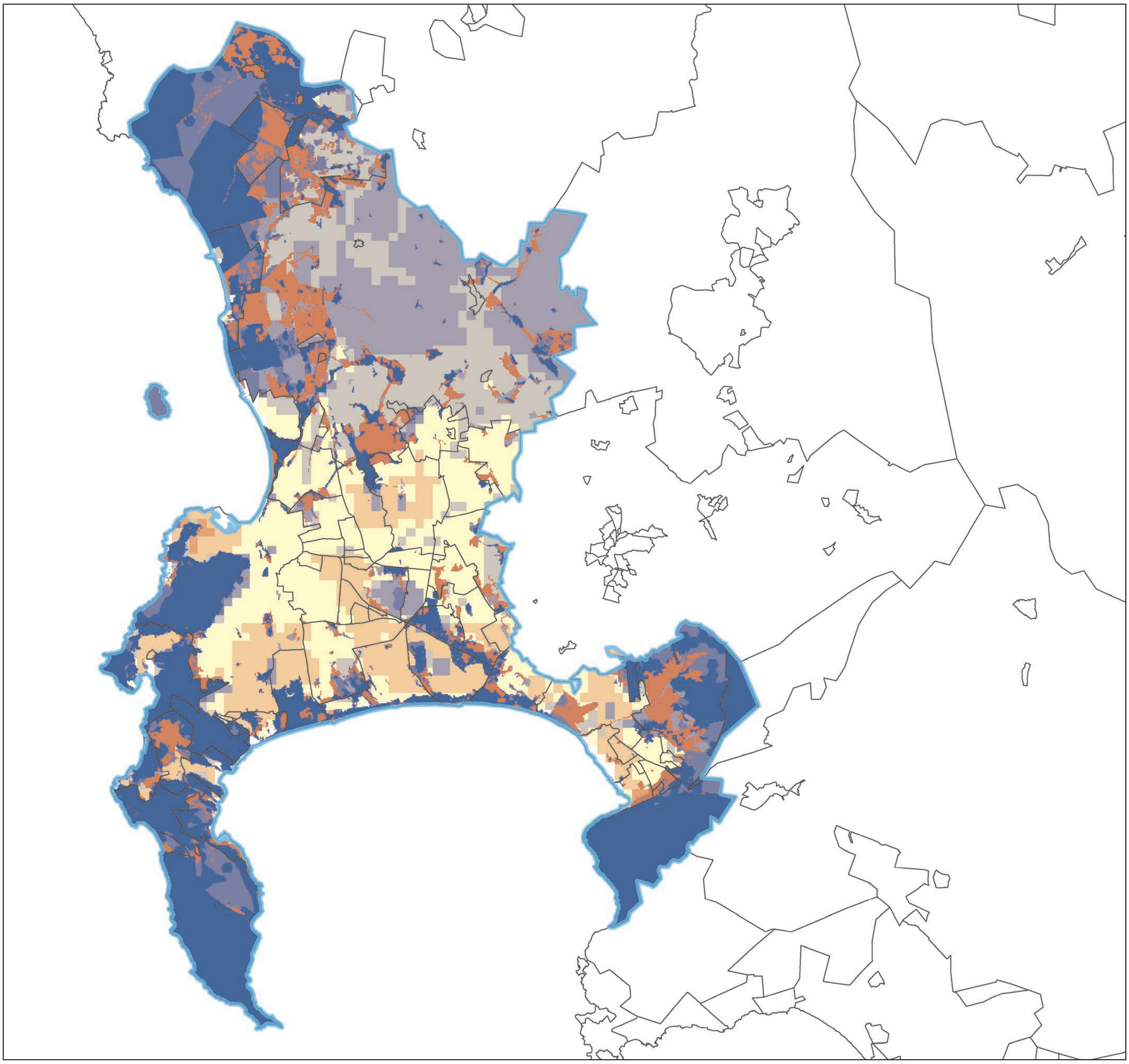
Biodiversity Services

category: resilience

time period: current conditions

weighting 4



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

For a measure of the degree to which biodiversity services are intact and fully functional we used the COCT Bionet dataset: Critical Biodiversity Areas (which takes account of protected species and habitats, climate refugia and protected area management and status). We reclassified the CBA categories following: 1,3 to 9; 4,5,6 to 8; 7,8,10,12 to 7; 9 to 6; 11,13 to 1; 0 to 0. This dataset leaves large parts of the city area with no recorded biodiversity value (where habitats are considered irreversibly modified). Yet variation of biodiversity services should exist here with more biodiversity present in less densely populated areas further from roads with some levels of protection. So we used a prior dataset for biodiversity value measured in these terms at 1km2 resolution for the whole of Africa to fill in the gaps between the CBA patches.

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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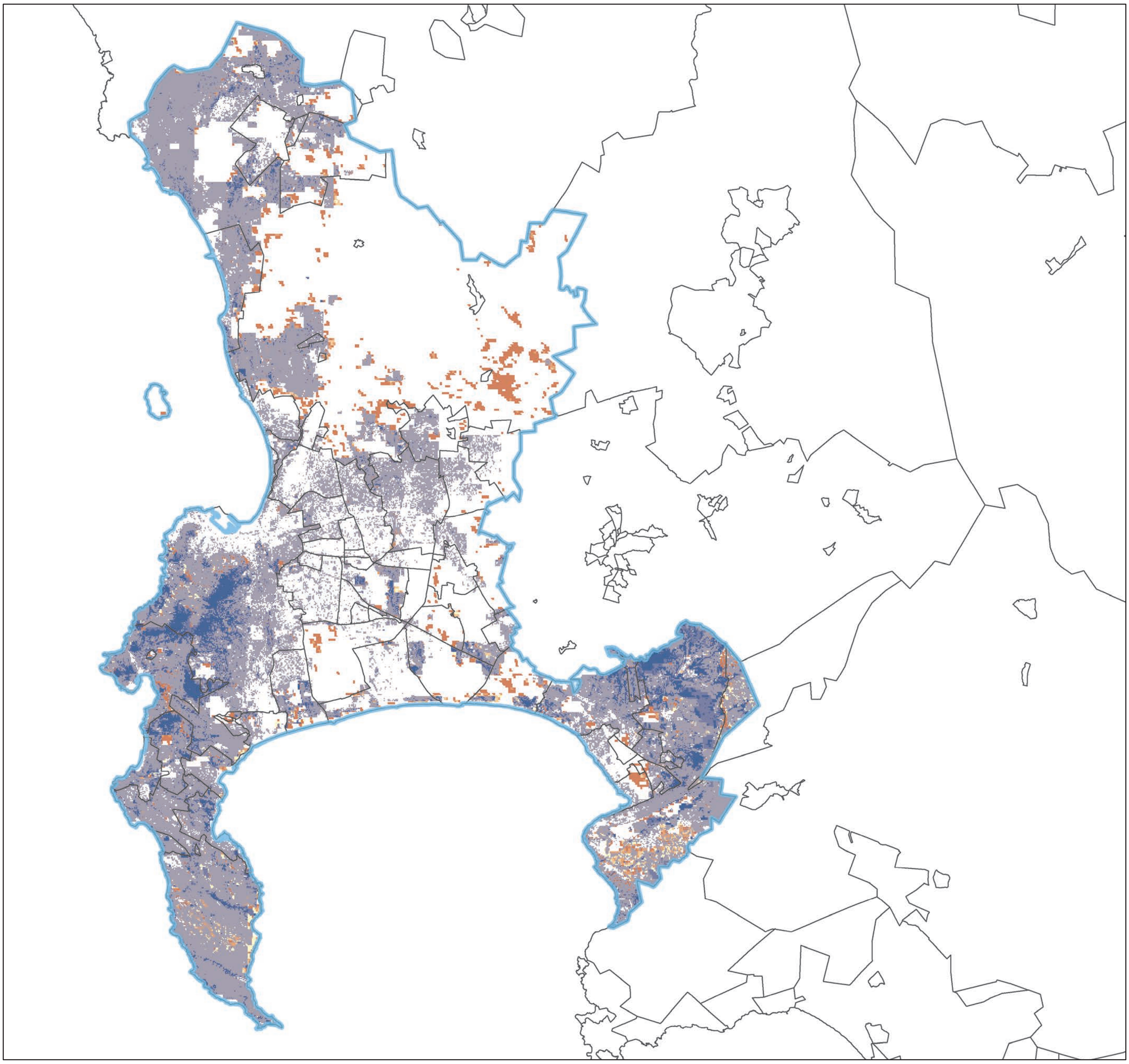
dataset reference: A_tree_services

Forest and Upper-storey Services

category: resilience **time period: current conditions** weighting 3



Legend

city_boundary

municipality boundaries

resilience

Value

- no data
- 1 = low
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9 = high

0 5 10 20 Kilometers

We combined two data layers to obtain a measure of the beneficial ecosystem services provided by forests, trees and upper-storey vegetation (e.g. forestry and timber, provision of shade and microclimate, production of oxygen, consumption of CO2). Layer one is the FAO Global Forest Resources Assessment (FRA 2010 v1.2) at 250m resolution. Percent forest cover was reclassified on the scale 0 – 9. Layer 2 is the same upper-storey fuel load assessment as used for determining high fire risk areas. We used the African Soil Information Albedo dataset to exclude areas with a high bare substrate reflectance (values >225). In areas where vegetation cover (mostly) produces lower reflectance we take the values from another global treecover dataset 2010 http://glcf.umiacs.umd.edu/data/vcf/ which scale from 0 - 100 representing % cover as an indicator of potential fuel load for combustion. These values were also reclassified on the scale 0-9. The two layers were then combined by taking the maximum value for any grid cell.

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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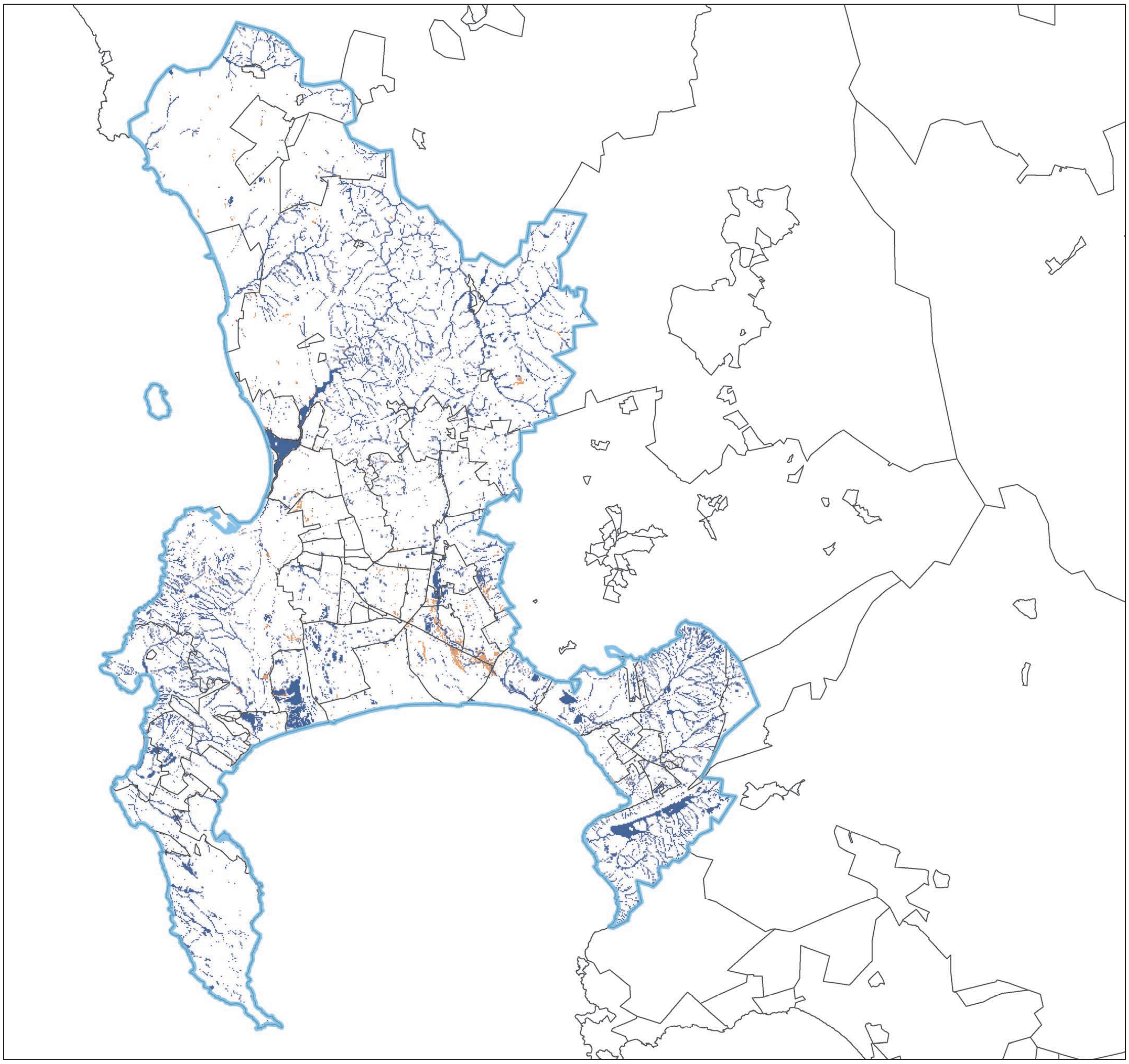
map produced 29/04/2019

dataset reference: A_wetland_services

Wetland and Watercourse Services

category: resilience **time period: current conditions** weighting 4



Legend

city_boundary

municipality boundaries

0 5 10 20 Kilometers

resilience

Value

no data

1 = low

2

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9 = high

For a measure of the ecosystem benefits provided by wetlands (e.g. filtration and retention) and watercourses (e.g. microclimates) we developed these two layers separately and then combined them into a single layer. For wetlands we were able to reclassify using the same lookup table on critical biodiversity area category from the bionet dataset because the latter includes wetlands. The only code value we found in this that did not match was the value 80 to which we reclassified as 5. For watercourses we obtained the Open Watercourse dataset from COCT. This dataset contains 164 different water course types all represented as lines. For each type we ascribed a buffer distance based on an estimate of the extent of influence of each microclimate on a scale 20m for drainage channels to 50m for natural rivers; and we ascribed a score for each watercourse type on a scale 0-9 based on the expected ecosystem benefits (e.g. ranging from 6 for a culvert to 9 for a natural river). We then buffered each line outward in both directions by the set buffer distance for that type and we converted these polygons to a raster grid which retained the score values. To combine wetlands with watercourse we overlaid these two datasets and obtained the maximum value using Cell Statistics.

blue areas represent high resilience

Coordinate System: Hartebeesthoek 1994 Transverse Mercator
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
False Easting: 0.0000
False Northing: 0.0000
Central Meridian: 19.0000
Scale Factor: 1.0000
Latitude Of Origin: 0.0000
Units: Meter

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map produced 29/04/2019