"Assessing Drought Exposure in South Africa: Spatial Patterns, Temporal Trends, and Future Projections"

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Foreword:

I am pleased to present this report, which has been written as part of my bachelor's thesis for the Earth, Economics & Sustainability program at VU University. This report aims to shed light on the spatial patterns and temporal trends of drought exposure in South Africa by using various methods, analysing changes over time and evaluating population distribution. I would like to express my sincere gratitude to my supervisor, Eric Koomen, for his invaluable guidance and support throughout this research project. I would also like to extend my thanks to the team at the PBL Netherlands Environmental Assessment Agency and Wageningen University for their collaboration and valuable contributions to this study.

Jan Albertsboer

Abstract

This study aims to examine the spatial patterns and temporal trends of drought exposure in South Africa, as well as assess the extent and distribution of the population exposed to drought-related problems, both currently and in the future. Three different methods of identification were used to identify current drought-prone areas and analyse changes over time. The results highlight that the western regions of South Africa, particularly the Northern Cape province, currently face the highest levels of drought. From 2015 to 2050, there is a moderate increase in drought conditions across most of the country, with notable changes observed in the western regions and the northern part of the Limpopo province. Furthermore, projections indicate that the Western Cape province, specifically around Cape Town, will experience the largest increases in drought severity by 2100. Overall, this study provides insights into the spatial and temporal dynamics of drought in South Africa, contributing to the understanding of its impacts on the population and informing future mitigation and adaptation strategies.

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Introduction

1.1. Background information, state of knowledge

The severity of drought is increasing in numerous regions around the world and is projected to continue to increase in the upcoming century (Vicente-Serrano, 2020). Increasing drought is considered one of the most significant problems associated with climate change due to its wide-ranging and severe impacts on millions of people (He, 2020). A significant portion of the South African population is already 'exposed' to drought and certainly no stranger to drought-related issues. The impact of drought on South Africa is far-reaching, affecting water availability, food security, ecosystems, economy, social well-being, and climate change vulnerability (The World Bank Group, 2021). According to the World Bank Group, the country of South Africa is highly vulnerable to climate variability and change due to the country's high dependence on rain-fed agriculture and natural resources, high levels of poverty, particularly in rural areas, and a low adaptive capacity. Besides vulnerability, exposure is also a crucial factor that determines the ultimate risk of a natural disaster related to drought. For this bachelor thesis, I will focus on drought exposure in South Africa. This research involves an assessment of the present distribution and future projections of drought, along with its influence on the exposure of the South African population.

1.2. Knowledge gaps, motivation, relevance

Despite the recognition of drought as a significant issue in South Africa, there are several knowledge gaps that need to be addressed. Firstly, there is a need for an improved understanding of the current drought-prone areas in the country. While some studies have examined specific regions like the Eastern (Botai, 2020) or Northern Cape Province (Jordaan, 2013), a study focusing on the entire country and employing multiple methods to investigate the severity of drought is lacking. Understanding the differences in results obtained from various approaches could provide valuable insights into the reliability and effectiveness of drought identification methods. For instance, a paper on drought risk assessment using remote sensing and GIS techniques (Belal, 2014) serves as an example where multiple methods were employed to assess drought. This research emphasises the significance of considering diverse approaches for a comprehensive understanding and evaluation of drought identification.

Furthermore, there is a lack of research on the observed changes in drought-prone areas over time. Examining the temporal trends can identify areas that have become more or less prone to drought, allowing for targeted interventions and adaptive measures. Additionally, limited research has focused on the extent and distribution of the population that is currently exposed to drought-related problems and how it varies across different regions. However, a recent publication in 'Nature Sustainability' (Lenton, 2023) has highlighted the future exposure of populations to drought and the global implications of climate change. This research reveals that an increasing number of people will be forced to flee due to increasing droughts. Lenton's study confirms that it is crucial to understand how drought exposure affects the population and their vulnerabilities.

The societal relevance of this research specifically lies in its potential to provide insights into a crucial aspect of assessing risks regarding droughts in South-Africa. The relevance of this project is further underscored by its consideration of the El Niño (ENSO) phenomenon, which has historically contributed to drought conditions in South Africa (Wander, 2018), and is expected to have a significant impact on future drought occurrences in the coming years (Stoddard, 2023). Recognizing the ongoing influence of natural phenomena such as El Niño in the future is crucial and constitutes a fundamental aspect of my study 'Earth, Economics & Sustainability'. This research will lay the foundation for a comprehensive drought risk assessment for South Africa, largely based on techniques acquired during my bachelor at the VU.

1.3. Research questions

Main question:
What are the spatial patterns and temporal trends of drought exposure in South Africa, and how much of its population are currently, and in the future, exposed to droughts?

Sub-questions:

1. What are the current drought-prone areas in South Africa, and how do the results differ when using three different methods of identification?
2. What are the observed changes in drought-prone areas in South Africa over time?
3. What is the extent and distribution of the population in South Africa that is exposed to droughts, and how does it vary across different regions?
4. What are the observed changes in the exposed population over time?
5. What is the primary driver of the total exposed population to drought: increasing drought or population growth?

Methods

2.1. Research approach

The research approach aims to determine the severity of drought by utilising three different types of data: the Aridity Index, Water Yield Gap data, and SPEI data (Table 1). These datasets provide valuable information for assessing the intensity and extent of drought conditions. The first part of the study involves comparing the three indices for the year 2015 to identify the most drought-prone areas, which will partly answer the first research question. Additionally, Aridity Index and Water Yield Gap data will be used to answer the second research question by identifying and analysing changes in drought-prone areas. The Water Yield Gap data will be examined specifically for the years 2015 and 2050, while the comparison of the Aridity Index will focus on the development across the years 2015, 2050, and 2100. Furthermore, 2UP population data will be employed to identify the current and future locations of populations at risk of drought exposure. By combining the Aridity Index, Water Yield Gap, and 2UP data, the third and fourth research questions will be addressed. Finally, the study will examine the main driver of the total exposed population to drought by comparing the aridity index with population trends for the years 2015, 2050, and 2100. To conduct the analyses, ArcGIS Pro will be used as the primary software tool. Geoprocessing tools such as the Raster Calculator and Zonal Statistics will be specifically employed to identify and analyse changes in exposed areas and population. The ModelBuilder in ArcGIS Pro, provided in the annexes (Section 7.2.), allows for a detailed examination of each step taken in this study. To answer the fifth research question, a decomposition analysis will be necessary, which can only be performed in a program comparable to Spyder. The corresponding script for this analysis is also included in the annexes (Section 7.3.).

Table 1: Data collection

Layer name	Spatial resolution	Dates	Contact
Aridity index	0,5 degrees	2015, 2050, 2100	Jonathan Doelman, pbl
SPEI	0,5 degrees	2015	Global SPEI Database
WaterGAP	0,5 degrees	2015, 2050	Marijn Gulpen, WUR
2up	1 km	2020, 2050, 2100	Eric Koomen, VU

2.2. Drought indices(Aridity index, SPEI and Water Yield Gap)

In this study, three different types of indices will be used to determine the severity of drought. First, the Aridity index will be utilised, with predictions based on SSP2, and results from the IMAGE model (pbl, 2021). The Aridity Index (AI) is a widely used measure of the dryness of a climate at a specific location. It serves as a simple yet convenient numerical indicator of aridity, calculated by considering the long-term climatic water deficits and expressed as the ratio of precipitation (P) to potential evapotranspiration (PET) (European Commission, 2019). In various studies, the Aridity Index has been employed to identify both current and future drought-prone areas. By utilising this index, I can determine where the most drought-prone regions exist and anticipate their presence in the future. The data is available every 5 years from 1970 to 2100. The aridity index will be employed to analyse the future development of drought and estimate changes in drought over the years. The scenario SSP2 will be assumed, and the selected years are: 2015, 2050, and 2100. To classify the aridity index, the widely adopted UNEP aridity index classification was utilised (Table A, Section 7.1.) , as observed in previous studies conducted by Boschetto et al. (2010), Li et al. (2017), and Qaisrani et al. (2022).

Climate aridity represents the long-term average state of the background climate, while meteorological drought events are unpredictable stochastic climate events (Zhang et al., 2023). The Aridity Index is an example of an index that is highly suitable for analysing a longer time period. In scientific research, it is common to find the utilisation of the Aridity Index for extended historical time periods (Zarch et al., 2017), as well as for future scenarios (Moral et al., 2023). The more severe the drought indicated by the index, the greater the likelihood of meteorological drought and drought disasters. Therefore, in this study, the Aridity Index is used not only to assess the current drought situation but also to examine future prospects. This index is essential for answering research sub-questions 2, 4, and 5, and ultimately the main research question.

The SPEI index will also be utilised, which can be freely accessed for a chosen time scale and temporal resolution through the Global SPEI Database. The SPEIbase relies on monthly precipitation and potential evapotranspiration data from the Climatic Research Unit of the University of East Anglia and the data is available for months between 1901-2022. This index will be used to examine the (current) spatial patterns of drought in South Africa and assess the impact of the intense El Niño year in 2015. SPEI-12 will be used, where the SPEI is calculated as the average of the past 12 months. This one-year time scale is commonly employed in drought trend studies, as seen in the research conducted by Ionita (2021). The classification of the SPEI utilised a commonly employed method, which has been used in multiple studies, such as those conducted by Vicente-Serrano et al. (2010), Zarei and Moghimi (2019), and Yao et al. (2019). The classification table can be found in the annexes (Table B, Section 7.1.).

Lastly, according to earlier research, using the climate aridity index to assess drought events may lead to inaccuracies when examining short-term droughts (Zhang et al., 2023). Therefore, SPEI may be more suitable for capturing drought conditions at a specific moment, such as the extreme drought caused by El Niño in 2015. Thus, SPEI could be a refined approach to address research sub-question 1 when focusing solely on the drought in South Africa of 2015.

The third index that is used in this study is waterGAP data. The water yield gap refers to the difference between the actual yield and the potential yield when water constraints are not present. It indicates the extent of yield losses resulting from water shortages (Biemans, 2019). In the case of irrigated crops, this water scarcity necessitates the extraction of non-renewable groundwater. The calculations were performed using five climate models from ISI-MIP2a, and the formula can be found in the appendix (Formula A, Section 7.4.). The waterGAP data is available as an average of 10 years for 2015, 2050 and 2065, and the years 2015 and 2050 have been selected to compare the current situation with the future exposure of the population to water shortages. Water yield gap data is commonly used at Wageningen University and has been published by PBL in 2018 in "The Geography of Future Water Challenges" (pages 32/33). Furthermore, it is occasionally employed in scientific research, for example, in "The Global Yield Gap Atlas" (n.d.). It has also been applied in studies conducted by R.A. Fischer (2015) and in determining a threshold for "sustainable" agriculture (The Sustainable Development Solutions Network, 2013). The WaterGAP data is commonly used in connection with agriculture and land-use (Feyen et al., 2009). Although the WaterGAP data is limited to assessing water availability and does not directly measure drought severity or duration, it can provide valuable information about the relationship with population, future perspectives, and guide land-use planning decisions. This data primarily assists in answering research sub-questions 2 and 3, while also providing additional insights into the overall narrative.

2.3. 2UP model

The 2UP model is a computational tool used to simulate and predict urban growth and its spatial distribution. It incorporates various data sources and factors to forecast future patterns of urban expansion. Additionally, the model considers both population and GDP scenarios, which are provided by the Shared Socioeconomic Pathways (SSPs). In this research, the 2UP model will be utilised to assess the potential exposure of populations to drought. The years selected for this research are the following; 2020, 2050 and 2100. Similar to drought indices, the 2up model is based on SSP2, the "Middle of the road" scenario. The 2UP model has diverse applications, including calculating the exposed population to assess various risks. For instance, the output generated by the 2UP model can be utilised as exposure data in the Aqueduct Flood Risk Analyzer (World Resources Institute, 2021). This online tool, developed by the World Resources Institute (WRI) in collaboration with Deltares, VU University Amsterdam, Utrecht University, and PBL, enables the assessment of global flood risks (pbl, 2018). The 2UP model is a valuable tool in science, particularly in urban studies, demography, and urban planning. It provides insights and forecasts that can contribute to a improved understanding of the complexity of urbanisation and population growth. In this study, the 2up data will be utilised for research sub-questions 3, 4, and 5, aiming to establish the connection between drought and the exposed population.

2.4. Analysing changes

For research sub-questions 2 and 4, the changes between 2015, 2050, and 2100 need to be examined. To analyse changes in drought conditions and the exposed population, the raster calculator tool will initially be utilised. This tool allows for the calculation and comparison of different raster datasets. The following relatively simple, formula has been used:

$$\Delta D_n = \frac{(D_n - D_o)}{D_o}$$

In this context, ΔD_n represents the output raster that illustrates the change between the raster layers of time period n. D_n is the input raster for the most recent year, and D_o is the input raster for the first year in the time period, for example 2015. Furthermore functions such as the Set Null and Zonal Statistics (as Table) are used in order to analyse change in attribute tables (Modelbuilder B&C, Section 7.2.).

2.5. Decomposition Analysis

Decomposition Analysis is a method used to break down a complex phenomenon into its constituent parts or factors. In the context of this research, it allows us to assess the individual contributions of population and drought to changes in the exposed population. The formula at the core of this analysis is derived from previous research (Rørmose, 2010) and can be expressed as follows:

$$x = Lf$$

In this context, x represents the vector of output variables. It refers to the resulting changes in the variable of interest, which is drought exposed population in this case. The Leontief Inverse (L) plays a crucial role in the analysis. This variable captures the relationships between the input variables and the output variables. It allows us to quantify the influence of changes in the input variables on the resulting changes in drought exposure. Essentially, L defines the multiplier effects or sensitivities of the input variables. The vector f represents the input variables, specifically the changes in the factors under investigation. In this research, it includes the variable "change in drought (aridity index)" and the variable "change of total population." Each component of f corresponds to a specific factor and represents the magnitude and direction of the change in that factor. The analysis was conducted using Spyder (Python 3.8). The script used for the analysis can be found in the annexes, section 7.3.

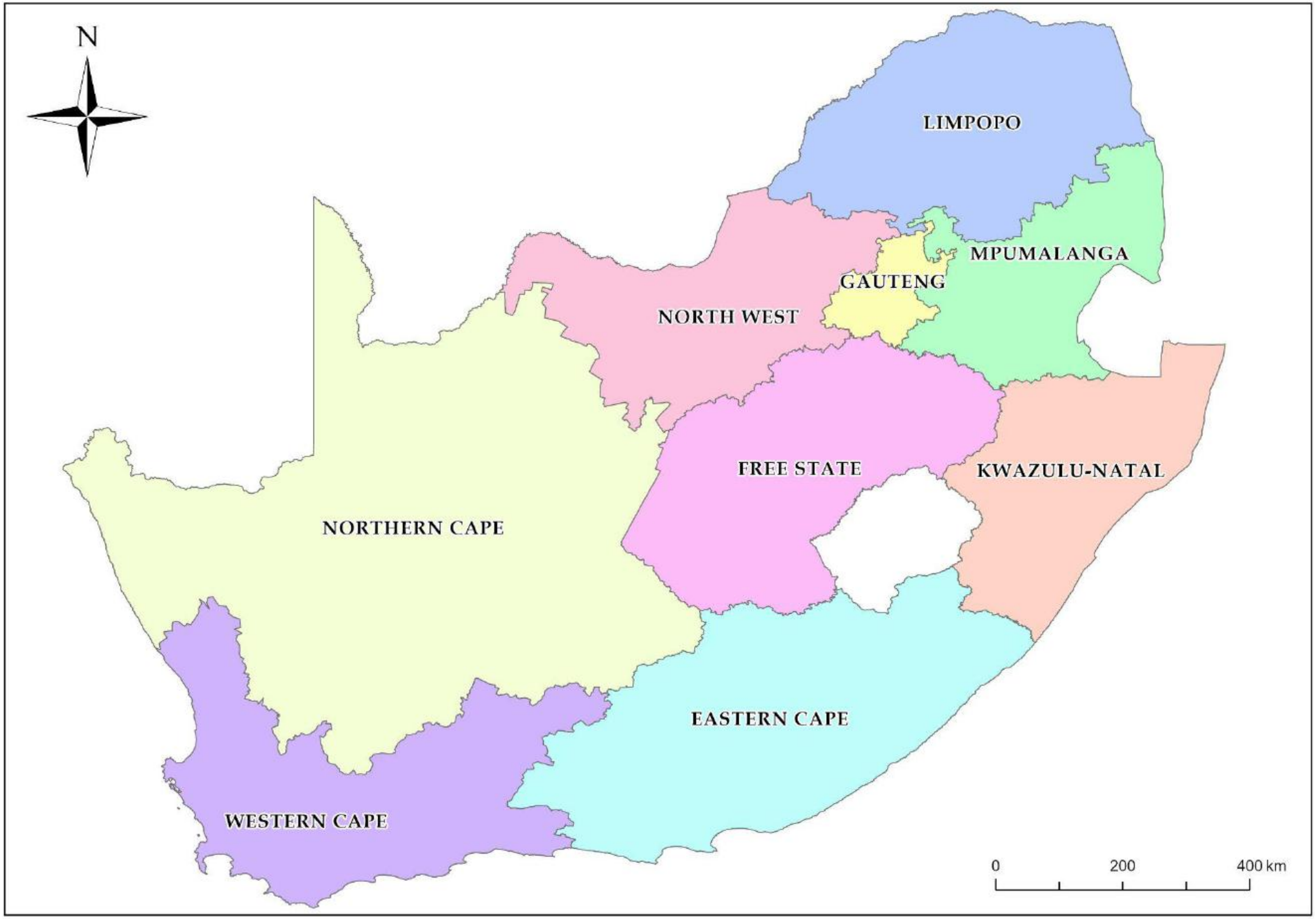

Figure 1: Provinces South Africa.

Results

3.1. Comparing methods

Figure 2 displays the spatial distribution of drought based on the Aridity Index, which demonstrates a clear pattern. The southeastern coastal areas exhibit the wettest humid conditions, while the western regions are characterised as the driest areas. The Northern Cape province (Figure 1) stands out as the most arid, with a prevalence of values below 0.2 on the Aridity Index. According to the results of the Aridity Index, the Eastern Cape and KwaZulu-Natal provinces are identified as the wettest regions in the country, benefitting from their proximity to the warm Indian Ocean. In contrast, the Western Cape experiences the influence of the cold Antarctic Benguela Current from the Atlantic Ocean, indirectly resulting in lower AI-values. There are several reasons why the Aridity Index may indicate dry conditions in the western part of South Africa and wetter conditions in the eastern coastal areas. For example, the western part of South Africa is characterised by a semi-arid climate with low precipitation and higher evaporation rates. Furthermore, the Aridity Index values along the South African coast are influenced by two contrasting currents of the Benguela current, known for its cold nature, and the Agulhas Current, characterised by its warm properties (Walker, 1990).

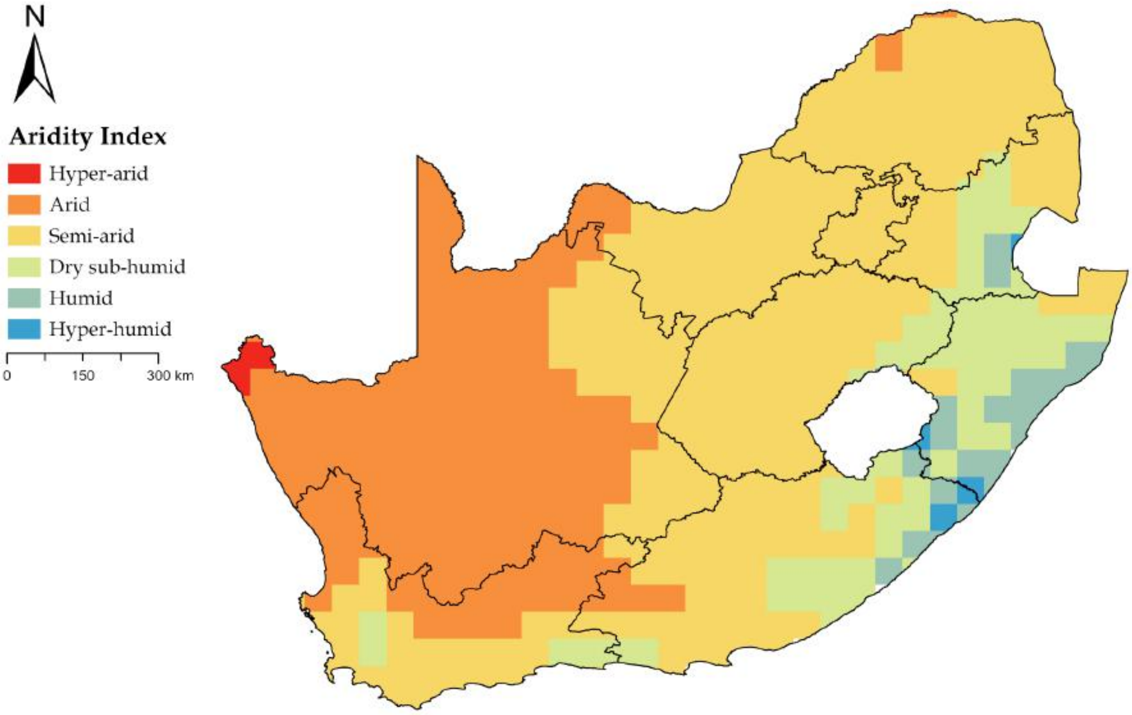

Figure 2: Aridity Index South Africa, 2015.

According to the Standardised Precipitation-Evapotranspiration Index (SPEI) method, the results reveal distinctive spatial patterns of drought conditions in South Africa. Based on Figure 3, it is evident that 2015 was a highly arid year for South Africa as a whole, with widespread negative SPEI values indicating extensive drought conditions throughout the country. Practically the entire North-West and Gauteng province falls under the 'Extreme dry' category, indicating severe drought conditions. The driest areas are located in the Free State province near the Lesotho border. On the other hand, the coastal regions of Western Cape, Eastern Cape, and KwaZulu-Natal provinces stand out as the wettest parts of South Africa, with more frequent occurrences of 'Normal' conditions according to the SPEI in 2015. Particularly in KwaZulu-Natal province, the impact of drought was relatively minimal, with most of the region experiencing values between -1 and 1 on the SPEI scale, which is classified as 'normal' based on the most commonly used classification method.

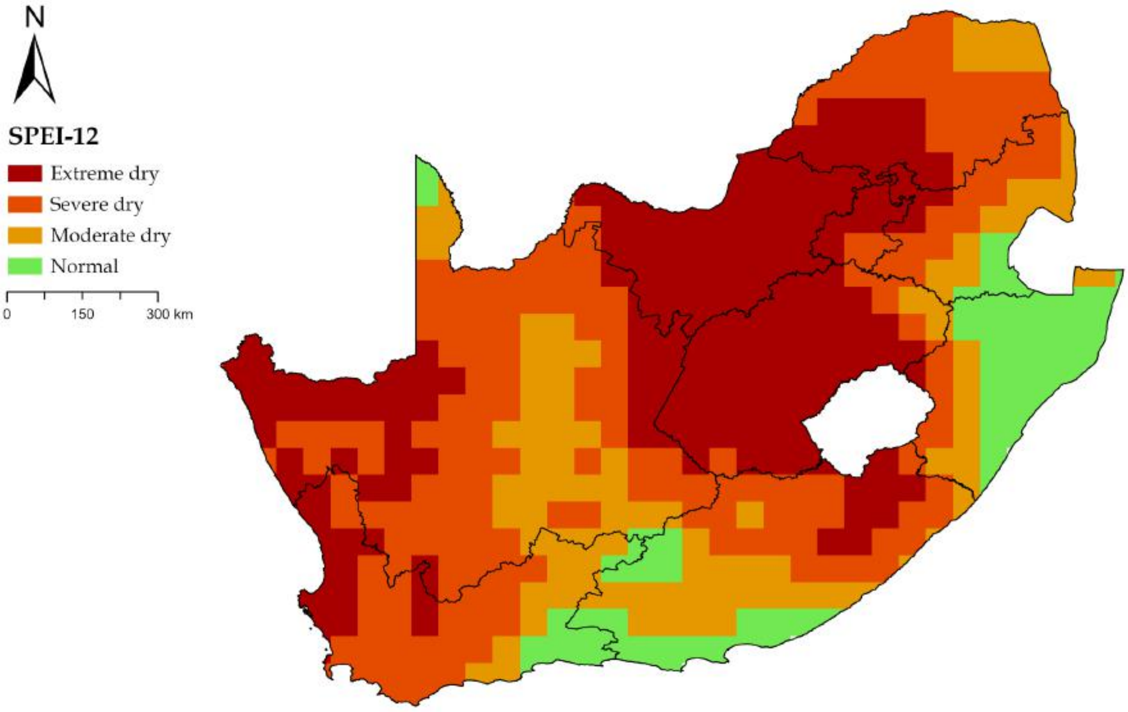

Figure 3: Standardised Precipitation-Evapotranspiration Index South Africa, 12 month period, 2015.

The distribution of drought based on the Water Yield GAP data is illustrated in Figure 4, providing insights into the spatial variations. The highest WaterGAP percentages, indicating significant water yield gaps, are observed in the northern part of the Limpopo province and the western regions of South Africa. The dark red value indicates areas with a water yield gap exceeding 100%, making agriculture unfeasible in those areas. These regions can be considered the most arid sections based on this criterion. According to the WaterGAP data, the driest values predominantly occur in the western provinces of Northern Cape and Western Cape. In contrast, the most suitable areas for human settlement and agriculture, similar to the findings of the Aridity Index, are identified along the coast of the Eastern Cape and KwaZulu-Natal provinces. Additionally, the province of Mpumalanga is highlighted as a favourable region for human habitation and agricultural practices according to the WaterGAP data.

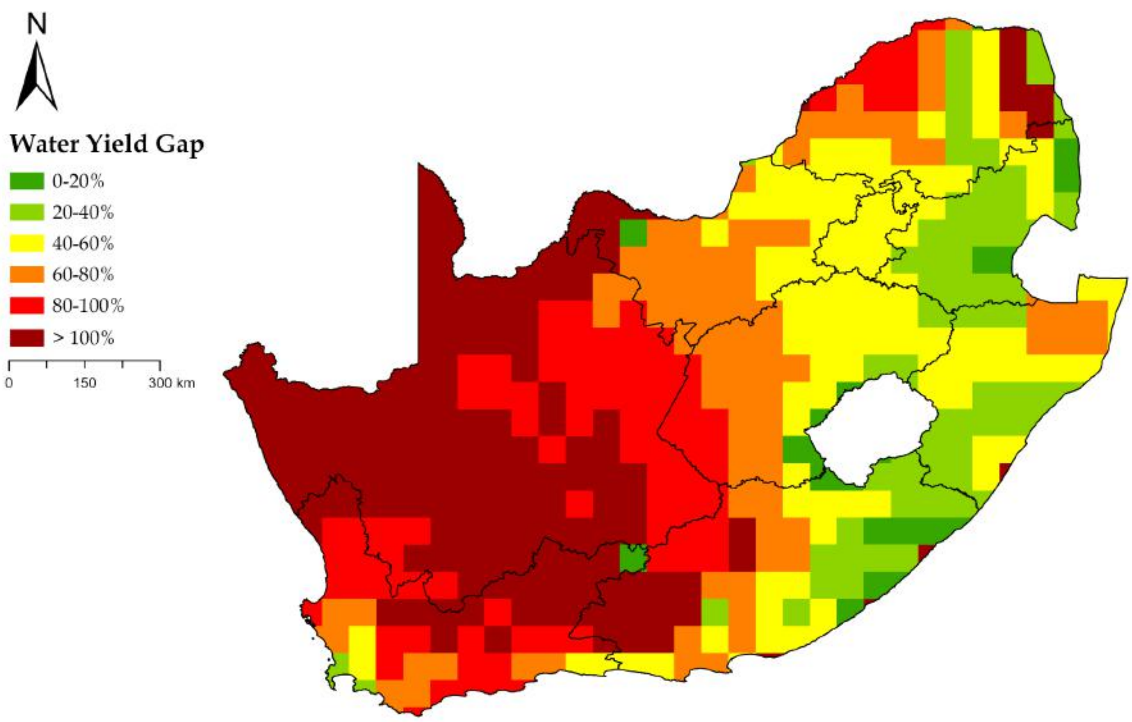

Figure 4: Water Yield Gap South Africa, 2015.

3.2. Temporal trends in drought

When examining the changes in the Aridity Index between 2015 and 2050 (Figure 5), it can be observed that minimal variations occur throughout most of South Africa. The most significant decreases in the Aridity Index, indicating increased drought, primarily occur in and around Cape Town, in the western cape province, and the northern part of the Limpopo province. However, even on this timescale, there are areas that experience increases in the Aridity Index, suggesting decreased aridity. These regions are predominantly found in Eastern Cape and parts of Western Cape province.

When considering the changes in the Aridity Index between 2050 and 2100, distinct patterns emerge, showcasing the persistence and intensification of these changes (figure 5). Notably, the largest increases in drought, as indicated by the Aridity Index, occur in the Western Cape province, particularly in the vicinity of Cape Town. Decreases of over 25% between 2050 and 2100 are observed, indicating a significant escalation in aridity. Furthermore, it is remarkable that the Eastern Cape also undergoes changes on this timescale. Cities such as Port Elizabeth and East London are projected to experience wetter conditions according to the Aridity Index in 2100, which can result in increased rainfall, and reduced issues regarding drought.
In conclusion, as the Aridity Index forecasts a significant increase in aridity for Cape Town, contrasting prospects lie ahead for Port Elizabeth and East London, where the Aridity Index projects wetter conditions in 2100.

Looking at the 2050 timeframe, the most significant changes/increases in the water yield gap are observed mainly in the eastern part of the country, specifically in the province of Mpumalanga, Limpopo and North West (Figure 6). Substantial increases in WaterGAP are also observed around Cape Town in the Western Cape province. Furthermore, it is noteworthy that there are relatively small increases in the Water Yield Gap, indicating that drought is projected to increase by only a few percentage points at most. These modest increases primarily occur at the edges of arid regions where the Water Yield Gap is already high, as well as along the coastal areas of South Africa. Given that the Water Yield Gap is already significantly high in numerous locations, the potential for a substantial increase is limited. However, there are also areas where the water yield gap has decreased, up to a maximum of about 2%. The negative values occur in the Eastern Cape province, indicating that these areas are expected to become more humid, resulting in a lower water yield gap.

Overall, the results indicate that there will be significant increases in the water yield gap in certain regions of South Africa, such as Mpumalanga and Cape Town. However, there are also areas, like the Eastern Cape, where the water yield gap is expected to remain relatively stable and even decreasing in some cases, with conditions not significantly deteriorating in terms of drought.

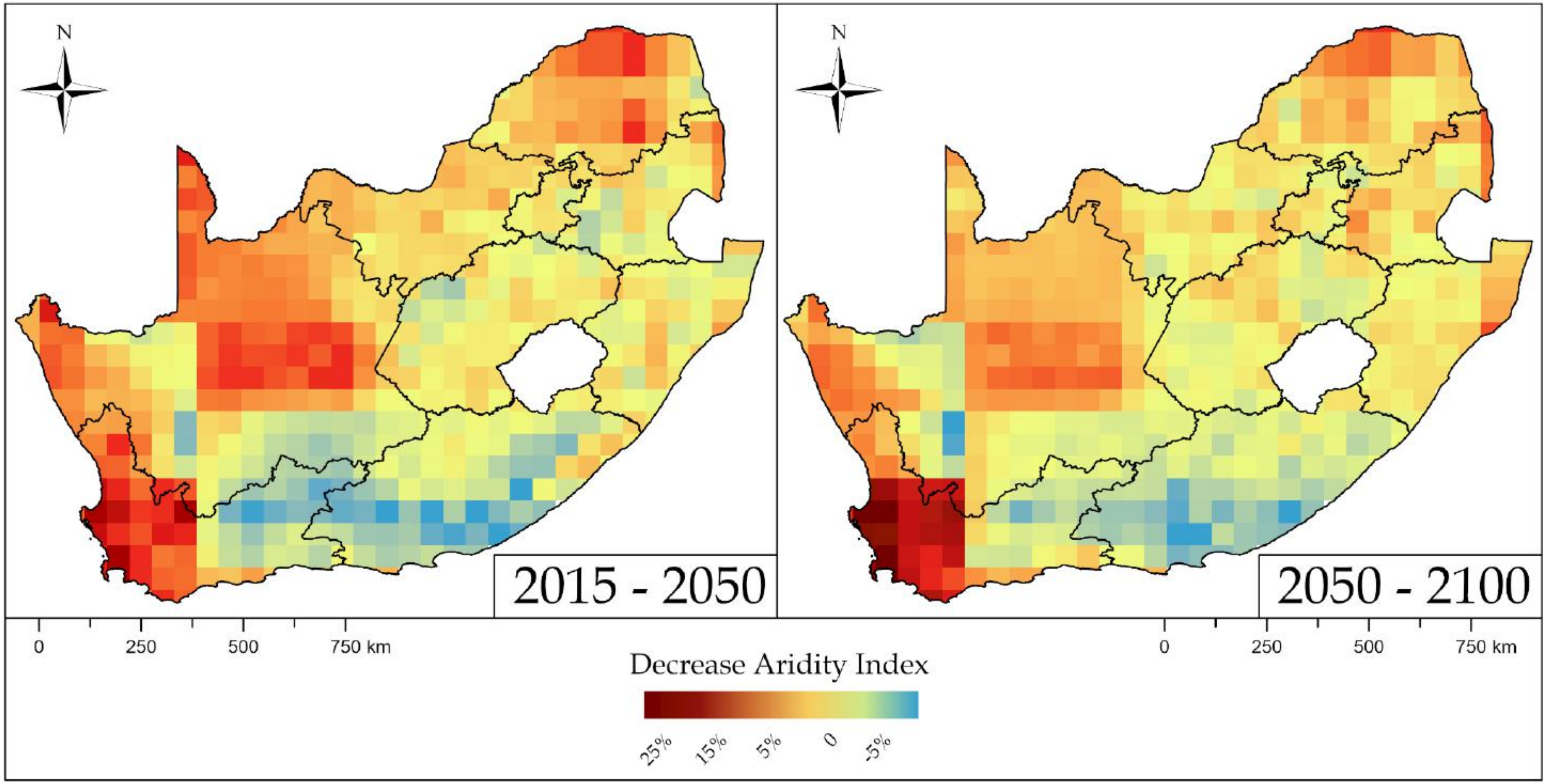

Figure 5: Change Aridity Index (%), based on SSP2. Time period 2015-2050 and 2050-2100

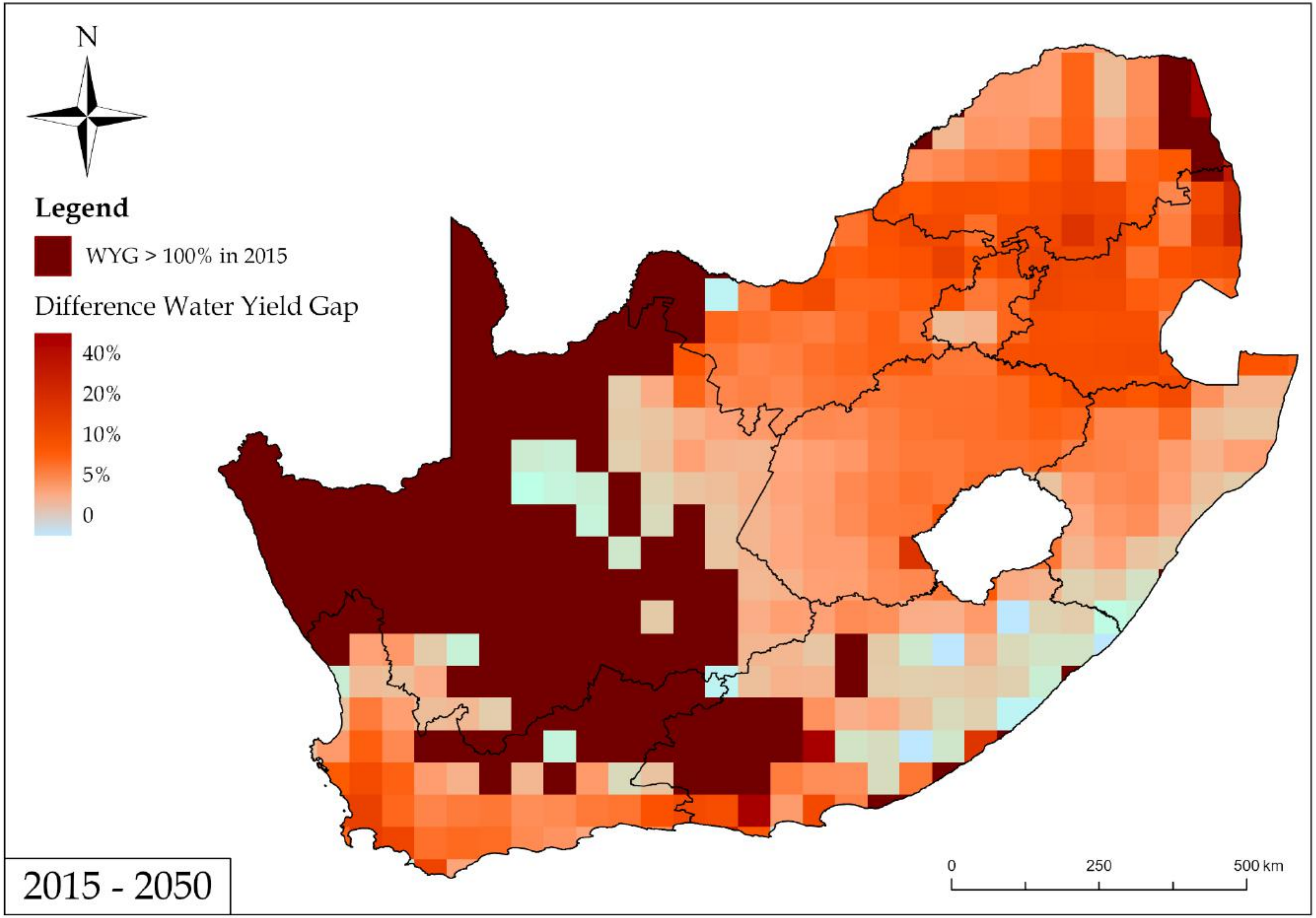

Figure 6: Difference in Water Yield Gap, based on climate models ISI-MIP2a. Time period 2015 - 2050.

3.3. Exposed population

The most populous areas in South Africa are concentrated in different regions across the country (Figure 7). Johannesburg, the largest city in South Africa, along with its surrounding metropolitan region situated in the Gauteng province, serves as a significant population hub within the heartland of the country. Cape Town, situated in the Western Cape province, is a highly populated city located along the southwestern coast of South Africa. Durban, a significant urban centre located on the eastern coast of the country in the KwaZulu-Natal province, is also home to a large number of people. Other densely populated areas include Port Elizabeth and East London, which are coastal cities in the Eastern Cape province, Bloemfontein in the Free State province, and Nelspruit in the Mpumalanga province. Despite being the largest province in terms of land area, Northern Cape is also the province with the lowest total population in 2020, with approximately 1.3 million people. A considerable portion of this population in the Northern Cape province is located in urban settlements along the Orange River. On the other hand, Gauteng, despite being one of the smallest provinces, has the highest population with approximately 15.7 million residents. The significant population size can be easily explained by the presence of Johannesburg, which accounts for a substantial portion of the total population in Gauteng.

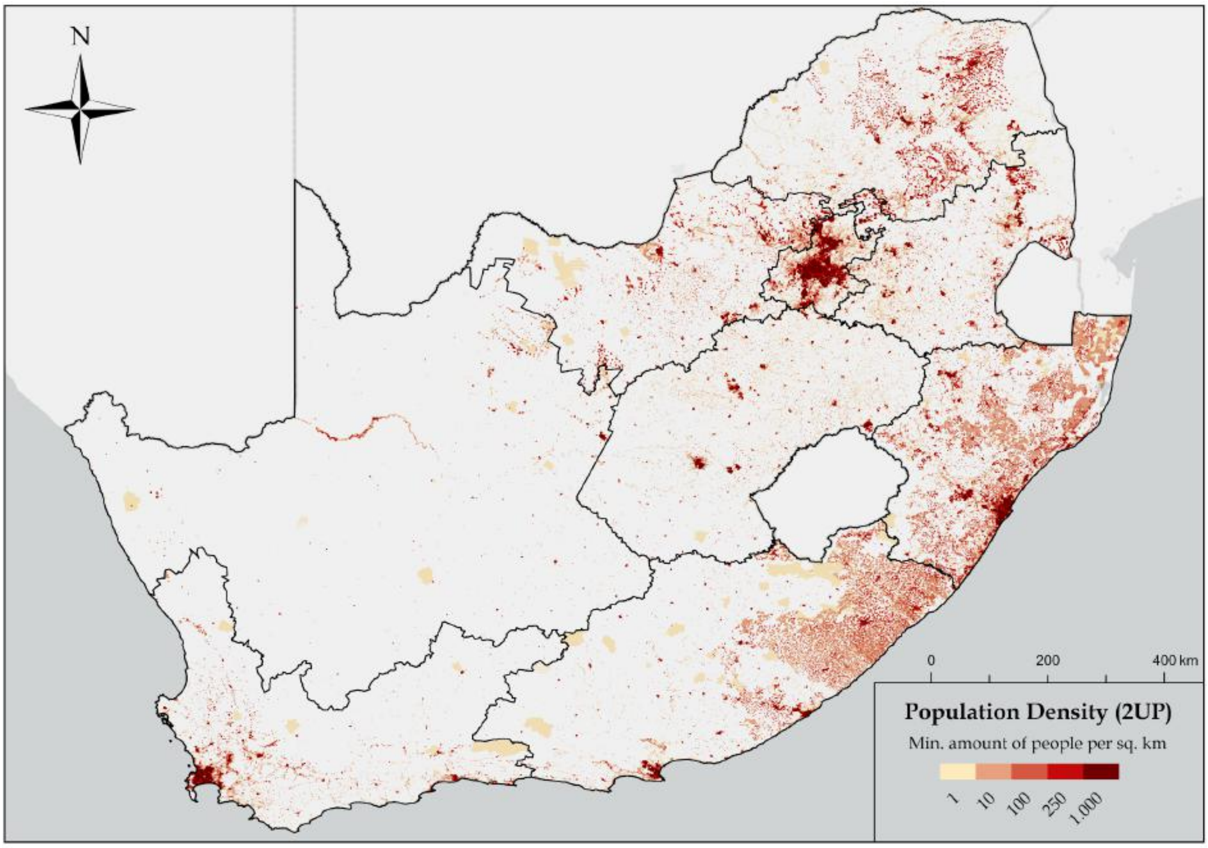

Figure 7: Population Density based on 2UP model, 2020.

Initially, it may seem that there is a minimal presence of people in Arid or Hyper-arid areas in 2015 (Figure 8). However, nearly 790,000 individuals inhabited arid regions, while around 5,700 resided in Hyper-arid zones. The majority of this population was concentrated in the western regions of South Africa, specifically in the Northern and Western Cape provinces. The vast majority of South Africa's population, approximately 38 million people, resides in Semi-arid regions. These areas experience a moderate level of aridity compared to the more severe arid and hyper-arid zones. The total exposed population per drought index can be found in table 2.

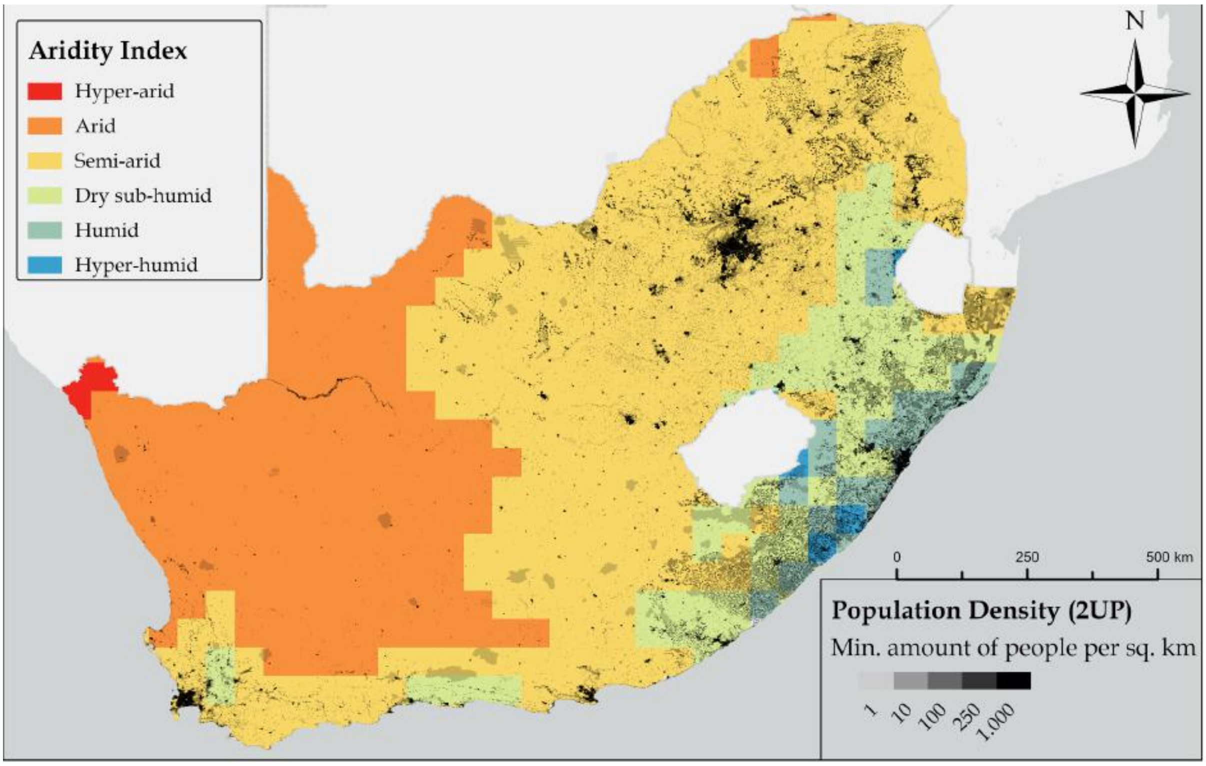

Figure 8 : Exposed population Aridity Index, Current.

Based on the SPEI12 method, the exposed population to drought in 2015 can be examined (Figure 9). The analysis reveals that a significant portion of the population in the Johannesburg region falls within the Extreme dry category. Approximately 18.8 million individuals were classified as Extreme dry, while around 19 million fell under the Severe dry category . Notably, a quarter of these 19 million individuals were located in Cape Town. Furthermore, nearly 11 million people reside in areas classified as 'Normal' according to the SPEI classification, indicating relatively stable drought conditions. The majority of these individuals live along the coastal areas, particularly in cities such as Port Elizabeth and Durban.

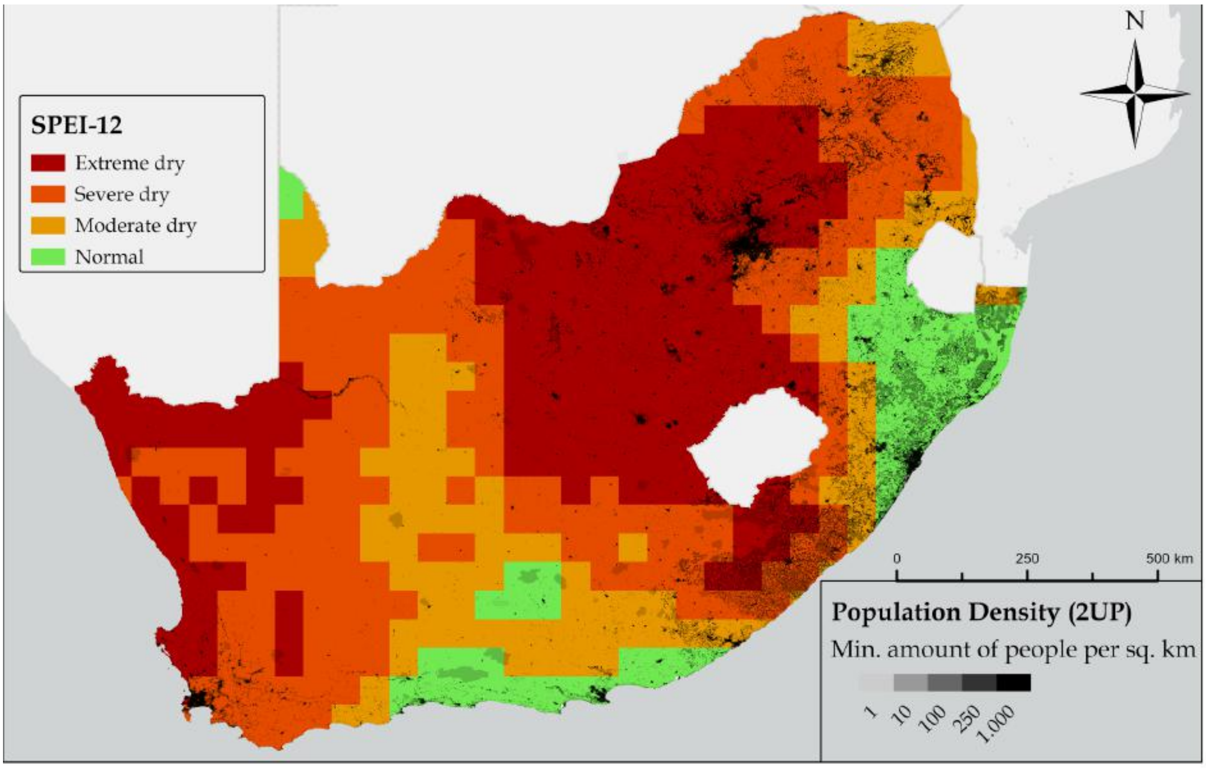

Figure 9: Exposed population SPEI, Current.

When examining the population exposed to drought in 2015 through the Water Yield GAP, several insights emerge (figure 10). A large portion of South Africa is classified as 'Arid land', and at first glance, it may seem that few people reside in these areas. However, approximately 470,000 individuals live in these arid regions. Additionally, there are nearly 1.5 million people residing outside the 80% threshold of the Water Yield Gap, on the border of arid areas. Optimal conditions for agriculture and livelihoods are scarce in South Africa, but these areas are often highly populated. Approximately 1.4 million people live in areas with the most favourable WaterGAP conditions ranging from 0-20%. It can be concluded that the most suitable areas, logically, are often those with high population density, yet a significant portion of the population resides in dry regions.

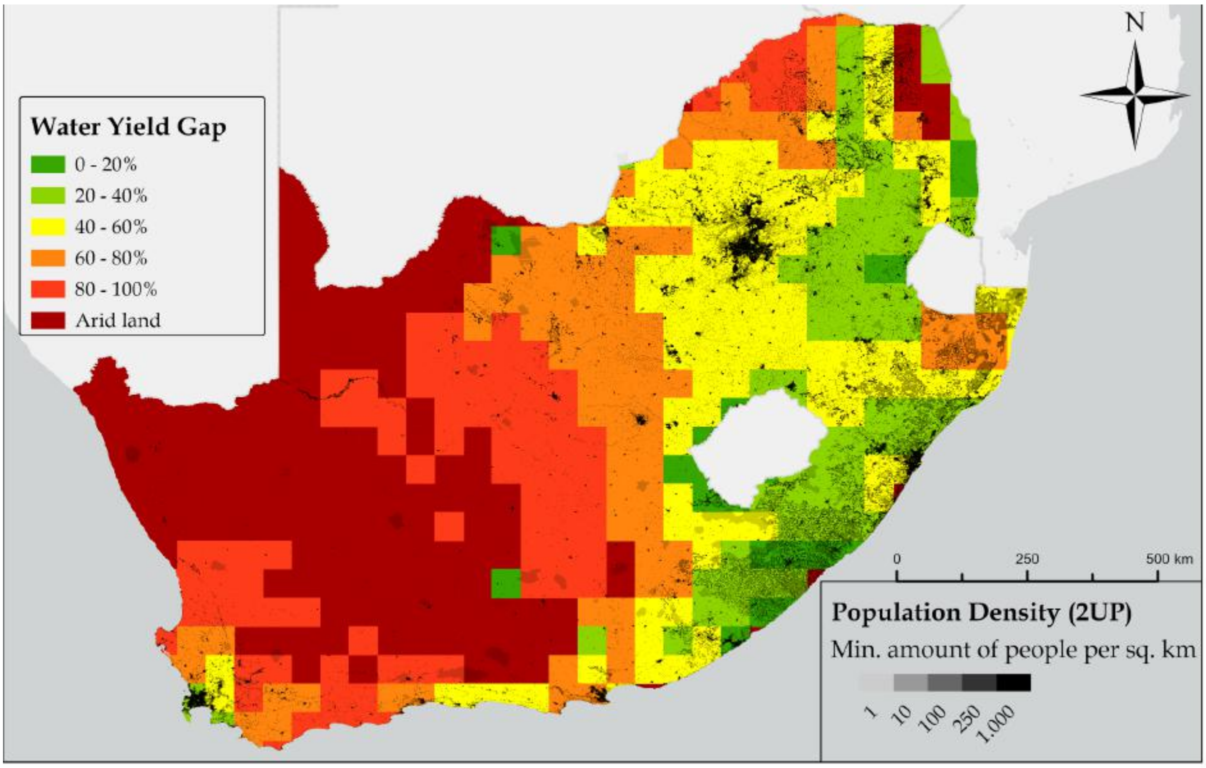

Figure 10: Exposed population WaterGAP, current

3.4. Changes in exposed population

Aridity index 2050

The total population, according to the 2up model, has significantly increased by 2050, especially in the two smallest provinces in terms of total population, Northern Cape and Free State. Additionally, the Eastern Cape province has also experienced a population increase of over 10%, reaching 7.7 million inhabitants in 2050. The population density in urban areas is also significantly increasing, with Johannesburg and Cape Town experiencing substantial growth in particular (figure 11). When examining the expected exposed population based on the Aridity Index, it can be observed that a larger proportion of the population falls into the Hyper-arid category, with around 7,000 people instead of approximately 5,700. The only category in which the number of people in 2050 is lower than in 2015 is the Hyper-humid category, which experiences a decrease of 40% to 430,000 people instead of 730,000.

In summary, according to the 2UP projections for 2050, there has been a notable overall population increase. When examining the exposed population, a larger percentage is categorised as Hyper-arid, indicating a higher number of people exposed to extreme aridity. Additionally, the Arid category shows the highest percentage increase, suggesting a growing population facing drought-related issues. Interestingly, the only category projected to experience a population decrease by 2050 is Hyper-humid.

WaterGAP 2050

When examining the projections from the Water Yield Gap data and population trends, several trends become evident. As previously mentioned, a substantial increase in population is expected, which leads to a larger number of people potentially exposed to drought. According to the WaterGAP data, the number of people living in arid areas, where the gap is greater than 100%, has increased. Furthermore, the categories between 60 and 100% Water Yield Gap in terms of the total exposed population and its proportion have also significantly increased, as shown in Table 2. It is also noteworthy that both the total number of exposed individuals and the proportion of the total population in the 20-40% category have nearly halved.

In summary, the WaterGAP data and population projections for 2050 indicate a considerable rise in the total population and the number of people living in (semi-)arid areas. We can conclude that an increasingly larger proportion of the total population is located in areas with higher Water Yield Gaps.

Aridity Index 2100

According to the 2up model, it is expected that by the year 2100, the population of South Africa will decline, resulting in a lower total population. The projections indicate that around 58.2 million people will inhabit the country at that time, representing a decrease of approximately 4.5 million people compared to 2050. Interestingly, the province of Gauteng, where Johannesburg is located, is the only region where the population is projected to increase, with an estimated addition of around 320,000 people (Figure 11). Conversely, the provinces of Eastern Cape, KwaZulu-Natal, and Limpopo experience the largest population decline. When it comes to the exposed population to drought, something interesting is happening. Even though the overall population is decreasing, the number of people living in arid areas is not affected much. However, it should be noted that there is a different pattern observed in other categories, where more people are expected to fall under the hyper-humid category and fewer individuals will face drought. These findings reveal the complexity of how the exposed population to drought may change in South Africa by 2100. However, it's important to keep in mind that these are long-term predictions based on models, and they should be taken with a grain of salt. It's not solely determined by the total population, but other factors also come into play.

Table 2: Exposed population drought indices.

Drought prone	**Aridity index**				**SPEI**		**Water Yield Gap**		
	scores	*Exposed population 2020*	*Exposed population 2050*	*Exposed population 2100*	*scores*	*Exposed population 2020*	*scores*	*Exposed population 2015*	*Exposed population 2050*
Strongly	*Hyper arid*	5.744 (0,01%)	6.954 (0,01%)	1.156 (0,00%)	*Extreme dry*	18.837.758 (34,56%)	*> 100%*	468.717 (1,22%)	715.413 (1,62%)
Strongly	*Arid*	788.738 (1,45%)	1.136.047 (1,82%)	1.382.874 (2,38%)	*Severe dry*	19.060.291 (34,96%)	*80 - 100%*	1.445.979 (3,77%)	4.152.406 (9,41%)
Partly	*Semi arid*	38.123.810 (69,94%)	43.559.514 (69,65%)	41.687.161 (71,86%)	*Moderate dry*	5.707.327 (10,47%)	*60 - 80%*	5.328.374 (13,87%)	11.961.446 (27,10%)
Partly	*Dry sub-humid*	7.939.333 (14,57%)	9.156.995 (14,64%)	10.523.607 (18,14%)	*Normal*	10.909.546 (20,01%)	*40 - 60%*	20.244.258 (52,71%)	20.610.815 (46,69%)
No drought	*Humid*	6.916.362 (12,69%)	8.251.684 (13,19%)	3.889.321 (6,70%)			*20 - 40%*	9.491.436 (24,71%)	5.522.616 (12,51%)
No drought	*Hyper humid*	731.572 (1,34%)	431.319 (0,69%)	526.804 (0,91%)			*0 - 20%*	1.425.088 (3,71%)	1.178.158 (2,67%)

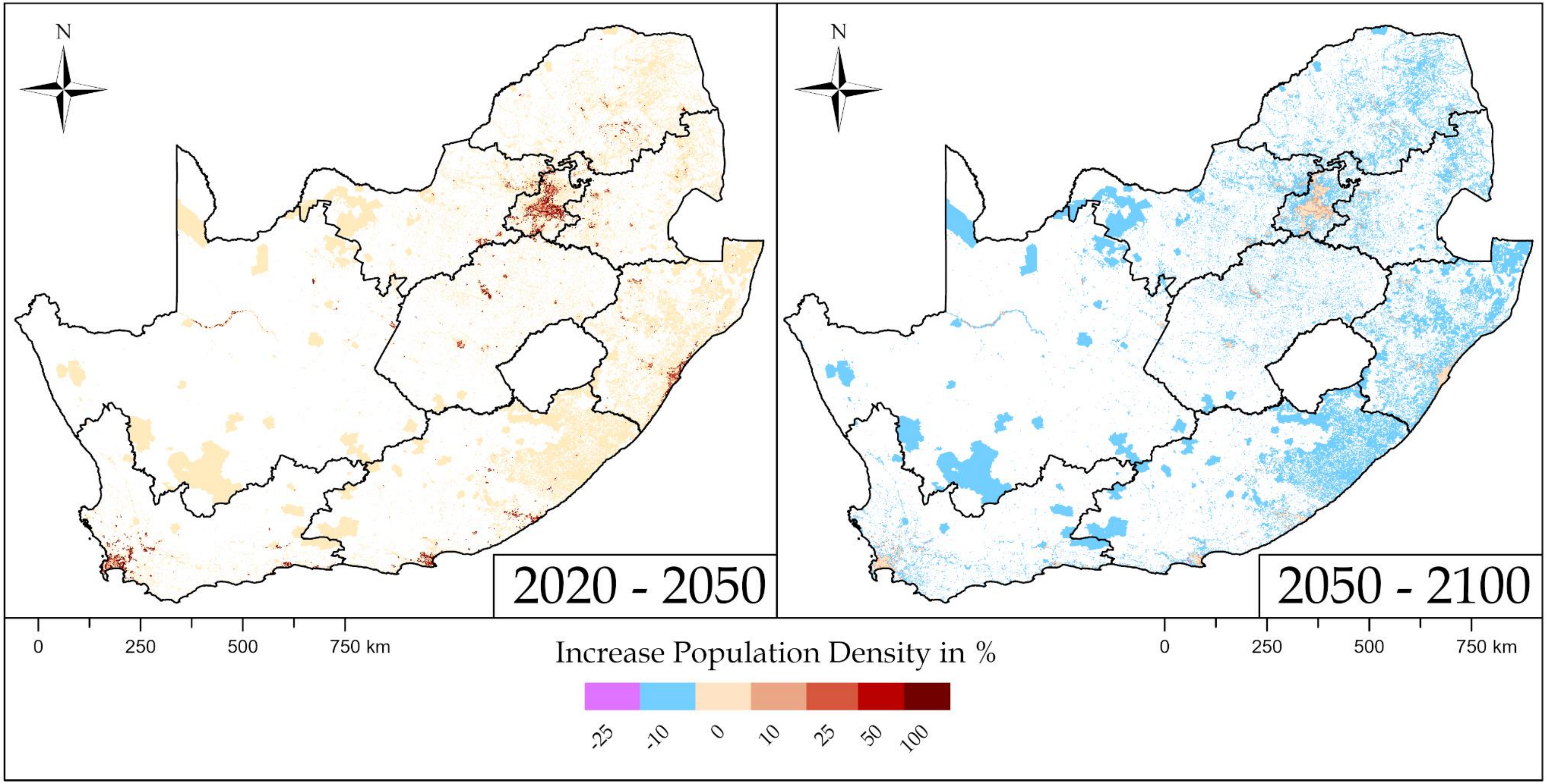

Figure 11: Increase in population Density (%), based on SSP2. Time period 2020-2050 and 2050-2100.

3.5. Decomposition Analysis

The result of the lines of code was as follows (Complete code can be found in the Annexes):

Contribution of changes from 2015 to 2050:	[0.14799984 ; -0.148]
Contribution of changes from 2015 to 2100:	[0.0649999 ; -0.065]
Total impact from 2015 to 2100:	[0.21299974 ; -0.213]

The results of the contribution analysis from 2015 to 2050 show that both population growth and changes in the drought index have significant impacts on the exposed population to drought. Regarding population, for every 1% increase in the population from 2015 to 2050, there is an additional 14.80% increase in the number of people exposed to drought. This means that as the population grows, the exposure of the population to drought also escalates. On the other hand, the drought index also plays a crucial role in influencing the exposed population. The value of approximately -14.80% indicates that for every 1% decrease in the drought index (reflecting a shift towards more aridity) from 2015 to 2050, there is an additional 14.80% increase in the population exposed to drought. In simpler terms, as the drought index worsens (represented by more negative values), the risk of drought becomes higher, causing a larger proportion of the population to face drought-related adversities. When considering the cumulative effect of both periods (2015 to 2050 and 2015 to 2100), the total impact on the exposed population to drought shows that both the increase in population and the decrease in the drought index contribute equally to the overall change observed during this entire period.

In conclusion, the decomposition analysis reveals that both the population and the drought index have a very similar influence on the changes in the exposed population to drought

Discussion

4.1. Sub-question 1

The Aridity Index employed in the analysis may not provide a highly precise assessment of current drought conditions. According to previous research, the use of the climate aridity index for assessing short-term drought events may result in inaccuracies (Zhang et al., 2023). The SPEI could therefore be a refined approach to address research sub-question 1 when focusing solely on the drought in South Africa of 2015. Depending on the context and formulation of the research questions, the most appropriate index may differ. The reliance on SPEI, despite using a 12-month calculation period, introduces a potential limitation due to its dependence on current weather conditions. This means that the reliability of the SPEI can be affected by unusual circumstances due to its time-specific nature. It is important to consider that the SPEI data was calculated using data from an extremely dry year, which does not represent a typical situation. The Water Yield Gap method is less frequently used in scientific research compared to the Aridity Index and SPEI. As a result, a straightforward approach for classification was not feasible, and instead, assumptions were made. Additionally, the assumption was made that the Nodata value indicates that the actual value is greater than 100%, although in theory, it could have a different cause. Lastly, the spatial resolution of the original data sources, such as WaterGAP and SPEI, was originally half-degree resolution, which may limit the accuracy of local-level analyses. Even though the pixel size was later changed to a 1 km resolution for visualisation purposes and geoprocessing tools, the underlying half-resolution values still persist.

4.2. Sub-question 2

The determination of drought changes over time involves several points of discussion. One of these points is related to the boundaries of arid areas, where the water yield gap approaches 100%. In such cases, the index shows a relatively small increase in drought over time. This is because the index has a maximum value of 100%. Furthermore, the resolution of the indices is another topic of discussion. The level of detail provided by the indices can impact the accuracy of assessing drought conditions and changes. While the severity of drought indicated by the index is associated with a higher likelihood of meteorological drought and drought disasters, it does not directly predict the specific areas where drought problems will be most significant. Other variables are needed to determine that. Lastly, it is important to note that the Aridity Index is based on SSP2 and the Water Yield Gap utilises climate models from ISI-MIP2a. These models and scenarios are built upon assumptions and simplifications of reality, which should be taken into account when interpreting the results.

4.3. Sub-question 3

The discussion regarding sub-question 3 focuses on the interpretation of drought 'exposure', emphasising that it should not be taken literally as the number of people affected by drought in 2015. Other factors play a crucial role in determining the actual impact on the population, such as vulnerability and the consequences of drought. This study specifically focuses on assessing the exposure of the population to drought and does not delve into the vulnerability or overall impact. It is also important to note that the drought indices were calculated for the year 2015, while the 2up model data was only available for 2020. As a result, the precise population figures should be taken with caution, as there might be variations between the two datasets. Furthermore, numerous discussion points from previous sub-questions apply to this aspect as well. Spatial resolution remains a topic of consideration and the advantages and disadvantages of different indices need to be taken into account.

4.4. Sub-question 4

Similar to the aridity index, the 2up population data relies on the SSP2 (Middle of the Road) scenario, which is a simplified representation of reality and involves certain assumptions. It is essential to take these assumptions into account when interpreting the results. Furthermore, the existence of NoData values occasionally results in slight differences in population numbers between layers. Small portions along the coast, where people reside, may lack available data and thus not be included in the analysis. Consequently, there may be slight variations of a few percentage points in the total population numbers between layers. Lastly, it is crucial to acknowledge that the water yield gap data prediction is based on a different model, which shares some similarities but also has distinct characteristics.

4.5. Sub-question 5

It is important to note that the results of sub-question 5 are based on the analysis of data from 2015 to 2100, and further research could be conducted to validate the robustness of these findings and explore additional factors that might influence the exposure of populations to drought in the future. To improve the accuracy of the model and its results, there may be a need to consider a more sophisticated model that takes into account non-linear relationships, additional relevant variables, and carefully validate the model against real-world data. It's also essential to critically assess the assumptions made in the model and ensure the quality of the input data. In conclusion, while the code provides some insights, the results should be interpreted with caution, and further analysis and refinement of the model may be necessary to understand the relationship between population, aridity index, and the exposed population to drought.

4.6. Future research & Recommendations

It is important to recognize that there are limitations belonging to this research, but based on the findings of this study, several recommendations and areas for future research emerge. Firstly, further investigations should explore the potential impacts of climate change on drought-prone areas in South Africa, with a particular emphasis on assessing the vulnerability of the population and considering socio-economic factors. Secondly, future research could also focus on regions where decreases in drought are projected, such as parts of Eastern Cape. Conducting flood risk assessments in these areas will provide valuable insights into the potential exposure of the population to flood hazards. Lastly, a possible suggestion is to consider a more comprehensive approach in this research, incorporating alternative methods and exploring the explanatory factors in order to enhance our understanding of drought exposure. By employing multiple methods and analysing the entire country, the study enhances understanding of drought-prone areas. Decision-makers can use this information to identify vulnerable regions and prioritise resource allocation and interventions. Additionally, the research raises public awareness about the consequences of climate change and population growth, motivating individuals to take proactive steps in conserving water and making sustainable choices. A city similar to Cape Town is already known for its water conservation practices and campaigns addressing water scarcity, and is familiar with the principle of water conservation (The Guardian, 2018), and more cities should follow.

Conclusion

The research concludes that depending on the index used, the location of the most drought-prone areas can slightly differ. However, it can be stated that the western regions of South Africa, particularly the Northern Cape province, face the highest levels of drought. An increase in drought conditions across most of the country from 2015 to 2050 is projected, with the western regions and northern Limpopo province experiencing significant changes. Additionally, the water yield gap analysis reveals complex patterns, with increased drought observed in the eastern parts of the country, while some coastal areas, specifically in the Eastern Cape province, may experience more humid conditions. The Western Cape province, including Cape Town, is expected to face the largest increases in aridity between 2050 and 2100. In 2050, the population living in arid or hyper-arid areas has increased, mainly in the Northern Cape. Despite the 2up model suggesting a decrease in the population by 2100, more people will reside in arid areas according to the aridity index. The decomposition analysis showed that the difference in impact between the Aridity Index and population growth on the exposed population to drought was minimal. Both factors had approximately equal effects on the population's exposure to arid conditions, but the impact of the Aridity Index was slightly greater.

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Annexes

7.1. Classification tables

Table A: Classification table of the Aridity Index (Boschetto et al., 2010).

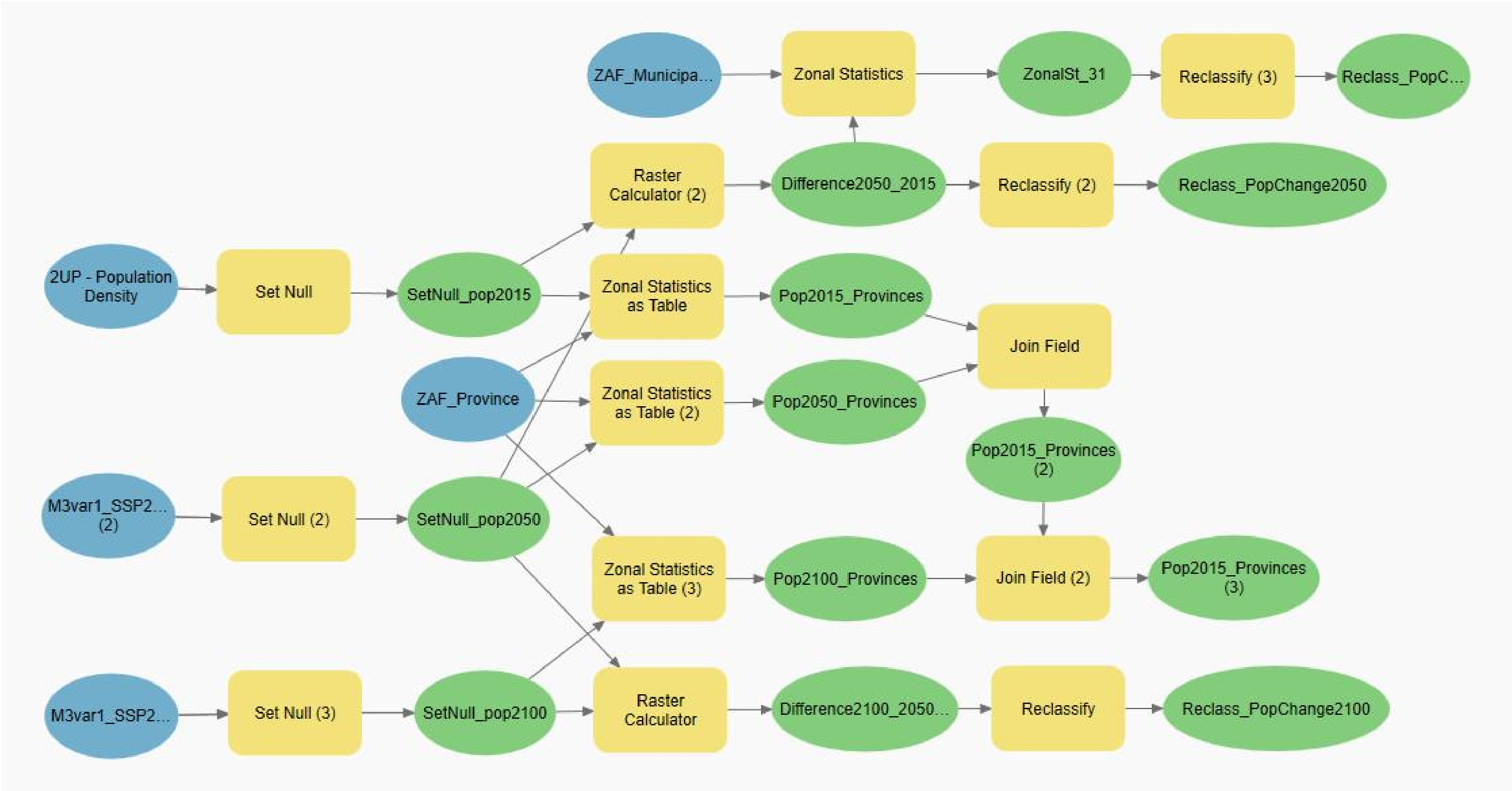
Aridity Index (AI) range	Category
AI < 0.05	Hyper-arid
0.05 <AI < 0.2	Arid
0.2 < AI < 0.5	Semi-arid
0.5 < AI < 0.65	Dry sub-humid
0.65 < AI > 0.75	Humid
AI > 0.75	Hyper-humid

Table B: Classification of the SPEI index (Vicente-Serrano et al., 2010)

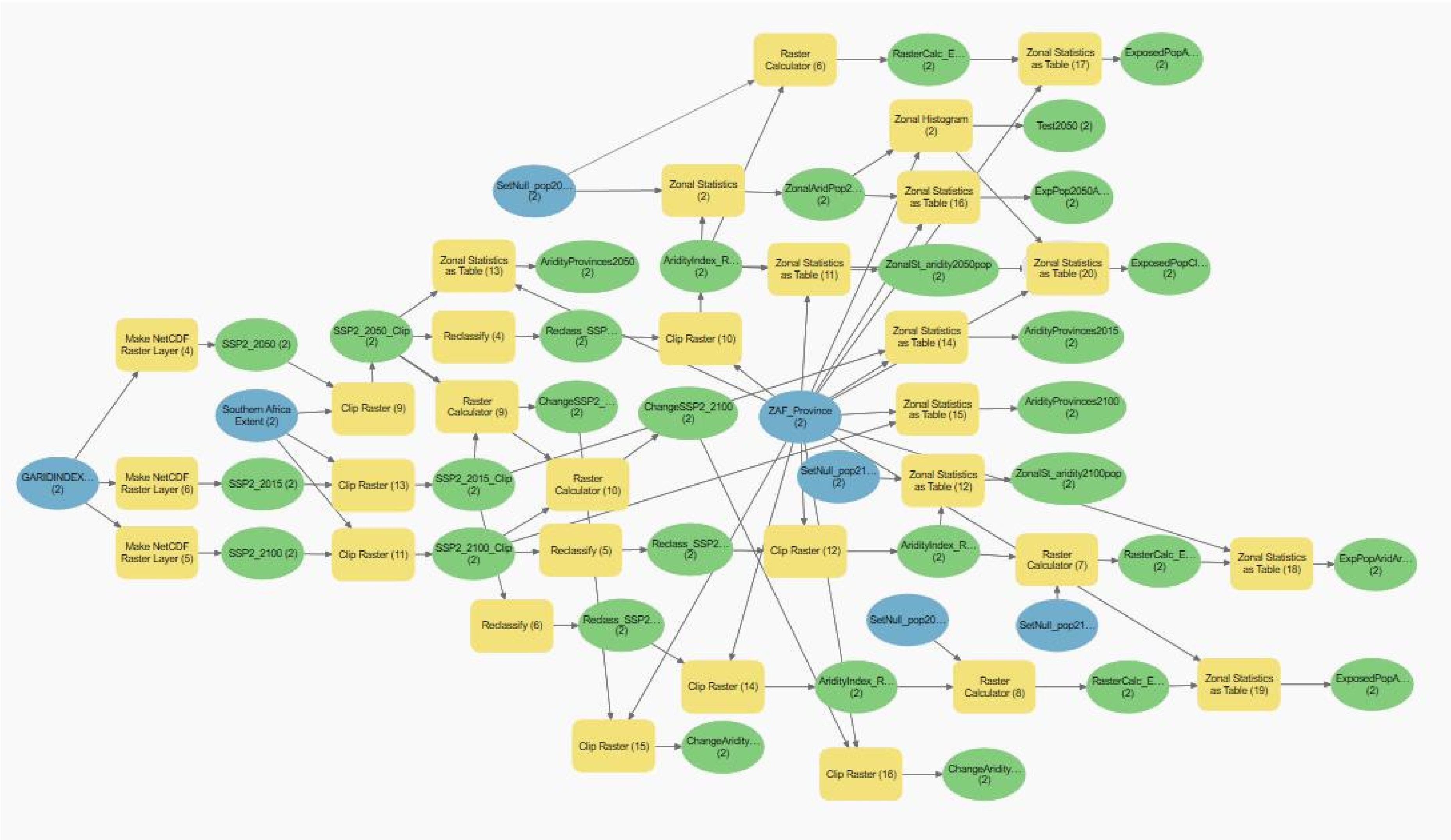
Category	Range of SPEI index values
Extreme wet	≥ 2
Very wet	1.5 to 1.99
Moderate wet	1 to 1.49
Normal	− 0.99 to 0.99
Moderate dry	− 1.49 to − 1
Severe dry	− 1.99 to − 1.5
Extreme dry	≤ − 2

7.2. ModelBuilder

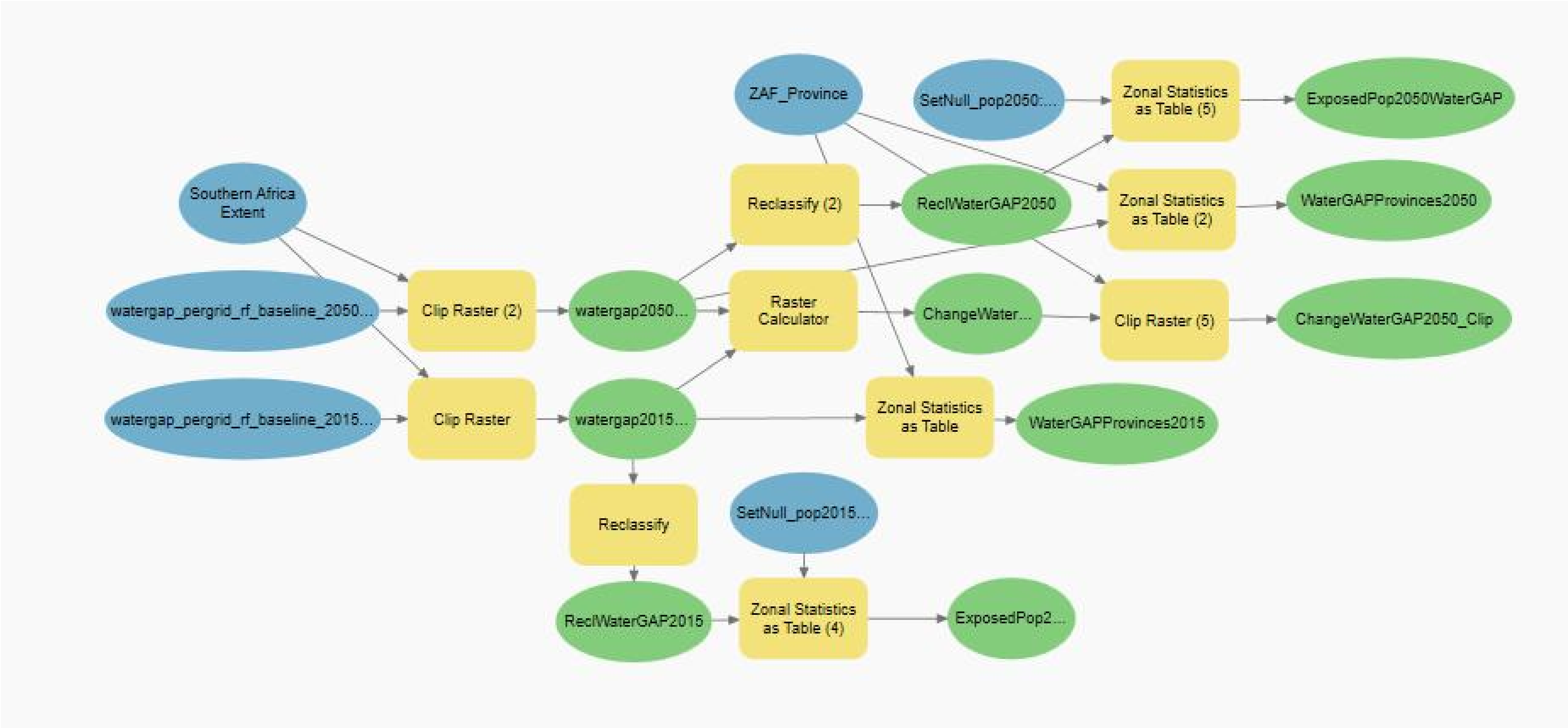
Modelbuilder A: 2UP model



Modelbuilder B: Aridity Index.



Modelbuilder C: Water Yield Gap



7.3. Python Script

```python
# -*- coding: utf-8 -*-
"""
Created on Fri Jun 30 14:52:09 2023

@author: janal
"""
import numpy as np

population_2015 = 1
population_2050 = 1.148
population_2100 = 1.065

drought_index_2015 = 1
drought_index_2050 = 0.989
drought_index_2100 = 0.969

# Define input-output tables and technical coefficients matrix (A-matrix)
Z = np.array([[population_2015, drought_index_2015]])

# Vector Total Output
x = np.array([population_2015, 1e-6])

# Technical coefficients matrix
A = Z / x[:, np.newaxis]

I = np.identity(len(x))
L = np.linalg.inv(I - A)

# Change in total output (between 2015 & 2050)
delta_x_2050 = np.array([population_2050 - population_2015, drought_index_2050 - drought_index_2015])

# Change in input (between 2015 & 2050) - Converted to proportions
delta_f_2050 = np.array([(population_2050 - population_2015) / population_2015, drought_index_2015 - drought_index_2050])

# Change in total output (between 2015 & 2100)
delta_x_2100 = np.array([population_2100 - population_2015, drought_index_2100 - drought_index_2015])

# Change in input (between 2015 & 2100) - Converted to proportions
delta_f_2100 = np.array([(population_2100 - population_2015) / population_2015, drought_index_2015 - drought_index_2100])

# Contribution of changes in input to changes in output
delta_x_contrib_2050 = np.dot(L, delta_f_2050)
delta_x_contrib_2100 = np.dot(L, delta_f_2100)

# Total impact over the entire period (2015 to 2100)
total_impact = delta_x_contrib_2050 + delta_x_contrib_2100
print("Contribution of changes from 2015 to 2050:", delta_x_contrib_2050)
print("Contribution of changes from 2015 to 2100:", delta_x_contrib_2100)
print("Total impact from 2015 to 2100:", total_impact)
```

Figure A: Screenshot Spyder script Decomposition Analysis.

Spyder script Decomposition Analysis in text:

```
"""
import numpy as np

population_2015 = 1
population_2050 = 1.148
population_2100 = 1.065

drought_index_2015 = 1
drought_index_2050 = 0.989
drought_index_2100 = 0.969

# Define input-output tables and technical coefficients matrix (A-matrix)
Z = np.array([[population_2015, drought_index_2015]])

# Vector Total Output
x = np.array([population_2015, 1e-6])

# Technical coefficients matrix
A = Z / x[:, np.newaxis]

I = np.identity(len(x))
L = np.linalg.inv(I - A)

# Change in total output (between 2015 & 2050)
delta_x_2050 = np.array([population_2050 - population_2015, drought_index_2050 -
drought_index_2015])

# Change in input (between 2015 & 2050) - Converted to proportions
delta_f_2050 = np.array([(population_2050 - population_2015) / population_2015, drought_index_2015
- drought_index_2050])

# Change in total output (between 2015 & 2100)
delta_x_2100 = np.array([population_2100 - population_2015, drought_index_2100 -
drought_index_2015])

# Change in input (between 2015 & 2100) - Converted to proportions
delta_f_2100 = np.array([(population_2100 - population_2015) / population_2015, drought_index_2015 -
drought_index_2100])

# Contribution of changes in input to changes in output
delta_x_contrib_2050 = np.dot(L, delta_f_2050)
delta_x_contrib_2100 = np.dot(L, delta_f_2100)

# Total impact over the entire period (2015 to 2100)
total_impact = delta_x_contrib_2050 + delta_x_contrib_2100
print("Contribution of changes from 2015 to 2050:", delta_x_contrib_2050)
print("Contribution of changes from 2015 to 2100:", delta_x_contrib_2100)
print("Total impact from 2015 to 2100:", total_impact)
```

7.4. Formulas

$$WYG_{rf} = \frac{(f_{rf} * Y_{allcrops}) - (f_{rf} * Y_{rf})}{f_{rf} * Y_{allcrops}}$$

Formula A: Water Yield Gap - Wageningen Environmental Research