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Report describingclimate risk assessmenton food security, waterand energy nexus

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Summary

FOCUS-Africa?s emphasis on user-centric climate services provision in Southern Africa provides an opportunity to promote and raise awareness about the climate risk in the water, energy, and food security (WEF) nexus in climate-sensitive sector plans. Water security is critical for the functioning of all economic sectors in Southern Africa, including agriculture, energy production, and industry. The WEF nexus approach is based on an understanding of the water-related synergies and trade-offs between the water, food, and energy sectors. The WEF sectors in the region are at risk due to climate change and the high population growth which may result in increasing competition for water resources in the future thus bringing the issue of the WEF Nexus to the fore. This report (D2.3) brought the principles of climate risk and WEF nexus together. Specifically, the report covered the assessment of climate risk on the WEF Nexus in Southern Africa. Due to the complexity of doing a detailed climate risk assessment and WEF Nexus at the Southern Africa-wide level, this report analyzed climate risk and the WEF nexus in Southern Africa from a broad regional perspective, including use of projections and short country overviews. In addition, a survey was used to compliment the climate risk aspects with perceptions of climate risks in the WEF nexus. The analysis then narrowed down to a detailed assessment using Malawi as an example. This report showed that water scarcity in the region is a pressing issue, as most of the countries in the region are experiencing droughts and a decrease in rainfall, which has been further exacerbated by increases in temperature. Moreover, the region's population growth, irrigation-based agriculture, and hydroelectric power all of which demand water, further highlight the need to ensure water security in the region. Water security is critical for the functioning of most economic sectors in Southern Africa, including agriculture, energy production, and industry. The survey conducted in this study demonstrated that the WEF Nexus has emerged as a critical issue in Southern Africa and that the region faces the challenge of ensuring reliable and sustainable access to water, energy, and food amidst high climate risk and changing environmental, economic, and social conditions. Energy security in Southern Africa is also important, as the region's growing population and economic development are contributing to increasing demand for energy. Despite havin...

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FOCUS-AFRICA

Full-value chain Optimised Climate User-centric Services for Southern Africa

Climate Risk and Vulnerability Assessment on WEF Nexus in Southern Africa

Deliverable D2.3

Lead Beneficiary: Council for Scientific and Industrial Research (CSIR)

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About FOCUS-Africa

FOCUS-Africa – Full-value chain Optimised Climate User-centric Services for Southern Africa – is developing sustainable tailored climate services in the Southern African Development Community (SADC) region for four sectors: agriculture and food security, water, energy and infrastructure.

It will pilot eight case studies in six countries involving a wide range of end-uses to illustrate how the application of new climate forecasts, projections, resources from Copernicus, GFCS and other relevant products can maximise socio-economic benefits in the Southern Africa region and potentially in the whole of Africa.

Led by WMO, it gathers 14 partners across Africa and Europe jointly committed to addressing the recurring sustainability and exploitation challenge of climate services in Africa over a period of 48 months.

For more information visit: www.focus-africaproject.eu

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Executive Summary

FOCUS-Africa's emphasis on user-centric climate services provision in Southern Africa provides an opportunity to promote and raise awareness about the climate risk in the water, energy, and food security (WEF) nexus in climate-sensitive sector plans. Water security is critical for the functioning of all economic sectors in Southern Africa, including agriculture, energy production, and industry. The WEF nexus approach is based on an understanding of the water-related synergies and trade-offs between the water, food, and energy sectors. The WEF sectors in the region are at risk due to climate change and the high population growth which may result in increasing competition for water resources in the future thus bringing the issue of the WEF Nexus to the fore. This report (D2.3) brought the principles of climate risk and WEF nexus together. Specifically, the report covered the assessment of climate risk on the WEF Nexus in Southern Africa. Due to the complexity of doing a detailed climate risk assessment and WEF Nexus at the Southern Africa-wide level, this report analyzed climate risk and the WEF nexus in Southern Africa from a broad regional perspective, including use of projections and short country overviews. In addition, a survey was used to compliment the climate risk aspects with perceptions of climate risks in the WEF nexus. The analysis then narrowed down to a detailed assessment using Malawi as an example.

This report showed that water scarcity in the region is a pressing issue, as most of the countries in the region are experiencing droughts and a decrease in rainfall, which has been further exacerbated by increases in temperature. Moreover, the region's population growth, irrigation-based agriculture, and hydroelectric power all of which demand water, further highlight the need to ensure water security in the region. Water security is critical for the functioning of most economic sectors in Southern Africa, including agriculture, energy production, and industry. The survey conducted in this study demonstrated that the WEF Nexus has emerged as a critical issue in Southern Africa and that the region faces the challenge of ensuring reliable and sustainable access to water, energy, and food amidst high climate risk and changing environmental, economic, and social conditions. Energy security in Southern Africa is also important, as the region's growing population and economic development are contributing to increasing demand for energy. Despite having a huge potential for hydropower energy, the region still faces challenges related to energy access, affordability, and reliability. This was clearly exemplified in the case of Malawi where about 90% of households are still without access to electricity. A case which is true for most other countries in the region. Despite having a considerable portion of irrigatable land in the region as highlighted and with a significant amount of fresh water being lost to the sea, food security is also still a critical issue in Southern Africa. Food production systems in the region are already under stress due to the impacts of climate change on agriculture as highlighted in the study. Food production is also constrained by limited access to water and energy, which affects productivity and leads to increased costs hence bringing the issue of the WEF Nexus to the core.

On the other hand, this report proceeded to indicate that climate risk also presents opportunities for positive change. The climate risk indicated for Southern Africa can drive the need for diversification in the energy sector, leading to investments in renewable energy sources and greater energy security as was highlighted for Malawi. Additionally, climate risk can incentivize the adoption of climate-smart agricultural practices, innovative water management techniques, and ecosystem-based approaches, enhancing water and food security while fostering environmental sustainability. Climate-smart agriculture and effective integrated water resources management are particularly crucial for Southern African circumstances identified in this report such as projected increase in drought conditions, amplified temperatures and the region being agro-centric. The report also highlighted that to effectively address climate risk in the WEF Nexus, Southern African countries must prioritize adaptation and resilience-building measures. This involves investing in climate-resilient infrastructure,

promoting sustainable land and water management practices, and fostering regional cooperation for shared resource management. Moreover, stimulating public awareness about the climate risk on the WEF Nexus is essential for promoting a culture of conservation and responsible use of resources. Education and engagement can empower individuals and local stakeholders to actively participate in sustainable development efforts and contribute to climate resilience. By recognizing and addressing the challenges while seizing the opportunities presented by climate risk, Southern Africa can create a more sustainable and secure future for its water, energy, and food systems and secure its future in the WEF sectors. Regional collaboration, innovative solutions, and long-term planning will be crucial in building resilience and adapting to the changing climate, ensuring the well-being and prosperity of the region's people and environment. Understanding the WEF nexus in the context of climate services provision including climate risk and vulnerability assessment has an important role to play in tailoring climate services and adaptation actions for maximum benefit in Southern Africa. With the indicated shared constraints in water resources caused by climate change and since water is key across economic sectors, then WEF nexus and climate services are necessary complements.

Keywords

Climate risk, WEF Nexus, Southern Africa, climate extremes, climate change

1 Introduction

1.1 Climate risk and vulnerability

Climate change poses a significant threat to Southern Africa, through rising temperatures, increases in extreme storms and prolonged droughts having devastating consequences for the region's economies and communities (S. Nangombe et al., 2018; S. S. Nangombe et al., 2019; Seneviratne et al., 2021). Southern Africa is already one of the most vulnerable regions in the world when it comes to climate change, and climate risks in the region need to be addressed with urgency (Ziervogel et al., 2022a). Southern Africa is home to about 277 million people, where 60% of the people live in rural areas, and its economies are highly dependent on agriculture and natural resources (Tanyanyiwa & Hakuna, 2014). However, the region is currently experiencing severe climate-related challenges, including water scarcity, flooding, and land degradation (Trisos et al., 2020). These challenges have a considerable impact on the region's food security, energy demand, infrastructure development, and health.

Rising temperatures and prolonged droughts have resulted in crop failures, putting huge stress on food security, agriculture livelihoods, and economies, as demonstrated during the strong El Niño of 2015/16 (F. A. Engelbrecht & Monteiro, 2021). In 2018, Cyclone Idai hit the region, leaving over 1,500 people dead, affecting over 3 million people and causing extensive damage to infrastructure and properties (Mutasa, 2022). These extreme weather events are expected to become more frequent and intense (Seneviratne et al., 2021)causing more damage and affecting more people. Southern Africa is also home to many low-lying coastal cities and towns, which are at risk of flooding and sea-level rise (IPCC AR6 WGI, 2021). Coastal cities like Maputo, Durban, and Cape Town are vulnerable to the rising sea level, which could cause massive economic losses and displacement (Mather & Stretch, 2012).

Other climate risks in the region include decreasing biodiversity, multiple diseases, and conflict (IPCC Report, 2022). These threats could substantially impact the social and economic systems of the region, making it harder to achieve sustainably. Climate change risks can't be taken lightly, and a coordinated and measured response is required to tackle the issue. Governments, civil societies, and private sectors all have a vital role to play in combating climate change risks. Governments can enact policies and regulations that reduce greenhouse gasses (GHG) emissions and increase resilience. Civil societies have an important role to play in building awareness and demand for climate action. The private sector can develop innovative ecosystem-based approaches and support resilience-enhancing investments. Southern Africa is on the frontline of climate change, with its economies and communities already feeling its impacts. Governments, communities, and the private sector should tackle climate change head-on and take action to reduce its risks. Time is of the essence, and all parties need to work together to mitigate these risks and to achieve sustainable and resilient development in the region.

1.2 WEF Nexus

Water, energy and food are essential resources for human wellbeing, poverty reduction and sustainable development (Rasul, 2016). Demand for freshwater, energy and food is projected to increase significantly over the next decades (Hoff, 2011). The principle of water, energy, and food security interrelatedness and interdependency together with the associated trade-offs and synergies is defined as the water-energy-food (WEF) nexus (Nhamo et al., 2020; Rasul & Sharma, 2016). For example, food production needs water, productive land and energy; energy generation needs water; while water depends on energy for its extraction, treatment, and redistribution (Rasul & Sharma, 2016). The WEF nexus considers the different dimensions of water, energy, and food in an integrated way and is recognized as a systematic approach to resource management, where the interrelatedness among WEF sectors is quantified and it supports the development of adaptation strategies and policy (Bazilian et al., 2012; Markantonis et al., 2019; Nhamo et al., 2020). In the context of resource scarcity and climate change, the WEF nexus interlinkages intensify and direct competitions or trade-offs between sectors increase, hence limiting countries' ability to meet the growing demand for resources (Markantonis et al., 2019). Therefore, exploring the WEF interlinkages under the climate change effects is important to anticipate sectoral conflicts and will help decision-makers in strategic resources planning and management at national and regional levels.

The WEF nexus and climate change are strongly interlinked (Rasul and Sharma, 2016). Climate change drives various phenomena such as rising temperatures, changes in precipitation patterns, extreme weather events, and rising sea-levels. These have negative effects on WEF security, for example, they may change the balance between the nexus resources and their interactions (Cramer et al., 2018). Traditional methods for WEF production may increase greenhouse gas (GHG) emissions that intensify climate change. Therefore, efficient use of land, water and energy and coordinated efforts to minimize trade-offs and maximize synergies is required for the planning and implementation of effective climate change mitigation and adaptation strategies (Cramer et al. 2018). Integrating the assessment of the WEF Nexus into climate services planning and provision can be one of the effective ways to ensure sustainability of the climate services policies and plans put in place. Climate services can provide information about the interactions between climate change and WEF nexus sectors while WEF nexus studies can help understand the implications of climate-informed decisions for other economic sectors across nexus resources (Cremades et al., 2016).

The WEF resources are crucial for development in society, but they are quite limited and are depleting at a faster rate than ecosystems can cope with (Cramer et al. 2018). The concept of the WEF nexus entails a holistic view of the system that surrounds society and interactions amongst the WEF sectors in a complex way which include feedback loops, different sectors and natural resources (Fang & Chen, 2017). Therefore, it's the epicenter, or meeting point of several complex components, which come together to represent something that is more than the sum of its parts (Howarth & Monasterolo, 2017). In addition to having a combination of inter-twined relationships between water, energy, and food systems and the intricacies that define them, the nexus also calls for an understanding of 'soft' factors complex to measure but are key in supporting decision-making (Howarth and Monasterolo, 2016). Examples of such factors include, human values and perceptions, natural and technical processes related to systems considered, and whether in the context of the past or the future.

In order to sustain resilience of resources and food, water, and energy security in the Southern Africa region, cross-sectoral integration is key, together with regional integration between different stakeholders or institutions, critical for ensuring water, food, and energy security. In this report, in the spirit of ensuring water, energy and food security in the Southern Africa region, the current and potential interdependencies, conflicts and trade-offs which exist or may arise in ensuring water security, energy security and water security in the region will be explored.

2 Data and Methods

2.1 Climate data

To determine climate hazards and extremes used in the clime risk assessment, an analysis was made for a baseline period (1961-1990) and for future global warming levels (GWLs). Four GWLs were considered namely 1.5 °C, 2 °C, 3 °C and 4 °C, where the first two are the Paris Agreement temperature thresholds, and the last two represent possible worst-case scenarios. For climate, ten bias-adjusted General Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) statistically downscaled to a common 0.5° horizontal grid was utilized and comprise of years ranging from 1961 to 2100. The selected ten models are: CAN-ESM5, CNRM-CM6-1, CNRM-ESM2-1, EC-EARTH3, MIROC6, GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1, MRI-ESM2-0, and UKESM1-0-LL. The bias-adjustment protocol done on the data was from the Inter-Sectorial Impact Model Inter-comparison Project (ISIMIP) (Lange, 2019). More details of these 10 models including their full names and source of origin can be found in Lange et al. (2021). CMIP6 based models were opted for here as CMIP6 provides the latest set of models which are currently being used widely for future climate projection assessments. CMIP-style models have also been widely used in climate change studies in Africa because they show as reliable for the region in climate model evaluation studies done in the past (Aloysius et al., 2016; Ongoma et al., 2019). For this report, the models under the low mitigation “business as usual” shared socioeconomic pathway (SSP5-8.5) scenario was used. Out of all the scenarios under CMIP6, the SSP5-8.5 is the scenario representing the world with the least or no mitigation efforts enforced to change the current anthropogenic emissions pathway (Rao et al., 2019).

2.2 Extreme indices

Three extreme weather-event definitions were employed in the analysis. The first set consist of the extreme climate indices from the ETCCDI recommended for use by the World Meteorological Organization (WMO). These are listed and defined in Table 1.

Table 1. Definitions of core and none-core ETCCDI extreme climate indices (Zhang et al., 2011) **used.**

	Extreme indices	Short Definition	Definition	Unit
1	TXx	Hot days	The annual maximum value of daily maximum temperature	°C
2	TNx	Hot nights	The annual maximum value of daily minimum temperature	°C
3	CDD	Longest dry spell	The maximum annual number of consecutive dry days (when PR < 1.0 mm)	days
4	R20mm	Count of heavy rainfall days	Annual count of days when PR >= 20 mm	days
5	RX5day	Maximum 5-day precipitation	Annual maximum of 5-day PR total calculated on a 5-day running window	Mm
6	Heatwave days	Heatwave days	Annual number of days characterized as heatwave days	days

Keetch-Byram drought index

The Keetch-Byram drought index, D, is defined in terms of a daily drought factor, dQ:

$$dQ = \frac{(203.2-Q)[0.968 \times e^{(0.0875T+1.5552)}-8.30]}{[1+10.88 \times e^{(-0.001736R)}]} \quad (1)$$

Here R is the mean annual precipitation (mm), and Q (mm) is the soil-moisture deficiency that results from the interaction between rainfall and evaporation. Once Q has been updated by dQ, the drought index is calculated from the equation:

$$D = \frac{10Q}{203.2} \quad (2)$$

Note that D ranges from 0 to 10, where D=10 indicates completely dried out soil and vegetation (C. J. Engelbrecht et al., 2015; Keetch & Byram, 1968).

Wind Power Density

The wind power density (WMD) (unit: W m−2) is one of the key measures for assessing the wind power generation potential. The literature defines wind power density through the relation.

$$WPD = \frac{1}{2}\rho V^3 \quad (3)$$

where V is the wind speed at the height of the hub adjusted to the turbine (here assumed to be 100 m) and ρ is the air density **(**assumed to be 1.225 kg m^{-3} under standard conditions**)** (Akinsanola et al., 2021) To calculate WPD, most studies interpolate wind speed at a reference high Z_{ref} the desired turbine hub height .

$$V(z) = V_0 \left(\frac{Z}{Z_{ref}}\right)^{\alpha} \quad (4)$$

In this study $Z_{ref} = 10$ and for the power law exponent for open surfaces, we assumed that $\alpha = 1/7$, while V_0 was taken from CMIP6 gridded model outputs of wind speed at a 10 m height. The WPD index is calculated for each grid point for the South Africa domain. There are many ways to estimate the height of a turbine hub from a 10 m surface wind measurement.

Photovoltaic Potential and its extremes

The PV power output is dependent on power generation potential PV_{pot} and installed capacity on site. It is a dimensionless magnitude that represents the performance of the PV cells in terms of the ambient environment. As such, the instantaneous PV power production is achieved by multiplying PVpot by nominal installed watts of PV power capacity. According to the literature (Jerez et al., 2015) the PV_{pot} can be expressed as:

$$PV_{pot}(t) = P_R\,(t)\ \frac{RSDS(t)}{RSDS_{\ STC}} \quad (5)$$

where STC refers to standard test conditions ($RSDS(t) = 1{,}000W\ m^{-2}$) whose nominal capacity PV is determined as its measured power output. The performance ration PR accounts for changes in PV cell efficiency due to changes in their temperature and is defined as:

$$P_R\,(t)\ = 1 + \gamma[T_{cell}(t) - T_{STC}] \quad (6)$$

where $T_{cell}(t)$ is the PV cell temperature, $T_{STC} = 25\,°\mathrm{C}$ and γ is taken here as −0.005 $°C^{-3}$, considering the typical response of monocrystalline silicon solar panels. Finally, $T_{cell}(t)$ is modelled considering the effects of TAS, RSDS and VWS on it as:

$$P_R\,(t)\ = C_1 + \ C_2TAS\,(t) + \ C_3RSDS\,(t) + C_4\,VWS(t) \quad (7)$$

The Student's *t-test* is employed to test the significance of the mean spatial changes of the climate variables in the future with respect to the 1961-1990 baseline period.

2.3 Climate change risks

There are several measures that have been developed and applied over the years for the quantification of climate change risks (Davis-Reddy et al., 2017). Those methods include using indicator-based quantitative assessments as well as participatory/ stakeholder engagement approaches, and combinations of these two main approaches. Although there is no agreed one single optimal approach to conduct climate change risk assessments, the widespread global IPCC framework of climate risk assessment which uses a combination approach was used in this report as a guide to conceptualize climate risk assessment in Southern Africa. Thus, this can allow acceptable comparison and possible aggregation of results with those from other regions since a relatively consistent concept would have been used. The latest IPCC conceptual framing of climate risk is where risk is a key concept while vulnerability is subset of risk. In this framework the respective risk associated with being impacted by climate is the interaction of climate hazards, exposure and vulnerability (See Figure 1), where vulnerability is based on the sensitivity and coping or adaptive capacity of those that are exposed to certain climate hazards (DFFE, 2020). Thus, vulnerability is defined as an internal pre-condition of a sector or people being assessed in relation to the risk of experiencing climate impacts.

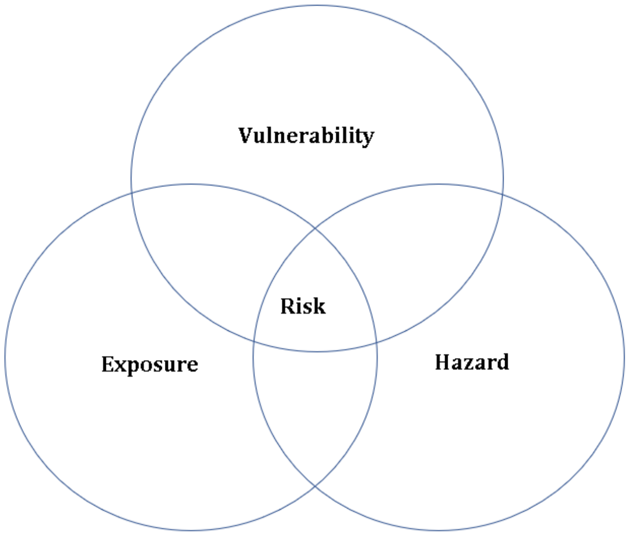

Figure 1. Adopted from the IPCC AR5 climate risk conceptual framework with risk at the centre (Allen, M.R. et al., 2014)**.**

From a broad climate risk perspective, the opportunities and/or risks emanating from climate change are largely linked to the interaction of climate-dependent hazards with the exposure and vulnerability of humans as well as the natural system. Changes in socio-economic conditions and the climate system together with issues of adaptation and mitigation can lead to the reduction or intensification of impacts on society and or the environment. When there is a high likelihood of a climate hazard occurring in an area or when people/assets in that area are highly vulnerable and their means to adapt are heavily compromised, then climate risk assessment in that area is key (Davis-Reddy et al. 2017). Thus, climate change in its broad sense does not directly translate to climate risk, but the interaction of climate hazards with the vulnerability and exposure of people/assets can give an idea of the climate risk level (Field et al., 2014). Undertaking a climate risk assessment is a complex exercise to do and carrying it out from a broad regional Southern Africa level complicates it even more. This is because the key arm of risk which is vulnerability is location- and context-specific from a political, socio-economic, and cultural point of view. This means that vulnerability is defined differently at different levels, ranging from individual to household, to community.

Therefore, in this report, a climate risk assessment for Southern Africa was first undertaken broadly and then at case study level, where the risk was analyzed in more detail, towards informing an assessment of climate change impacts on the WEF nexus. The Malawi Case Study of the project were selected for further detailed analysis in this report. The first step in risk analysis is the identification and assessment of climate hazards where the concept of hazard includes the probable range of intensity of the event (DFFE 2020). The second part is the analysis of climate vulnerability. Vulnerability is determined by the damage that can arise because of the extreme event. Damage can be caused to the population (life, health, well-being, etc.), to property (buildings, infrastructure, etc.) and to natural resources. To analyze vulnerability, an indicator-based approach has been used. The indicator-based approach for climate risk assessment which was opted for here uses a set of proxy indicators to produce quantifiable and comparable results at different scales. Although this approach has an advantage that it is measurable and, hence can be used by decisions makers for monitoring trends and give evidence for the implementation of adaptation options, it has a disadvantage of scarcity of reliable data. The first stage of the approach is thus to identify and select the most appropriate indicators to be used as proxies for vulnerability, i.e., characterizing coping/adaptive capacity and sensitivity to climate hazards in general. This stage is followed by gathering data for the generation of indicators. The final stage involves analysis of the data by normalizing and aggregating the indicators to show comparative levels of vulnerability.

We developed a list of indicators that were potential proxies for climate vulnerability and risk, representing the components being measured (exposure to climate stressors, sensitivity of communities and the adaptive or coping capacity of these communities). A Social Climate Vulnerability Index which compares vulnerability across districts, without considering a specific climate hazard) was first constructed. A subset of these indicators was subsequently combined with a selection of climate hazards to develop indices that are more representative of the vulnerability associated with each of these climate hazards.

2.4 WEF Nexus approach

Undertaking a detailed WEF Nexus assessment is too complex an exercise to do at a Southern Africa region-wide level (Howarth & Monasterolo, 2017). The security issues in the water, energy and agriculture sector are not similar in all Southern Africa countries. Specifically, the existence of different agro-ecological regions in SADC means that water and food security differ from region to region and also the difference in the sources of electricity (e.g. thermal, hydro) contribute to differences in energy status across SADC. Therefore, for this report, the WEF Nexus assessment in Southern Africa was approached, firstly from a broad regional sense and then, secondly for a selected country where the WEF Nexus approach was explored in more detail. Malawi was chosen because of its uniqueness in terms of the water, hydro-energy and agriculture sectors being intertwined and pillars of the country's economic wellbeing.

A survey was conducted to collect information on the WEF Nexus being done in different areas of Southern Africa. Participants of the survey were selected, based on their knowledge, country, expertise on climate change and nexus-related issues such as decision-making processes directly related to, or with implications for water, food and/or energy interactions. Representatives of the survey included those in academia/research, donors or international financial institutions, government, intergovernmental bodies (e.g., regional organizations, United Nations agencies), Non-Governmental Organisations, parastatal and from private sector. The information sought from the survey included synergies and trade-offs related to climate services, climate risk management and climate resilience interventions in the water, energy, and food sectors, i.e., the Water-Energy-Food (WEF) nexus. The objective of the survey was to gauge the understanding of climate impacts, policy support, synergies and trade-offs in the water, energy, and food security nexus. Understanding the WEF nexus in the context of climate services, climate hazards and climate change is an important building block in tailoring climate adaptation actions for maximum benefits.

3 Climate risk assessment results

In the climate risk assessment procedure, the first step is to identify and assess climate hazards, including climate extreme events. Since climate risk encompasses exposure to climate hazards and climate vulnerability, the next step is the climate vulnerability analysis. Vulnerability is usually determined by the damage that can be caused by the hazard, in the form of an extreme event or a trend. This damage can be directed to property (infrastructure, buildings etc.); to the population (health, life, well-being etc.) and to natural resources. A climate risk can be subjective in the sense that the risk is perceived by the people impacted which determines their willingness to accept the likely hazard (e.g. settling in area prone to flooding or wildfires).

3.1 Climate Change Projections and Hazard Assessment

World-wide, climate variability and change have direct impacts through climate hazards especially through extreme events such as flooding, droughts, heatwaves, and other extreme weather events. An increase in extreme weather events can already be detected in every region of the world, due to climate change (Seneviratne et al., 2022). The impacts can be even more severe in developing countries such as those in Southern Africa where capacity to adapt is less (Intergovernmental Panel on Climate Change, 2023). These climate change-induced extremes can have widespread consequences in Southern Africa by affecting markets (demand and supply) for goods and services in sectors such as water, agriculture and energy. In this section, a detailed climate hazard assessment for the future under different global warming levels is done for Southern Africa. This climate hazard assessment is the first stage of the climate risk and vulnerability analysis undertaken in this report.

3.1.1 Climate change analysis

The following section looks at changes in climate in the baseline period (1961-1990) and specific global warming levels (GWLs; 1.5°C, 2°C, 3°C and 4°C) over southern Africa at an annual and seasonal timescale. The GWLs were calculated with respect to pre-industrial temperature. It focuses mainly on changes in temperatures, precipitation, as well as their extreme indices, drought indices, and maize suitability.

1. Temperature: Average, maximum and minimum

Figure 2 below presents the simulated but bias-corrected spatial distributions of the mean (Tmean), maximum (Tmax) and minimum (Tmin) baseline temperatures over southern Africa annually as well as during the summer and winter seasons between the years 1961 and 1990. There is a general spatial pattern in terms of the spatial distribution of temperatures over southern Africa. Most parts of southern Africa generally experience high temperatures, especially over the central and eastern parts of the regions due to the influence of the warm Indian Ocean. Lower temperatures which mostly occur over the western and southern parts of the region (e.g., Lesotho) can be attributed to the regions being at high escarpment areas as temperatures generally decrease with increasing altitudes or being influenced by the cold Atlantic Ocean coast. The high climate variability that exists in southern Africa due to the presence of atmospheric pressure systems and the seasonal migration of the inter-tropical convergence zone (ITCZ) is evident during the winter and summer seasons. In summer, maximum temperatures can reach and exceed 40°C over large parts southern Africa including the Kalahari Desert, Botswana, Namibia and South Africa. Such extremely high daytime temperatures often result in many communities being exposed to heatwaves. Minimum temperatures on the other hand are generally lower, making the diurnal range reach approximately 20°C. During the winter season, the northward shift of the ITCZ brings about decreases in temperatures over Southern Africa, especially over the southern part of the region where minimum temperatures can fall below 5°C.

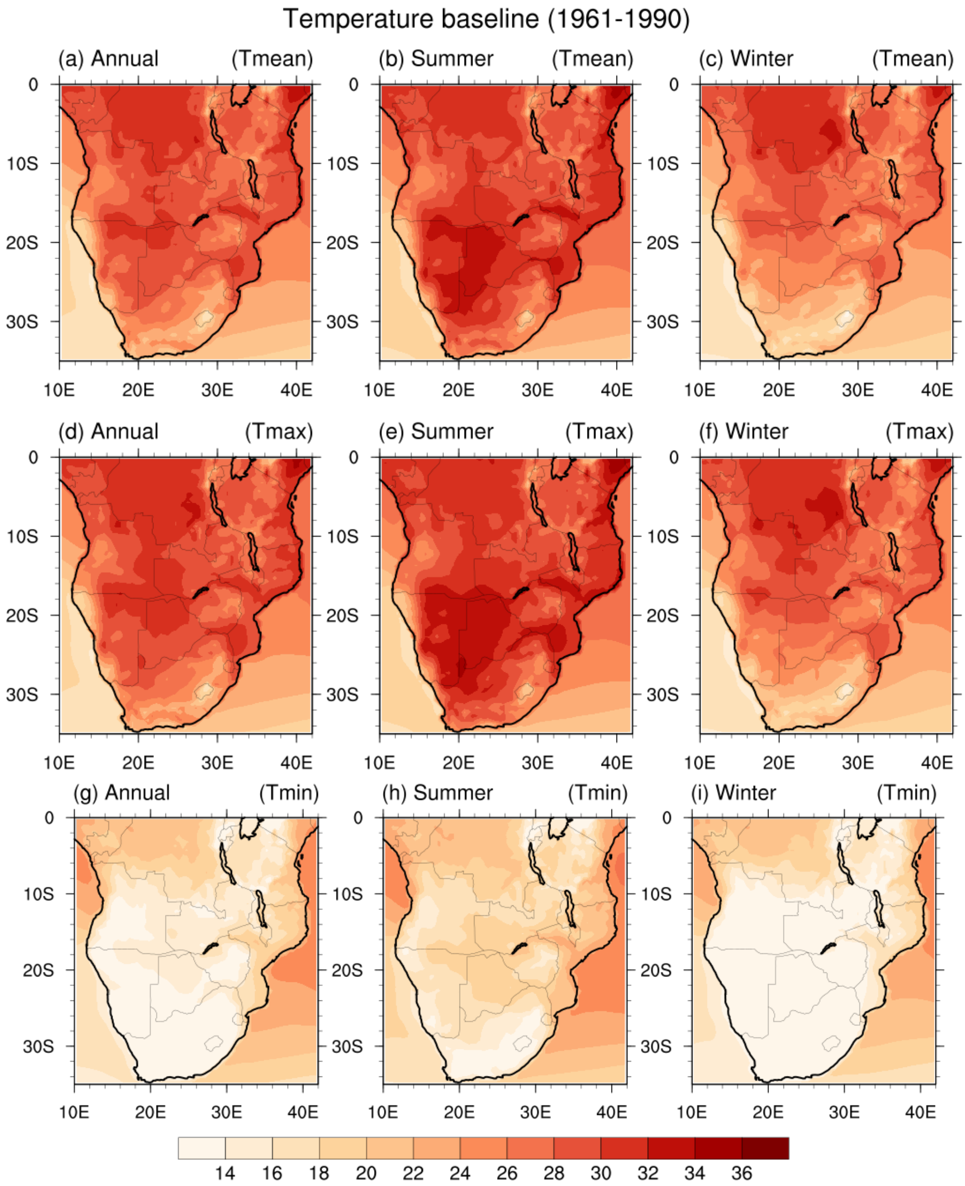

Figure 2 Temperature (°C) over southern Africa simulated by the CMIP6 SSP5-8.5 ISIMIP3b ensemble-average, across various seasons averaged over the 1961-1990 baseline period: (a-c) annual, summer and winter averages for mean temperature. (d-f), and (g-i), same as (a-c) but under maximum temperature and minimum temperature, respectively. The units are in °C.

Figure 3 below presents the spatial distribution of the projected changes in mean temperature over southern Africa at different global warming levels (i.e., 1.5°C GWL, 2°C GWL, 3°C GWL and 4°C GWL) at an annual and seasonal scale. The projections show a general increase in the magnitude of mean temperatures from the southwestern part the region with increasing global warming levels. In comparison to the spatial distribution of the baseline period, the winter season is expected to become predominantly warmer over the southern part of southern Africa as opposed to the northern part.

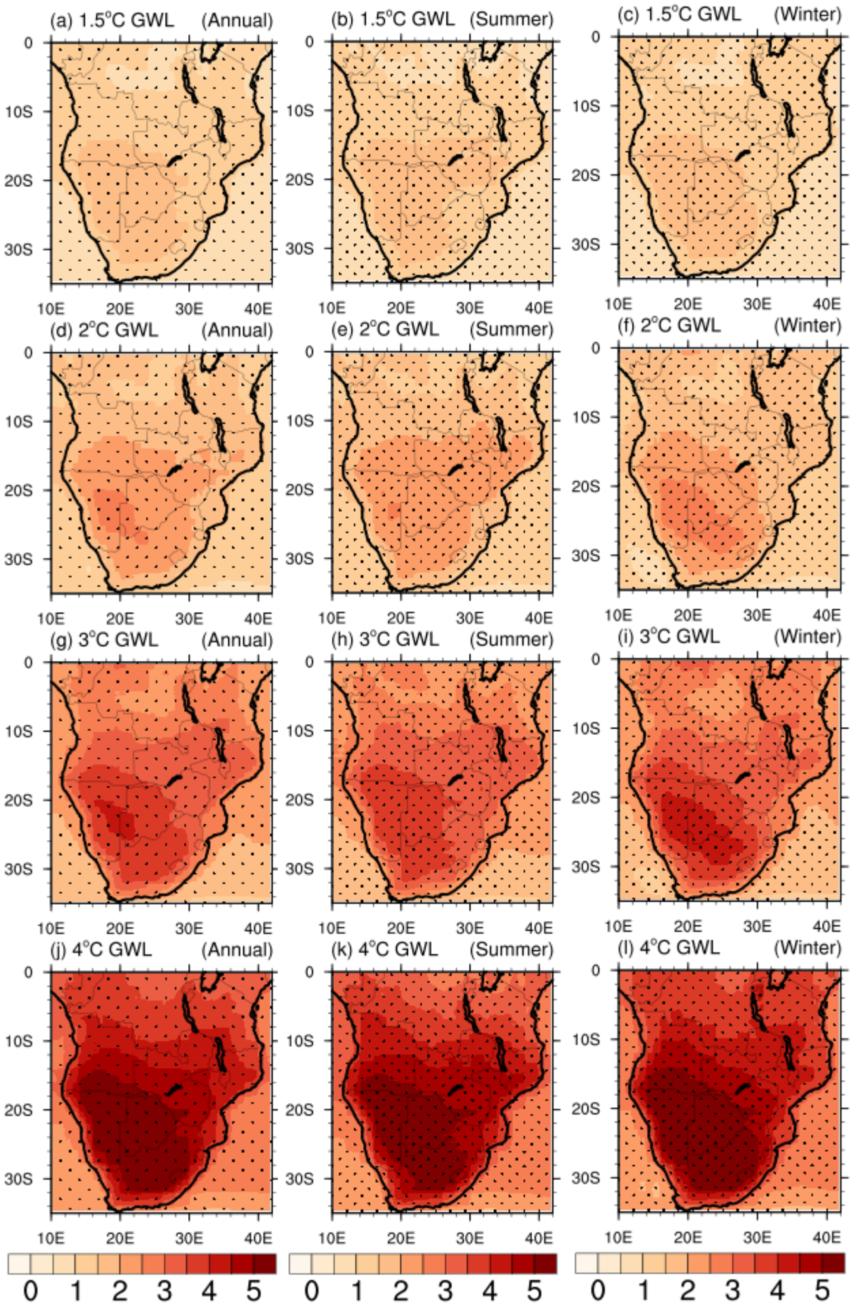

Figure 3 Changes in average temperature (°C) over southern Africa projected by the CMIP6 SSP5-8.5 ISIMIP3b ensemble-average, across various levels of global warming reached with respect to the 1961-1990 baseline period:
(a-c) annual, summer and winter temperature averages under 1.5°C GWL. (d-f), (g-i), and (j-l) same as (a-c) but under 2°C, 3°C and 4°C GWLs, respectively. The units are in C. The upper two panels directly represent the thresholds of the global mitigation goal expressed in the Paris Accord. Stippling show areas that are significant at the 95% level

2. Total precipitation

Figure 4 below shows that southern Africa is characterized by high spatial rainfall variability as well as two distinct rainfall seasons. During the summer season (Figure 4(b)), normal precipitation occurs over most part of the region with more heavy precipitation (>1000mm) generally occurring over the north-western and central and eastern parts. In winter however (Figure 4(c)), heavy rainfall generally occurs over the southwestern region of South Africa as well as closer to the equator. The occurrence of precipitation over the southwestern tip of southern Africa is driven by a Mediterranean climate, which brings the bulk of rainfall during the winter season, caused by the cold fronts that form in the Atlantic Ocean. Over the northern part of the domain precipitation is strongly controlled by the meridional displacements of the ITCZ. Annually, precipitation occurs over most parts of the region (as seen in Figure 4(a) during the summer half-year of October to March. Subtropical southern Africa, south of about 15 °S and excluding the Mediterranean climate of the southwestern Cape of South Africa, is relatively dry, due to the predominant sub-tropical high-pressure systems and relates subsidence (F. A. Engelbrecht et al., 2009).

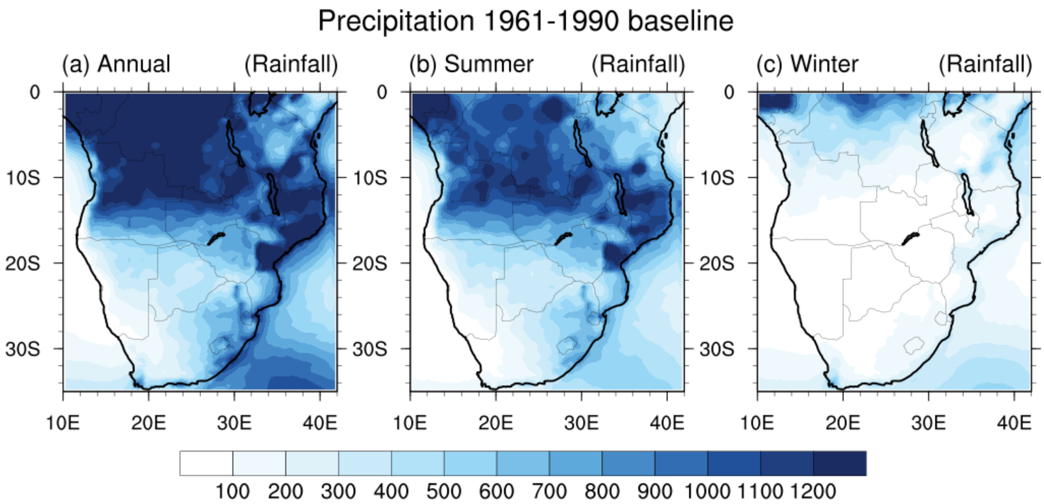

Figure 4: Total rainfall total (mm) over southern Africa simulated by the CMIP6 SSP5-8.5 ISIMIP3b ensemble-average: (a) annual total, (b) summer total, and (c) winter total.

Figure 5 below presents the spatial distribution of the projected changes in total precipitation over southern Africa at different global warming levels (i.e., 1.5GWL, 2GWL, 3GWL3 and 4GWL) at an annual and seasonal scale. There is a projected general decrease in annual precipitation over most of southern Africa, even under a 1.5 °C GWL. An exception is the tropical region north of 10 °S, where increases in precipitation is projected, as large as 10%. This pattern has been linked to increases in tropical convection and the expansion of the topics, with associated increases in subsidence in the subtropics (Engelbrecht et al., 2009). The winter season is projected to become drier over the majority of southern Africa (from south-western to north-eastern parts) including the southwestern part of South Africa that generally receives winter rainfall due to its Mediterranean climate. The magnitude of the projected precipitation changes over southern Africa are projected to amplify with increasing global warming levels, although the pattern of change remains similar.

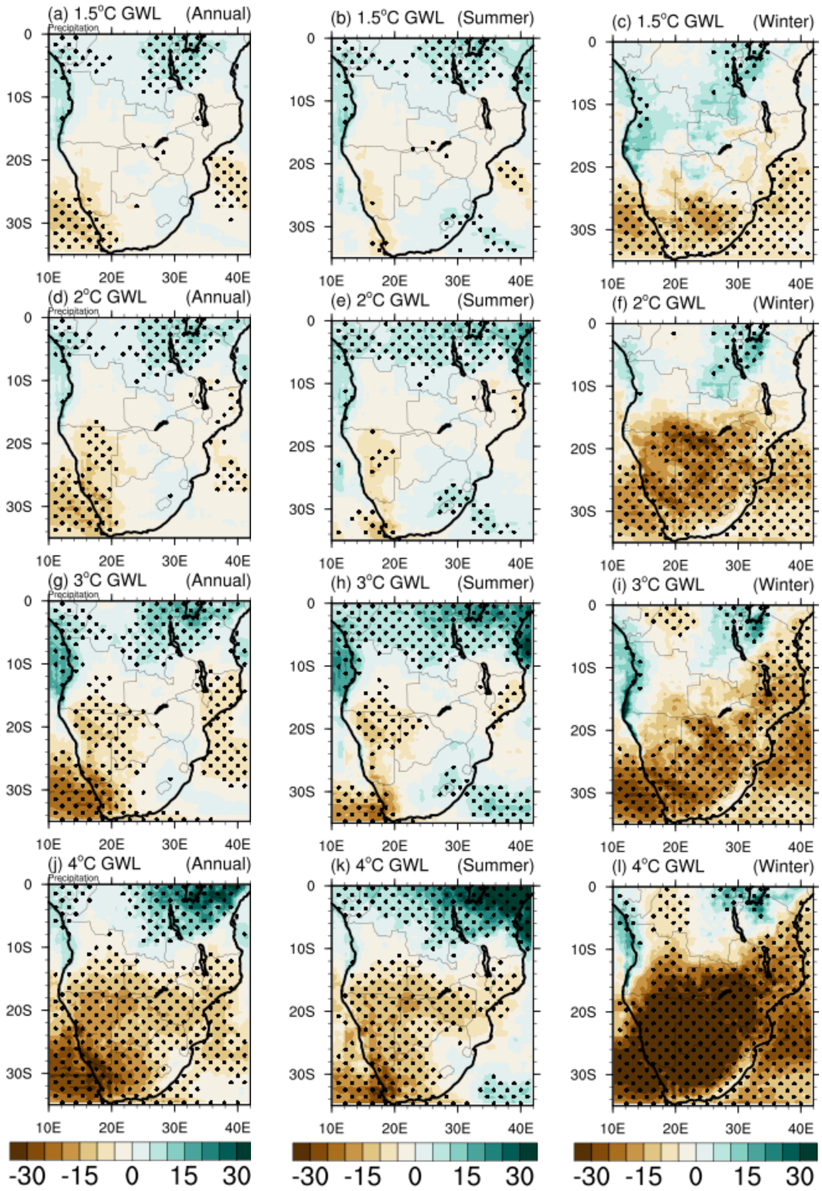

Figure 5 Changes in total precipitation (%) over Southern Africa projected by the CMIP6 SSP5-8.5 ISIMIP3b ensemble-average, across various levels of global warming reached with respect to the 1961-1990 baseline period:

(a-c) annual, summer and winter rainfall totals under 1.5°C GWL. (d-f), (g-i), and (j-k) same as (a-c) but under 2°C, 3°C and 4°C GWLs, respectively. The units are in C. The upper two panels directly represent the members of the global mitigation goal expressed in the Paris Accord. Stippling show areas that are significant at 95% level.

3. Extreme temperature and precipitation indices

Figure 6 below illustrates the projected changes in the extreme temperature index, TXx (Maximum value of daily maximum temperature). TXx are expected to increase in magnitude as the GWLs increase. Extreme changes are projected to occur especially in the central part of the Southern African region, and especially at a 3 and 4°C GWLs, indicating the likelihood of oppressive temperatures occurring with both increasing frequency and intensity.

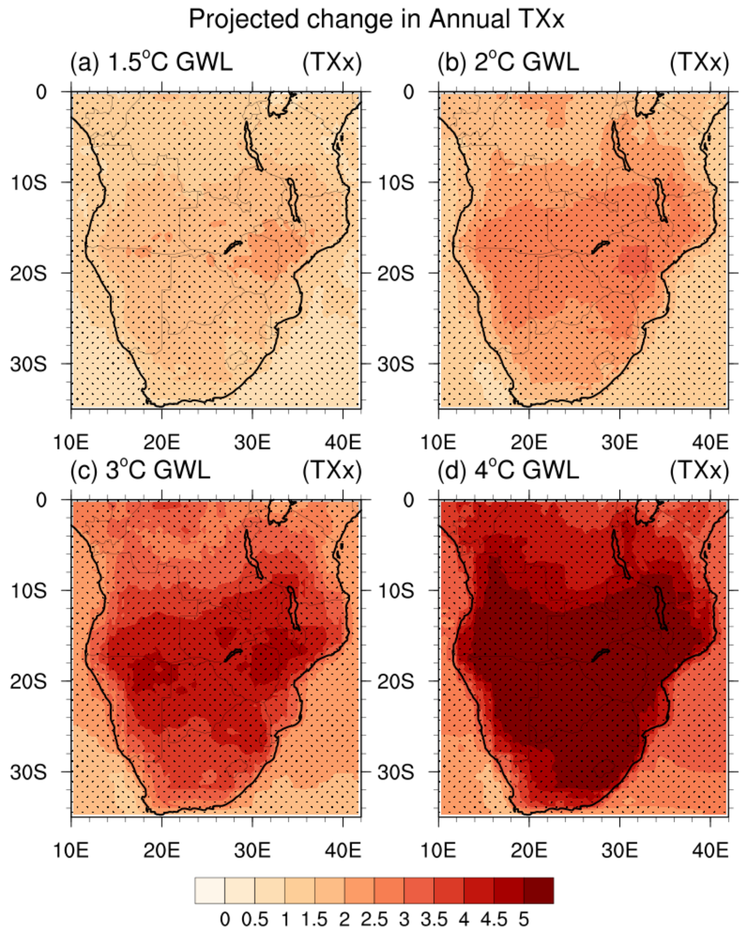

Figure 6 Changes in TXx extreme temperature index (°C) over southern Africa projected by the CMIP6 SSP5-8.5 ISIMIP3b ensemble-average, across various global warming levels. Anomalies are calculated under (a) 1.5°C, (b) 2°C, 3°C and (d) 4°C GWLs. The anomalies are with respect to the 1961-1990 baseline. Units are in °C. Stippling show areas that are significant at 95% level.

To explore changes in the heatwaves, Figure 7 shows the projected changes in the annual average count of heatwave days index. The count of heatwave days is projected to increase in magnitude as the GWLs increase. The changes are more amplified in the western and northern parts of Southern Africa in countries like Botswana, Namibia, Angola, DRC, and Tanzania. Specifically, in Angola and Tanzania, the highest changes across the GWLs are projected to have about 30 more heatwave days relative to the 1961-1990 baseline under the 1.5*°C*. This change increases to about 100 days and over 150 days under the 3*°C* and 4*°C* GWLs, respectively. The lowest change is found in the coastal areas in South Africa, Lesotho, Swaziland and southern parts of Zimbabwe and Mozambique.

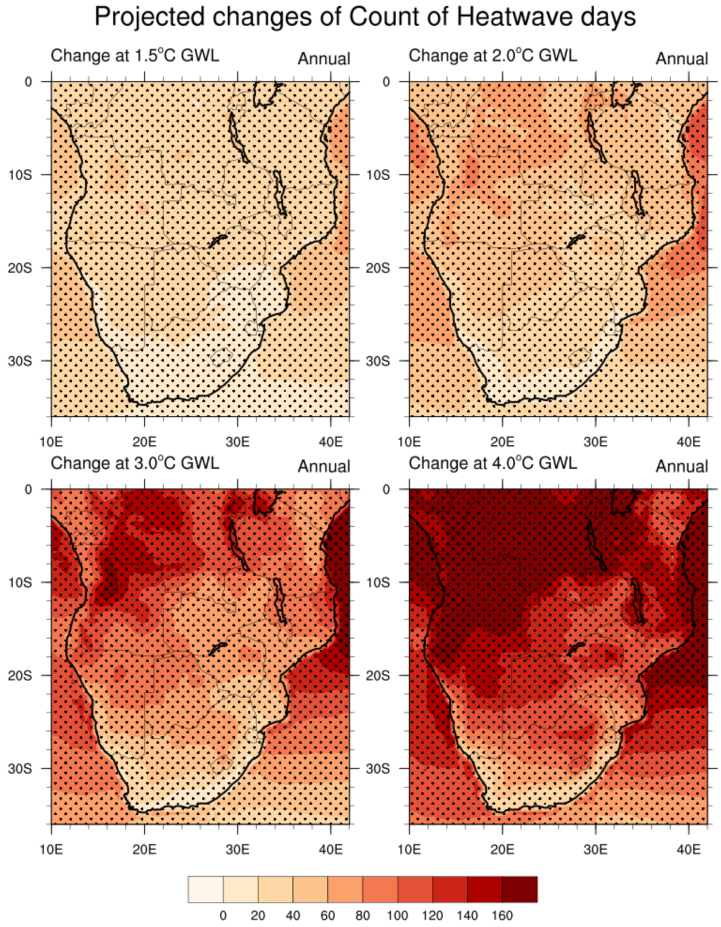

Figure 7: Same as Figure 6 but for count of annual heatwave days.

4. Extreme precipitation indices

The frequency and intensity of heavy precipitation over southern Africa is projected based on the extreme precipitation indices below (i.e., very heavy precipitation days with 20 mm or more precipitation (R20mm), maximum 5-day precipitation (Rx5day) and consecutive dry days (CDD) across the four GWLs (1.5°C, 2°C, 3°C and 4°C). General increases in R20mm is projected north of 10 °S, but with increases over the larger southern African region to the south. This pattern amplifies with higher levels of GWL (Figure 8). An exception is the eastern escarpment areas of South Africa, where increases in R20mm events are projected, consistent with the findings of the IPCC AR6 (Ranasinghe, 2021). A similar regional trend is seen with Rx5day albeit with lower magnitudes. CDD on the other hand are projected to also intensify and increase in magnitude with increasing GWLs, consistent with the general pattern of drying projected for the region (Figure 6).

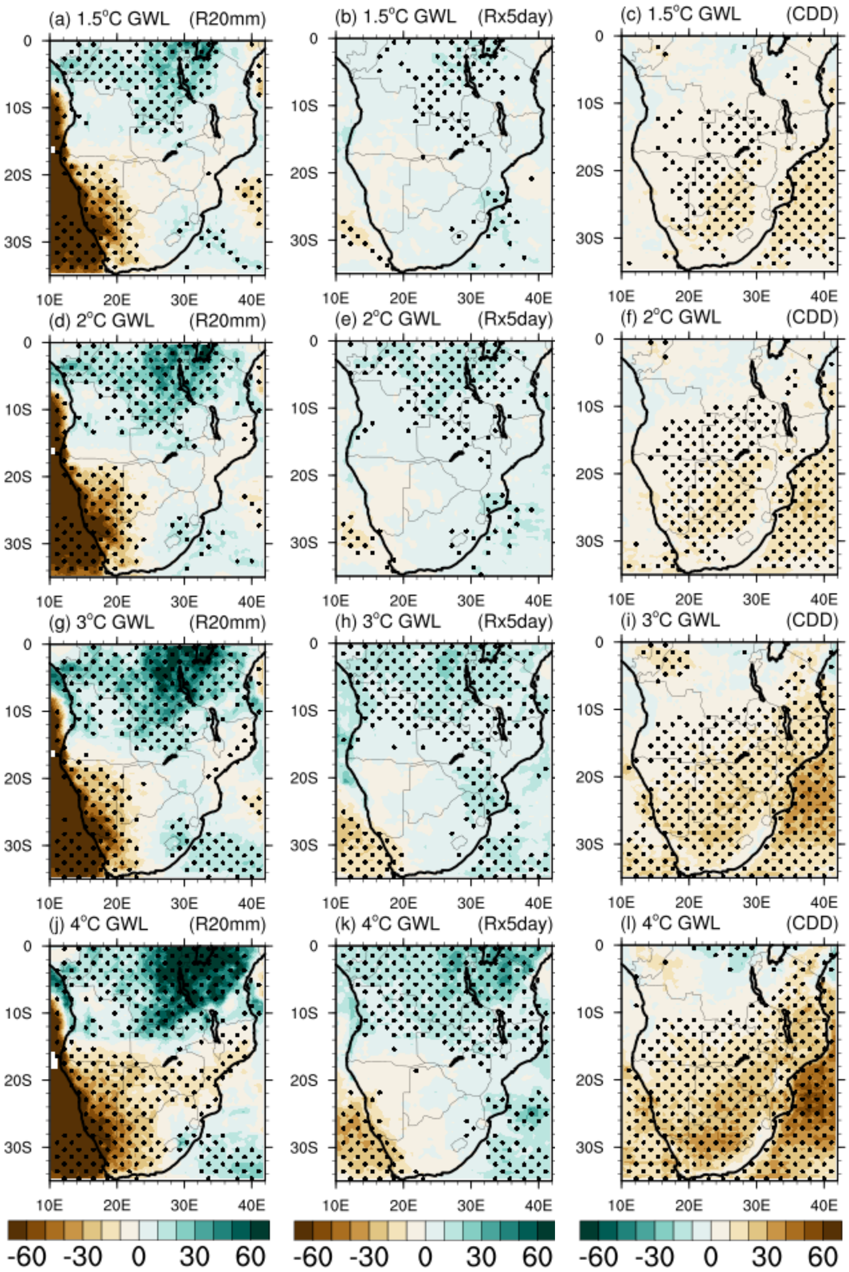

Figure 8: Changes in precipitation extreme indices (%) over Southern Africa projected by the CMIP6 SSP5-8.5 ISIMIP3b ensemble-average, across various levels of global warming reached with respect to the 1961-1990 baseline period. (a-c) R20mm, Rx5day and CDD extreme precipitation indices under 1.5°C GWL. (d-f), (g-i), and (j-k) same as (a-c) but under 2°C, 3°C and 4°C GWLs, respectively. The units are in %. The upper two panels directly represent the members of the global mitigation goal expressed in the Paris Accord. Stippling show areas that are significant at 95% level.

For drought, a description was extracted from the FOCUS Africa D2.2 Report on hazard assessment. The report used a unique index called the Keetch-Byram drought index shown here in Figure 9. As D2.2 notes, the projected changes in the Keetch-Byram drought index are indicative of general reductions in soil moisture availability across southern Africa under 3 °C global warming. This is an important finding: although there is variation in the pattern of rainfall change in the model ensemble considered here (variations across individual models), all projections are in agreement of general reductions in soil moisture availability, even in the areas of projected increases in rainfall. These reductions are the consequence of enhanced evaporation in a substantially warmer region. The report concludes with some certainty on this index by highlighting that Southern Africa is likely to become generally drier in terms of rainfall totals but is virtually certain to become generally drier in terms of soil moisture availability, a crucial element for crop production in the region.

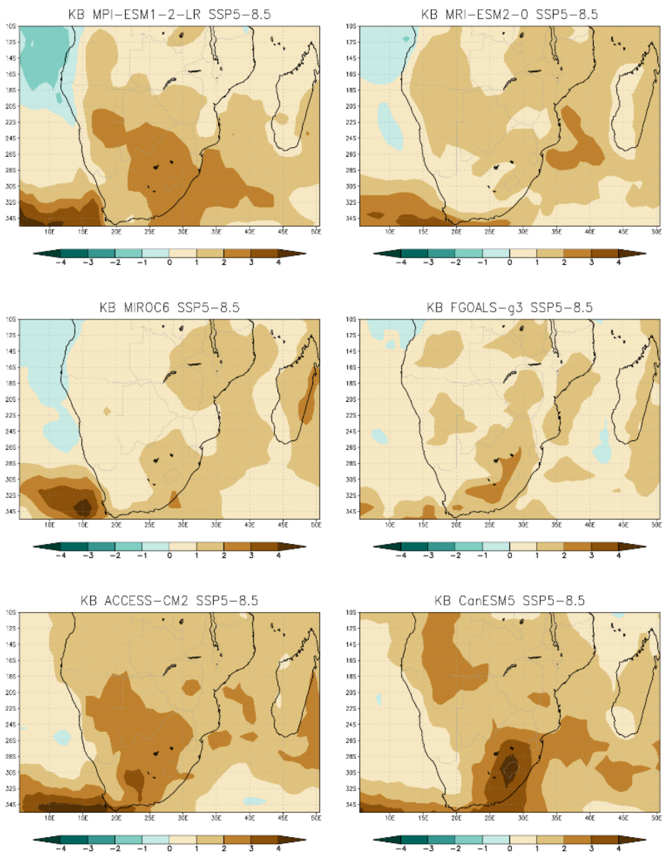

Figure 9: Projected changes in the Keetch-Byram drought index over southern Africa under 3 °C of global warming relative to pre-industrial climate, as per an ensemble of six CMIP6 GCMs. (Source: FOCUS Africa - D2.2).

A description of the maize suitability in southern Africa (Figure 10) is described in FOCUS Africa's D2.2, a deliverable/report preceding this one. It notes that under 3 °C of global warming, regions in western and central southern Africa currently assessed to be marginally suitable for maize production are projected to become unsuitable, due to reductions in rainfall and an increasing frequency of occurrence of hot extremes. Drastic increases projected in hot extremes in areas surrounding the Limpopo River valley and Zambezi River valley are similarly resulting in larger areas in eastern southern Africa becoming unsuitable for maize production. Increases in suitability are projected over Lesotho and the resulting eastern escarpment regions of South Africa, due to reductions in cold extremes and in particular, the occurrence of frost. Steep mountains slopes may however make it difficult to take advantage of enhanced climatic suitability of this subregion. At least, over northern southern Africa, where climate models project increases in rainfall, maize suitability is similarly projected to increase.

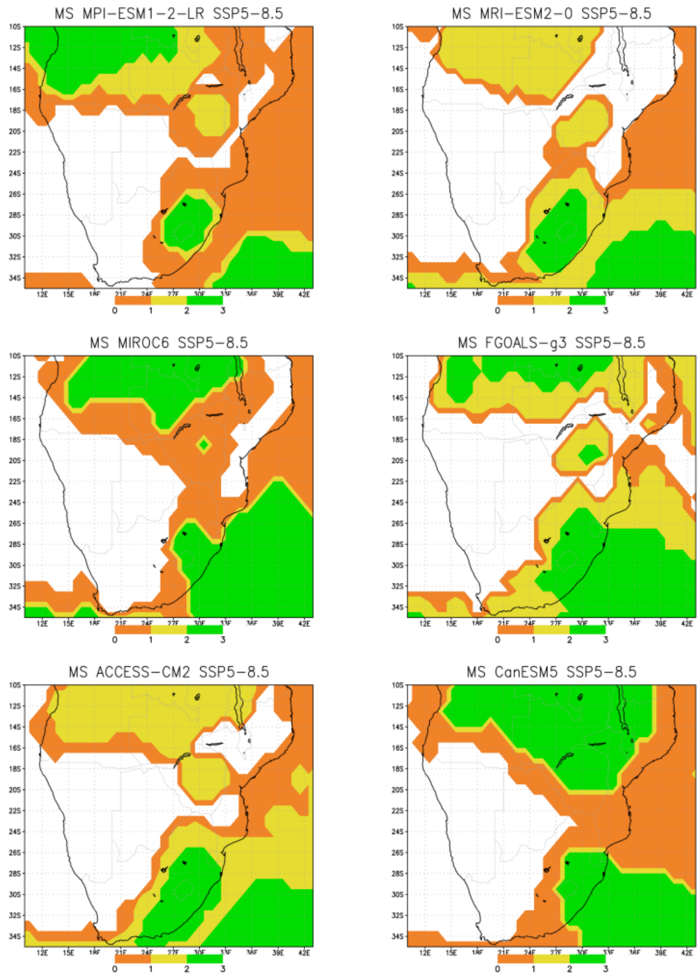

Figure 10: Maize suitability in southern Africa based on moisture availability and the impact of extreme temperature events, here calculated for climate corresponding to 3 °C of global warming (Source: FOCUS Africa - D2.2).

3.1.2 A glance at renewable energy in Southern Africa

a. Photovoltaic Power Potential

Changes in the mean annual photovoltaic power potential in Southern Africa under 1.5 °C, 2.0 °C, 3°C and 4°C global warming worlds in relation to current levels are shown in Figure 11. Under all the GWLs, the model ensemble mean estimates a minimal percentage change of photovoltaic power potential with respect to the baseline period in the northern and eastern side of Southern Africa. The highest changes are estimated in the south-eastern parts in countries like South Africa, Botswana, Namibia and Southern parts of Angola and Zambia with a change of about 6%. However, there is not much difference between GWLs in terms of the photovoltaic power potential. Thus, the conditions in terms of annual photovoltaic power potential in the region is expected to persist into the four different future "temperature worlds". Such conditions are that the western parts of the country are estimated by the model ensemble to have more favorable conditions for solar energy harvesting than the eastern and northern parts. This is linked to the frequent drought/ (low number days with rain-bearing cloud cover) conditions experienced in the western regions and high rainfall conditions in the eastern regions of the subregion. Specifically, the photovoltaic power potential is as high as 2300 KWh/KWP in the western parts of the region and is lowest (<1800 KWh/KWP) in the easternmost parts of KwaZulu Natal in South Africa and the areas towards the equator (not shown). Therefore, the region has an option to use solar power for electricity in the future, an important factor since hydropower energy may reduce due to projected decrease in rainfall.

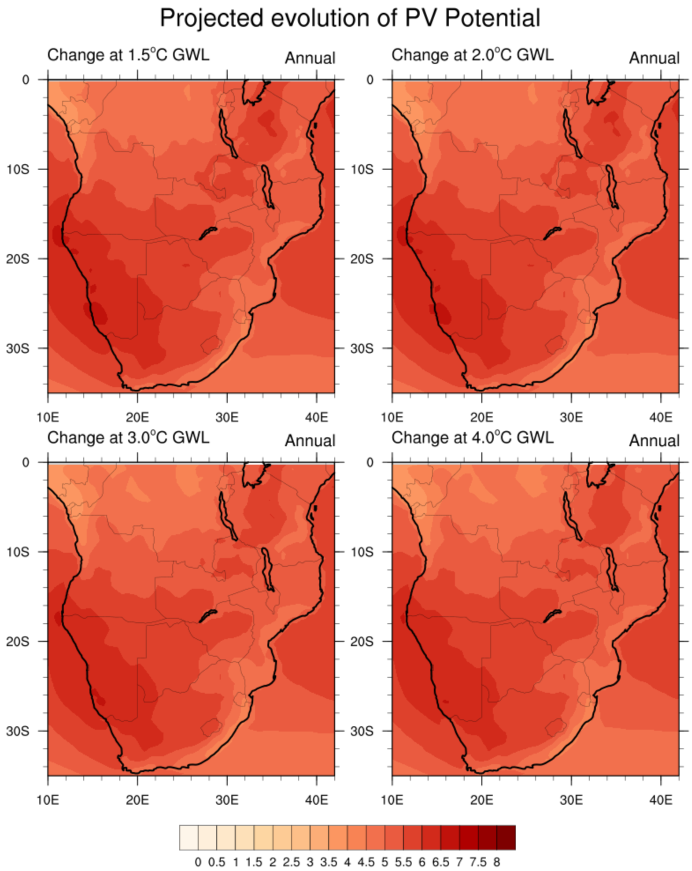

Figure 11: Evolution in photovoltaic over southern Africa projected by the CMIP6 SSP5-8.5 ISIMIP3b ensemble-average, across various global warming levels. Anomalies are calculated under (a) 1.5°C, (b) 2°C, 3°C and (d) 4°C GWLs. The anomalies are with respect to the 1961-1990 baseline. Units are in °C. Stippling show areas that are significant at 95% level.

b. Wind power density

Respective changes in wind power density from the baseline period to the 1.5 °C, 2 °C, 3°C and 4°C GWLs are shown in Figure 12. The models confirm the existence of high wind density potential along the coastal regions, the Western and Eastern Cape, as well as parts of the Karoo in the Northern Cape as can be seen on the global wind atlas (https://globalwindatlas.info accessed on 31 July 2023). The difference in wind density potential across the GWLs is small however it gets subtly high with global warming. The place with highest wind density potential in the three Cape provinces of South Africa which also include the Karoo region. According to the models, the bulk of Southern Africa is not conducive for wind power generation. Generally, the western parts of the region are projected to have more favorable conditions for wind energy harvesting than the eastern part.

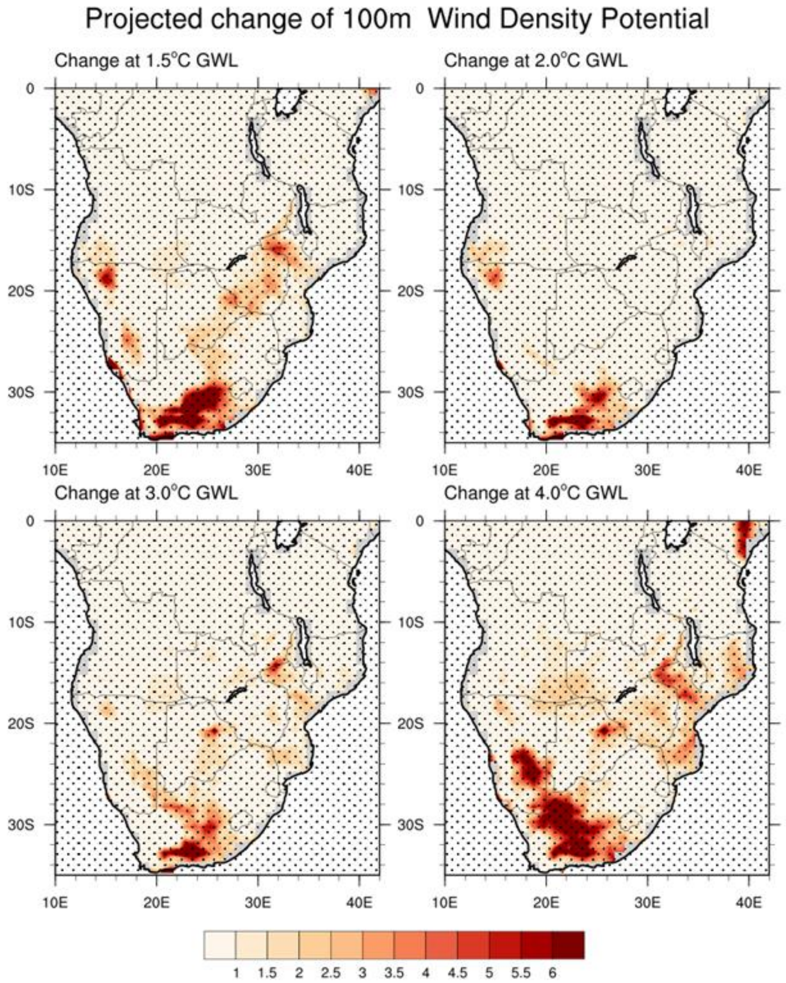

Figure 12: Changes in wind density potential over southern Africa projected by the CMIP6 SSP5-8.5 ISIMIP3b ensemble-average, across various global warming levels. Anomalies are calculated under (a) 1.5°C, (b) 2°C, 3°C and (d) 4°C GWLs. The anomalies are with respect to the 1961-1990 baseline. Units are in °C. Stippling show areas that are significant at 95% level.

3.2 Climate Risk in Southern Africa

Climate variability and climate change is causing many challenges through impacting the environment and people across much of the world, more so in developing countries such as Southern Africa where the adaptive capacity is low (Field et al., 2014; Intergovernmental Panel on Climate Change, 2023). The most reported impacts over the Southern Africa region are in the form of tropical cyclones, wildfires, floods, droughts, and heatwaves and have cost the region an estimated USD 10 billion in damages between 1980 and 2015 (Davis-Reddy et al., 2017). These impacts pose substantial threats to the functioning of society through affecting water, food and energy security in the region where most livelihoods are dependent on agriculture and hydropower contributes to electricity supply. With climate change, these impacts are projected to increase, unless robust adaptive action is enforced to reduce climate change exposure, vulnerability, and risk. To ensure effective adaptation capacity in the region since these impacts are not experienced equally everywhere, it warrants assessing where, to what degree and by whom these climate impacts are being felt (i.e., current exposure, risks and vulnerabilities), and how impacts might change into the future (DFFE, 2020). Understanding climate risk and vulnerability in Southern Africa is essential in its climate mitigation agenda as it solidifies the case for investing strongly in more effort and measures to reduce greenhouse gas emissions, both nationally and internationally.

Even though climate change may create new opportunities is some parts of the world, it is projected to cause substantial distress to people and natural resources in Southern Africa (IPCC 2018). Climate risk assessment often involves analysis of the inter-dependence of three components namely: climate hazards, exposure and vulnerability where vulnerability can be split into sensitivity and coping or adaptive capacity. In terms of the scale of impact, it largely depends on the extent to which climatic changes are influencing the system (exposure); characteristics of the system (sensitivity); and the capability of the environment and people to handle the effects (coping/adaptive capacity). Climate risk assessment is an important exercise in drawing-up climate adaptation strategies as it can be used by decision makers to identify the most vulnerable areas/sectors that need earlier intervention than others. Since there is generally a lack of consensus regarding the appropriate frameworks and best methodologies for assessing vulnerability for different countries, here we compile and analyze information on climate risk and vulnerability assessments in Southern Africa from a broad point of view, using readily available data. For these definitions and other key ones, the reader is referred to the IPCC AR5 glossary of Working Group 2 (IPCC 2014, pages 1757-1776).

Climate events account for the largest percentage (67%) of natural disaster deaths in Southern Africa where 491 disasters were recorded in the period 1980-2015, which resulted in 110 978 loss of life, 2.47 million people were left homeless and it impacted approximately 140 million people (EMDAT, 2019). As shown in the climate hazards chapter, Southern Africa's exposure to hazards such as floods, drought and heatwaves is projected to increase into the 21st century which, without reductions in vulnerability, will significantly increase the risk of adverse impacts. Early warning systems (EWS) of extreme events are one of the ways of trying to reduce climate risk in Southern Africa and is usually set up and implemented at national and regional level. Early warning systems are important in that they help in the development and implementation of various preparedness and response strategies which ultimately reduces the risk of climate-related death and damage. At regional level, the OCHA Regional Office for Southern Africa assist in setting-up a climate-related EWS which involves the cooperation between international, regional and national organizations in the region. The Advanced Fire Information System (AFIS) is one example of EWS at Southern African level which is based on a real-time satellite fire monitoring system and was developed by partners in the region to monitor fires across Africa in real time (Davies et al., 2008; Frost & Annegarn, 2007).

According to the latest IPCC Assessment AR6 Report (IPCC Report, 2022), on average, the rate of sea-level rise around Southern Africa is higher than the global mean, hence bringing the issue of climate risk in the region's coastal areas to the fore. Some of the highest rates of sea level rise are in Tanzania, Mozambique, and the eastern coast of South Africa where the rate exceeds 3.9 mm/yr. The rate is even much higher along the western coast of South Africa and Namibia reaching as high as 3.8 mm/yr. (WMO, 2022). This WMO report also notes that by 2030, 108–116 million people in Africa are expected to be exposed to sea-level rise. Millions of people's livelihoods in Africa are facing severe climate risk due to average temperature increases which has contributed to as much as 34% reduction in agricultural productivity growth and this level is the highest compared to any other region in the world

(WMO, 2022). This risk is expected to carry on into the future. For example, a 20-60% decline in Southern Africa's wheat yield is projected under the future 1.5 °C scenario (IPCC Report, 2022). Furthermore, in Sub-Saharan Africa, climate change is projected to significantly affect jobs and consequently livelihoods across the food production food value-chain as 55%-62% of the labour force work in agriculture alone.

3.2.1 Brief country-specific climate risks

All the countries in the Southern Africa region show concerning climate risks through high vulnerability and exposure to climate change, albeit at different levels (IPCC Report, 2022). The following sections briefly describe the climate risks in some of the countries in the region.

Mozambique

Southern African countries such as Mozambique, Malawi, South Africa, and Zimbabwe have experienced severe floods in 2000, and most recently in 2018, 2019, 2020 and 2022 with tropical cyclone being the main driver (Neves et al., 2022). Most parts of Mozambique are facing an increased climate risk linked to flooding over time, largely attributed to population increase; urban growth; and land-use change; as well as increased horizontal urban spread of industrial, commercial, housing areas etc. (Neves et al. 2022). For example, inhabitants who were at medium risk of flooding occupied 12% of land in Matola, but this number will rise to as high as 39% by 2040. The report also showed that the flood risk levels in Mozambique before and around 2000 was low, but by 2020 the flood risk had increased to a high level, and by 2040, the risk will increase further to an extremely high level. This is in the backdrop of increases in cyclones observed over the years and projected for the Southwest Indian Ocean region (Malherbe et al., 2013; Muthige et al., 2018).

Tanzania

In Tanzania, climate risk and vulnerability mapping was done to identify areas where climate change is expected to have high impacts in, for example, the two main Wami-Ruvu and Rufiji basins. These areas were identified as 'vulnerability hotspots' representing areas where there is high exposure; high sensitivity to climate change; and low adaptive capacity of social systems to cope with negative impacts. Millions of livelihoods depend on the Wami-Ruvu basins based on the rain-fed and irrigated agriculture; livestock; forest produce and leading industries of Tanzania. It is also the only permanent source of water for Tanzania's large commercial capital-Dar es Salaam. On the other hand, 50% of Tanzania's hydropower comes from the Rufiji basin. The results showed hotspots of high relative vulnerability of communities and water resources in Tanzania's Wami-Ruvu and Rufiji basins as areas with high climatic stress, high sensitivity and low adaptive capacity (Macharia et al., 2020).

Mauritius

Small Island Developing States (SIDS) including Mauritius face an existential threat, being at risk to climate change through Sea Level Rise (SLR). Among the SIDS, the coastal areas of Mauritius are ranked among the most vulnerable to SLR, where data shows that there has been a 2.1 mm/year SLR around Mauritius in the period from 1987 to 2007 (Beeharry et al., 2022). The high levels of climate risk of the country's coastal regions is linked to inundation; saltwater intrusion to rivers and estuaries; and coastal erosion. Furthermore, the extreme impacts of SLR are already being felt within the island and are projected to further amplify in the future causing far-ranging effects on the prevailing and future environment and economic activities as well as the health of society. Due to the topographical characteristics of the land, Grand Baie, Port Louis Harbour, Tamarin and Pereybere are among the list of extremely vulnerable areas to flooding. Some of the high vulnerability can be linked to widespread unplanned infrastructural development within the coastal zone.

Botswana

Climate risk assessment in Botswana shows that livestock keepers and crop farmers are most sensitive to climate change through their high exposure to droughts, and extreme temperatures (Masundire et al., 2016). The climate vulnerability of farmers is compounded by their inability to undertake adaptive strategies such as venturing into non-farm-based income generating options. A lack of development planning, the inability to attract investment and chronic poverty have resulted in no such options being available. Women are at most risk to the vagaries of climate change. Gender inequality and responsibilities interact with poor rainfall to increase the burden on women both in terms of time and distance to access water, increased stress linked to inability to provide water for domestic and childcare tasks as well as most acutely damaging subsistence farming livelihoods. This holds true not only for Botswana but for various Southern African countries too.

3.2.2 Summary

Some communities in Southern African countries face high levels of climate risk. The nexus of drought, low rainfall, high temperatures, water scarcity, poor water quality, crop failure, livestock deaths, food insecurity, low purchasing power, and climate-related illnesses affect Southern Africa communities in a cyclical manner with one problem often linked or leading to many others. Island states like Mauritius and coastal cities also face a challenge of sea level rise as it is linked to inundation; saltwater intrusion to rivers and estuaries; and coastal erosion. To reduce climate risk or to adapt in Southern Africa, the approach can either involve reducing vulnerability by lowering sensitivity or increasing capacity, or both. The reduction in capacity can be through building raised platforms in a flood zone while increasing capacity can be through capacity building of people living in flood plains or increasing access to home and crop insurance. Reducing exposure can be achieved by people moving out of flood prone areas. There is need for an updated regional integrated approach to combat the effects of climate change in Southern Africa. This is especially required since the latest IPCC Report has identified the region as a climate change hotspot (Hoegh-Guldberg et al., 2018; F. A. Engelbrecht & Monteiro, 2021; IPCC Report, 2022; Ziervogel et al., 2022b). The region thus needs to come together to tackle climate change at a regional level as climate does not follow political boundaries. Approaching it at a country level will, ultimately use up more financial and human resources than if it is done at a regional integrated level.

3.3 In Focus: Climate risk and vulnerability assessment in Malawi

3.3.1 Background

Malawi, a landlocked country in south-eastern Africa covering 118 000 km^2 with a population of about 19 million, is highly vulnerable to climate change due to its geo-location and its dependence on agriculture (IPCC Report, 2022). The country has a long history of climate risks, including droughts, floods, and tropical cyclones, which have had significant impacts on the country's economy and people. In addition, future climate risks in Malawi are expected to increase, with potentially devastating consequences for the country's development and well-being (PCC Report, 2022). Droughts have been particularly devastating, leading to crop failures, food shortages, water shortages, low hydro-power generation, and increased poverty (Census, 2018). Droughts have led to a decline in the availability of water for drinking and irrigation, which has further exacerbated the country's food insecurity. Floods have also been a significant risk, leading to the displacement of thousands of people and the destruction of homes, crops, and infrastructure especially around Lake Malawi. Tropical cyclones have also had significant impacts, with Idai in 2019 and Freddy in 2022 causing widespread damage and loss of life in the country.

Future climate risks in Malawi may increase, with potentially devastating consequences for the country's development and well-being. Climate models project that the country will experience more frequent and severe droughts, floods, in the coming decades as shown later in this section. This will have significant impacts on the country's agricultural sector, which employs over 80% of the population and is highly dependent on rainfall. In addition, climate change shown in this report is expected to lead to a decline in the availability of water for drinking and irrigation, which will further exacerbate the country's food insecurity. Climate change may lead to increased migration and displacement, as people are forced to leave their homes in search for areas with availability of water and low risk of climate extremes.

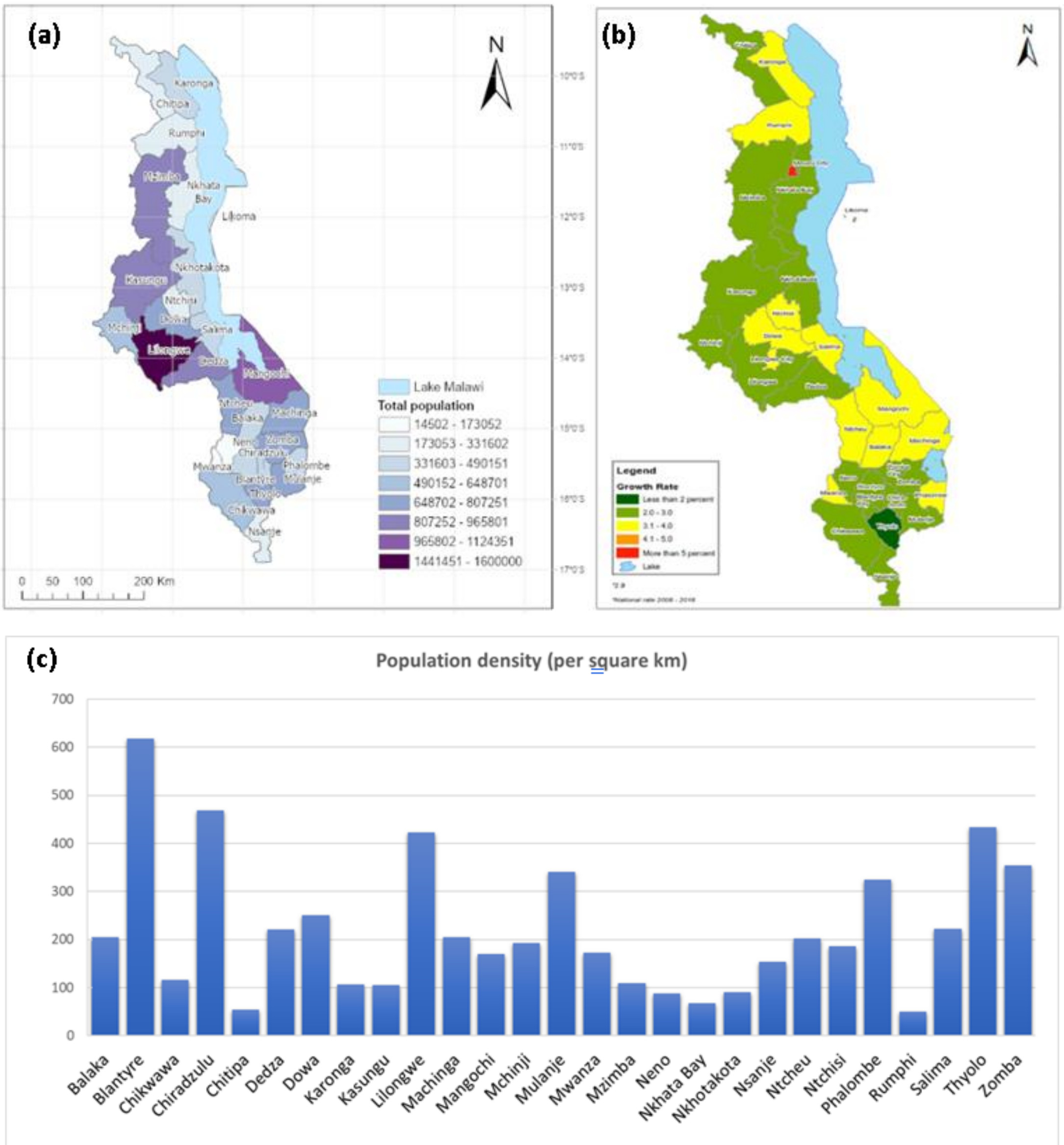

Figure 13: (a) Malawi total Population, (b) population annual growth rates by district 2008-2018, and (c) normalised population density in 2018 (Population growth map source: (Malawi National Statistical Office, 2018)**.**

Most of the 19 million people in Malawi are sensitive to climate change in one way or the other (NCO, 2019). The country is one of the poorest in the world, with a gross domestic product (GDP) per capita of just $398 and over half of the population living below the poverty line (Ndeketa 2020). In addition to poverty, the country has one of the highest levels of income inequality in the world, with the top 10% of the population accounting for over 40% of the country's income (Durevall 2012). This inequality is reflected in people's access to basic services such as healthcare, education, and clean water, with those living in rural areas and those with lower levels of education and income having limited access to these services. As is the case for the other countries in Southern Africa, Malawi's poverty rate is particularly high in rural areas, where most of the population lives and relies on subsistence agriculture for their livelihoods (NCO, 2019). Poverty in Malawi is also closely linked to food insecurity, with over a third of the population experiencing chronic malnutrition (Census, 2018). Malawi has high rates of infant and maternal mortality rates where the life expectancy at birth is 40 years and the proportion of the population under the age of 15 years is 47%, while the proportion above the age of 60 years is only 5% (Kauye et al. 2007).

Figure 13 shows the district distribution of the total population in Malawi in 2018, population annual growth rates between 2008 and 2018, and the population density in 2018. The Population of Malawi in 2018 was found to be almost 4 times the size of the 1966 population and 1.3 times of the 2008 census while in terms of growth, the total population surged by 35 percent between 2008 and 2018 thus highlighting an intercensal growth rate of 2.9 percent per annum (National Statistical Office, 2020). According to the projections, Malawi's population is projected to double in 2042 (National Statistical Office, 2020). The Blantyre district has the highest population density in 2018 (618 people/m2), followed by Chiradzulu and Thyolo.

The results for the climate risk assessment in Malawi are presented here sequentially, (1) first by looking at the exposure assessment component; (2) followed by the climate coping/adaptive capacity component, (3) the vulnerability component, and (4) finally the compounded climate risk component based on all the other components. We chose a classified color scale using the defined interval option to classify the different categories for each map into 10% intervals.

Table 2 shows the different indicators used per each category (i.e., sensitivity, adaptive capacity and exposure) and the respective sectors relevant to the indicators. It shows the selected indicators and, where relevant, the individual indicators that were combined to form an aggregated indicator. The relevant exposure (climate hazard) component for each indicator is also shown). Each indicator was subsequently normalized against the maximum value for that particular indicator, after which the indicators were summed, and the final indicator normalized again. With more time and resources, this type of analysis can be replicated in other countries in Southern Africa and this type of analysis is useful for programmatic interventions and decision making.

Table 2. Different indicators are used for each climate risk category and the respective sectors relevant to the indicators.

	Indicator	*Variable*	*Sectors relevant to the indicator:*		
			Energy	**Water Resources**	**Food Security**
Exposure	Precipitation	Average precipitation	yes	yes	yes
	Drought	Standardized Precipitation index	yes	yes	yes
	Flood	Days with rainfall of >20mm (R20mm)	yes	yes	yes
	Dry spells	Cumulative Dry Days Index (CDD)		yes	yes
	Heatwave	Warm spell duration index (WSDI)	yes	yes	yes
	Temp. extremes	Annual maximum of daily maximum temperature (TXx)	yes	yes	yes
	Max Temperature	Average maximum temperature	yes		yes
Sensitivity	Population with access to safe water Health	No safe access to water (combine water from unprotected wells, springs, rivers, dam		yes	
		Population with no access to sanitation		yes	
		Use of unsafe water		yes	
		Using wood for cooking, lighting, and heating	yes		
		Albinism			
		Orphanhood (child < 18 years of age who has lost one or both biological parents)			
		No education (combined no education, never attended school, illiterate)			
		Unemployment (combining unemployed, and being economically inactive)			
		Disability (combing hard-to-hear, walk, speak, intellectual challenges, and other disabilities)			
		The main source of livelihood: fishing			
Adaptive capacity	Income	Access to finances (combine business, house rental, livelihood: employed, save money, access to credit through commercial bank	yes	yes	yes
		Income through agriculture		yes	yes
		Income through fishing		yes	yes
	EWS access	Access to communication (combine cell phone, landline computer, radio, tv)		yes	yes
		Access to transport (combine motorcycle, car)			
	Durability of houses	Population living in their own houses			
		Population living in traditional non-robust houses			
	Literacy	Literate (reported to be able to read and write a simple sentence in any language - >5 years old).			
	Food preserving	Owns a fridge/freezer	yes		
	Source of water	Access to a protected water source (Piped water into the house)	yes		
	Source of electricity	Population using firewood for cooking, heating, lighting	yes		
		Access to cleaner sources of energy (combine electricity, gas, charcoal)	yes		

3.3.2 Exposure component

As part of the climate risk assessment, climate hazards are analyzed for the area in question. Here, climate hazards assessment for Malawi represented by past, present, or future climate variability and climate extremes was done using a suite of CMIP6 downscaled to 50km and bias corrected global models. Table 3 lists the extreme climate indices used in this study as part of climate exposure assessment of Malawi.

Table 3. ETCCDI extreme climate indices analysed for Malawi

	DEFINITION	UNITS	DESCRIPTION	INDEX SELECTED FOR RA
TXX	Annual max. value of TX	°C	Annual daytime hottest temperature	X
TXN	Annual min. value of TX	°C	Annual daytime coolest temperature	
TX	Max. daytime temperature	°C	Maximum day time temperature	X
TN	Min. nighttime temperature	°C	Minimum nighttime temperature	
T2	Average daily temperature	°C	Average daily temperature	
TNX	Annual max. value of TN	°C	Annual night-time hottest temperature	
TNN	Annual min. value of TN	°C	Annual night-time coldest temperature	
PR	Annual total precipitation	mm	Annual total precipitation	X
RX5DAY	Annual maximum 5-day pr	mm	Highest five rainfall days per year	X
R20MM	Count of days when pr ≥20mm	days	Annual number of days with high pr	
CWD	Max. number of consecutive days with pr ≥ 1mm	days	Annual maximum length of wet spell	
CDD	Max. number of consecutive days with pr < 1mm	days	Annual maximum length of dry spell	X
WSDI	Warm Spell Duration Index	days	Annual count of days contributing to "warm spells", when Tx remains above its climatological 90th percentile	X

Figure 14 shows the changes in total precipitation (%) over Malawi projected across various levels of global warming (i.e., 1.5°C, 2°C, 3°C and 4°C) at an annual and seasonal scale. Annual precipitation is projected to decrease, driven by general decreases in both summer and winter precipitation. This signal of drying amplifies over time and is particularly pronounced in the southern part of the country during winter under 3°C and 4°C GWLs These findings are consistent with the general drying projected for Malawi by a larger (although not bias-corrected) ensemble of GCMs in the IPCC AR6 WGI report (Lee et al., 2021).

Figure 15 presents the changes in rainfall extreme indices (%) over Malawi projected across various levels of global warming. Heavy precipitation frequency and intensity over Malawi are projected based on extreme precipitation indices which include very heavy precipitation days with 20 mm or more precipitation (R20mm), maximum 5-day precipitation (Rx5day) and consecutive dry days (CDD) across the four GWLs (1.5°C, 2.0°C, 3.0°C and 4.0°C).

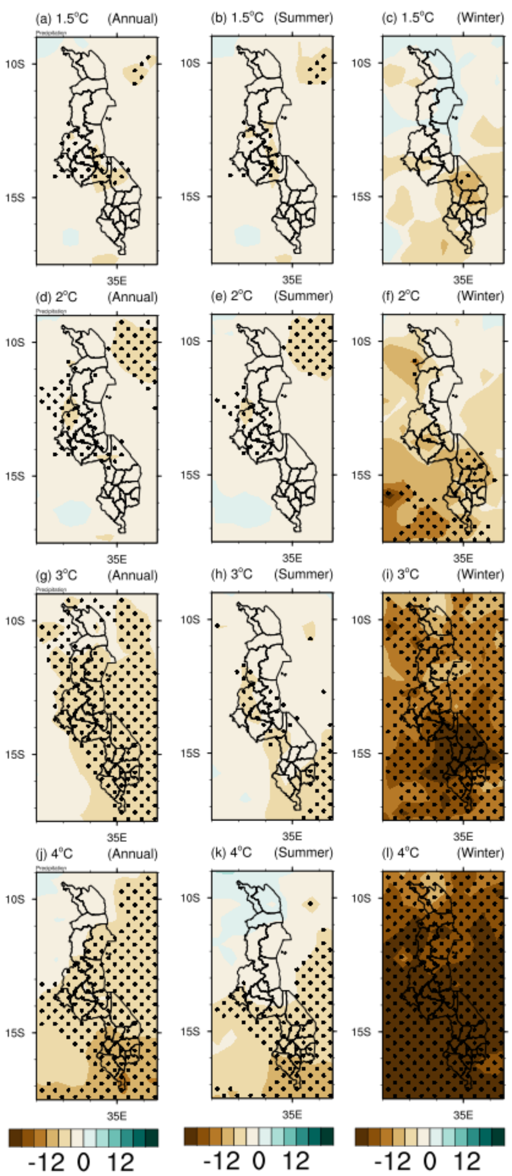

Figure 14: Changes in total precipitation (%) over Malawi projected across various levels of global warming. (a-c) annual, summer and winter rainfall totals under 1.5°C GWL. (d-f), (g-i), and (j-k) same as (a-c) but under 2°C, 3°C and 4°C GWLs, respectively.

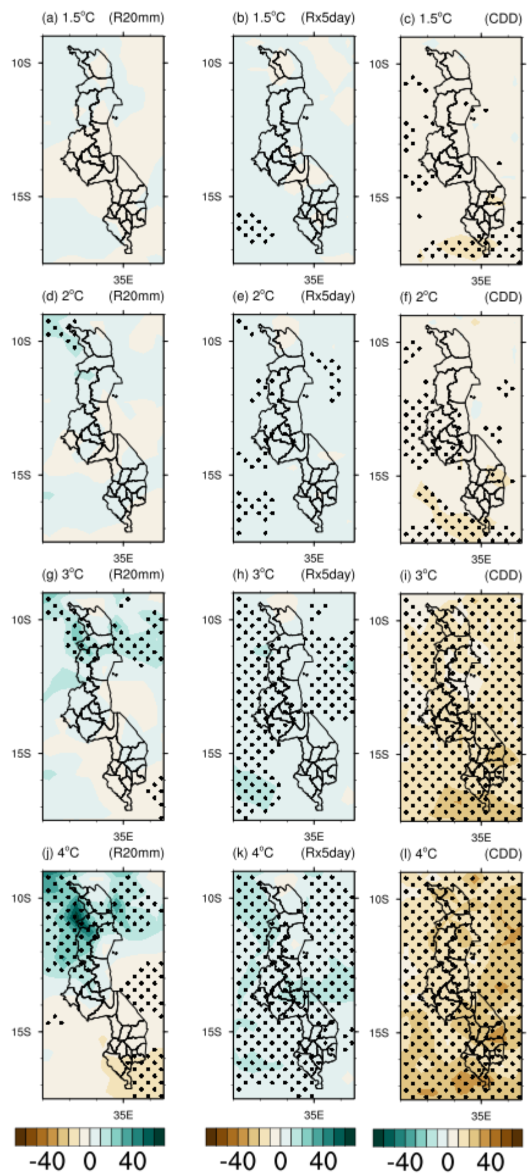

Figure 15: Changes in rainfall extreme indices (%) over Malawi projected across various levels of global warming. (a-c) R20mm, Rx5day and CDD extreme precipitation indices under 1.5°C GWL. (d-f), (g-i), and (j-k) same as (a-c) but under 2°C, 3°C and 4°C GWLs, respectively

The frequency of very heavy rainfall events (R20mm) is projected to increase in the northern parts of the country at global warming levels of 2.0°C or higher. These increases are projected to amplify as the GWL increases from 2.0°C to 4.0°C. General increases in Rx5day are also projected across the country, with amplification of the signal from 3.0°C and 4.0°C of global warming. The intensity and magnitude of CDD are projected to increase across the country and to be more pronounced under 3.0°C and 4.0°C global warming levels, consistent with the projected general decreases in annual precipitation (Figure 12). Since water resources are crucial for the economic development of Malawi, a generally drier climate with more CDDs may have serious socio-economic consequences for the country. A previous study noted that an increase of 1°C is estimated to decreases average lake water level and outflow by 0.3 meters and 17%, respectively, while a 5 percent decrease in total rainfall is estimated to lead to a decrease in lake water level by 0.6 meters (Mtilatila et al., 2020). The decrease in water level in the lack due to increase in temperature signify the importance of intense evaporation in the water budget in lake Malawi. Therefore, in conclusion, the combination of amplified temperatures and the decrease in rainfall may lead to substantial lower flows in the Shire River which supplies Lake Malawi (Mtilatila et al., 2020).

Figure 16 presents the spatial distribution of the projected changes in mean temperature in Malawi at different global warming levels (i.e., 1.5°C, 2°C, 3°C and 4°C GWLs) at an annual and seasonal scale. There is a projected general increase in the magnitude of mean temperatures during winter and summer seasons. This general increase in mean temperature is more pronounced under 3°C and 4°C GWLs across the country. Figure 17 presents the changes in temperature extreme indices (°C) over Malawi projected across various levels of global warming. Projected temperature extremes over Malawi are shown for a number of extreme temperature indices, which include the monthly maximum value of daily maximum temperature (TXx), monthly maximum value of daily maximum temperature (TNx) and warm spell duration indicator (WSDI) across the four GWLs (1.5°C, 2.0°C, 3.0°C and 4.0°C). All these temperature extreme indices are projected to significantly increase with the increase in global warming levels throughout the country with more intense increases under 3.0°C and 4.0°C global warming levels. Although WSDI is projected to significantly increase across the country, somewhat smaller increases are projected for the southern part of Malawi under 3.0°C and 4.0°C global warming levels.

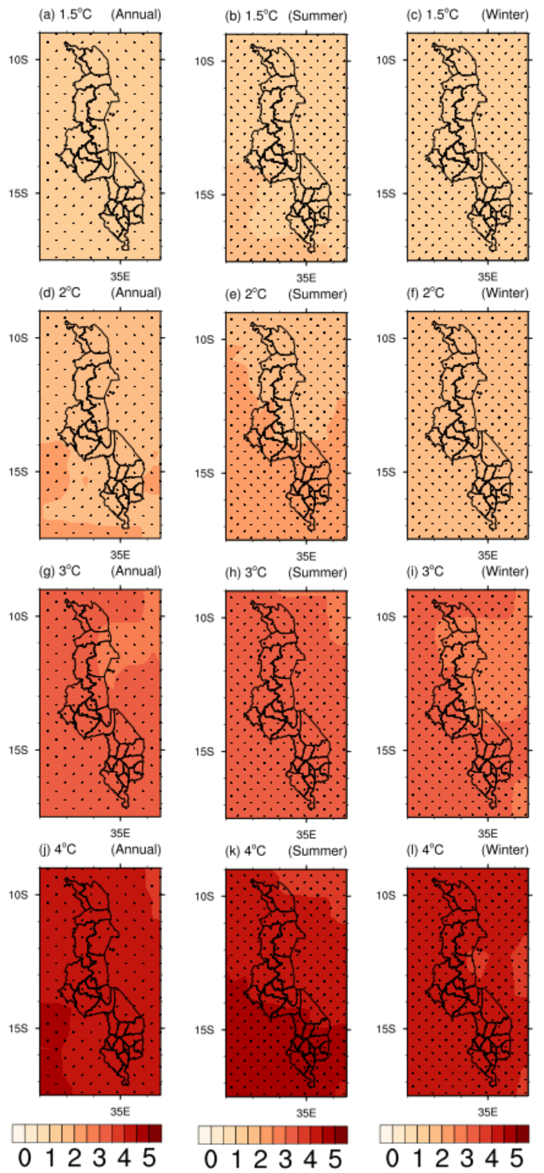

Figure 16: Changes in mean temperature (°C) over Malawi projected across various levels of global warming. (a-c) annual, summer and winter temperatures under 1.5°C GWL. (d-f), (g-i), and (j-k) same as (a-c) but under 2°C, 3°C and 4°C GWLs, respectively.

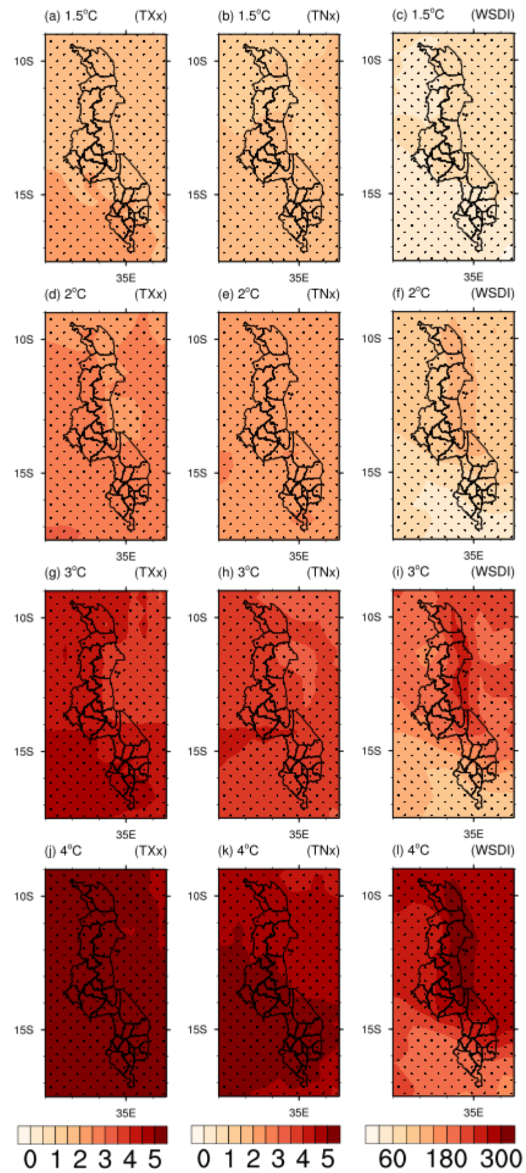

Figure 17: Changes in temperature extreme indices (°C) over Malawi projected across various global warming levels. (a-c) TXx, TNx and WSDI temperature extreme indices under 1.5°C GWL. (d-f), (g-i), and (j-k) same as (a-c) but under 2°C, 3°C and 4°C GWLs, respectively

Two exposure indices were created: a high temperature index and a high precipitation index, as shown in Table 11 in the Annexure. The high precipitation index combines changes in average precipitation; extreme precipitation indices, while the temperature/drought index combines average maximum, minimum and mean surface temperature; extreme temperature indices and cumulative dry days calculated for Malawi. The high temperature and high precipitation indices were combined with cumulative dry days to generate an indication of the spatial distribution of high exposure to all these climate indicators. The highest exposure is in areas where the decline and variability in rainfall has been largest, as well as in areas with higher maximum temperatures, higher extreme daytime temperatures, and highest increase in extreme rainfall events. The indices show that, considering the contributing variables, the highest exposure to high temperatures is in the Chikwakwa district, followed by Nsanje and Thyolo. The highest exposure to cumulative dry days is in the Kasungu district, followed by Mchinji, Dowa and Dedza. The highest exposure in high and extreme precipitation is in Mulanje district, followed by Chitipa and Karonga. The index that combined these three indices shows the highest combined exposure in the Nkhotakota district, closely followed by Chitipa and Dedza.

3.3.3 Vulnerability component

Using readily available data from the Malawi 2018 Census, we derived a list of indicators that were potential proxies for climate vulnerability mapping, representing the components being measured (sensitivity and the coping/ adaptive capacity of these communities). All the socio-economic data was available at district level. A bivariate correlation analysis was performed to identify individual indicators that were highly correlated to remove redundancies (Table 10 in Annex). This was done for indicators of sensitivity as well as indicators of coping or adaptive capacity. The selection was guided by the degree and direction of correlation. Where appropriate, new variables of sensitivity and coping capacity were created, using the average of the highly correlated indicators to ensure that they are represented but don’t increase the overall weighting.

Sensitivity component

Table 4 shows the Climate Social Sensitivity Index for each district and city in Malawi, together with the individual indicators that drives the sensitivity for each location. It is important to note that an indicator does not reflect sensitivity to a particular hazard, i.e. some indicators may be more and others less important when a particular climate hazard is considered. The final sensitivity indicator therefore characterizes a component of social vulnerability. The overall climate social sensitivity distribution is also shown spatially (Figure 18a) and by means of a spider diagram (Figure 18b).

Table 4. The Climate Social Sensitivity Index used in this study obtained from aggregating multiple contributing factors shown for each district and city in Malawi.

District	Population	Traditional dwelling	Livelihood, fishing	Orphan child	Disability (comb)	Economic unemployed, inactive	Wood for cooking, lighting, heating	Water not piped	No education (comb)	Albinism	Climate Social Sensitivity Indicator
Dedza	830512	99.64	0.92	84.12	82.98	69.74	95.79	60.14	96.15	100.00	100.00
Nsanje	299168	64.55	5.72	100.00	61.70	82.29	100.00	46.98	95.24	83.33	92.80
Kasungu	842953	75.09	0.23	62.40	53.19	87.27	95.59	100.00	77.46	75.00	90.83
Dowa	772569	94.18	0.00	66.30	61.70	72.32	95.59	79.00	82.04	75.00	90.81
Neno	138291	78.36	0.00	76.39	53.19	64.02	94.48	85.77	76.42	91.67	89.97
Machinga	735438	66.36	5.49	71.03	59.57	66.24	95.39	72.24	95.11	83.33	89.17
Mangochi	1.10E+06	74.00	9.61	78.13	57.45	78.04	88.77	38.79	100.00	83.33	88.20
Lilongwe	1.60E+06	92.55	0.23	64.83	57.45	81.18	93.78	54.45	87.90	75.00	88.09
Nkhotakota	393077	53.09	12.13	70.26	61.70	95.39	86.86	70.46	82.22	75.00	88.06
Nkhata Bay	284681	14.00	18.08	81.20	97.87	83.03	94.28	91.81	67.44	58.33	87.90
Thyolo	721456	32.55	0.00	90.39	70.21	66.61	95.89	90.75	79.66	75.00	87.17
Ntchisi	317069	100.00	0.00	59.19	61.70	76.57	96.99	54.80	81.00	66.67	86.58
Rumphi	229161	40.73	7.78	67.90	100.00	77.12	89.57	86.48	57.97	66.67	86.18
Ntcheu	659608	62.36	0.00	85.17	63.83	64.39	93.28	69.04	81.00	75.00	86.16
Chikwawa	564684	71.45	0.46	82.66	48.94	76.57	93.18	42.35	93.10	83.33	85.87
Mzimba	940184	40.00	0.00	78.55	76.60	79.34	94.78	58.36	70.25	83.33	84.30
Salima	478346	75.09	7.32	75.70	57.45	78.23	85.86	33.45	88.76	75.00	83.67
Likoma	14527	37.09	100.00	77.79	63.83	98.34	76.93	28.47	51.31	33.33	82.25
Phalombe	429450	64.91	1.60	84.05	65.96	64.02	95.19	33.10	85.52	66.67	81.37
Blantyre	451220	50.36	0.00	96.31	78.72	73.99	79.94	46.98	67.62	66.67	81.31
Chitipa	234927	23.27	0.23	71.31	72.34	79.15	95.79	70.46	62.61	83.33	81.00
Karonga	365028	28.18	15.33	89.55	63.83	100.00	86.96	38.08	63.41	66.67	80.06
Mulanje	684107	40.36	0.00	89.62	65.96	68.08	91.78	49.11	78.86	66.67	79.83
Chiradzulu	356875	52.36	0.00	97.42	72.34	65.50	91.07	25.98	73.12	66.67	78.97
Mchinji	602305	53.82	0.23	59.33	46.81	83.21	92.78	40.57	81.86	83.33	78.60
Zomba	746724	58.00	0.69	79.39	68.09	59.59	94.18	25.27	78.50	75.00	78.13
Mwanza	130949	47.82	0.00	74.23	63.83	59.78	81.04	48.75	76.97	66.67	75.29
Balaka	438379	40.73	1.37	82.66	63.83	64.94	84.75	26.33	75.99	66.67	73.58
Mzuzu City	221272	10.00	0.00	69.64	36.17	97.42	25.98	13.52	37.51	50.00	49.35
Lilongwe City	989318	12.18	0.00	66.02	27.66	82.47	14.24	10.68	43.01	58.33	45.63
Blantyre City	800264	4.18	0.00	78.41	29.79	81.92	7.62	12.46	38.85	58.33	45.19
Zomba City	105013	8.73	0.00	80.99	40.43	77.49	19.86	3.56	38.18	33.33	43.88

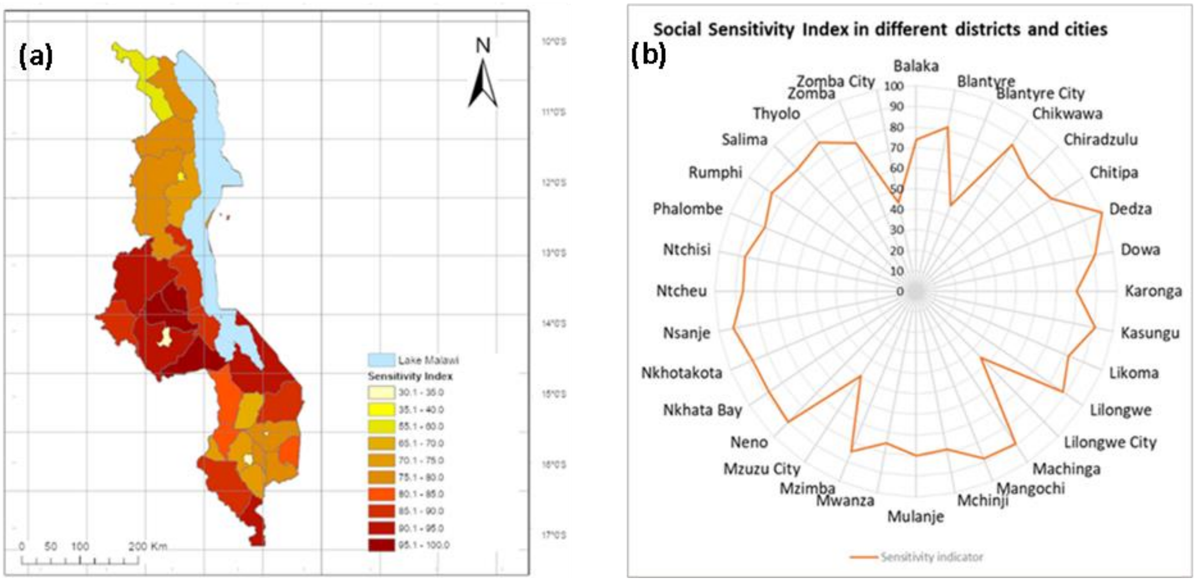

Figure 18: Climate social sensitivity in Malawi. (a) spatial map of the sensitivity index. (b) spider diagram for the climate social sensitivity index in Malawi's districts and cities

The most sensitive areas relative to other areas (> 92) are in Dedza and Nsanje while the least sensitive areas with a sensitivity factor < 50 are located mainly in the cities like Blantyre, Zomba, Lilongwe and Mzuzu cities. The four cities had, as expected due to their economic development and socioeconomic circumstances, the lowest relative climate social sensitivity. All the indicators seem to influence sensitivity in different locations in various ways. In Dedza, the sensitivity is driven mostly by the prevalence of albinism, traditional dwellings and no education, whereas for Nsanje the main drivers were the presence of orphaned children and the use of wood for cooking, heating and lighting. It is important to note that these indicators are reported relative to other districts; also, no weighting was applied to increase the importance of a particular indicator over the others.

Coping/adaptive capacity component

Indicators were selected to reflect the ability to cope or adapt, with high prevalence indicative of a better coping/adaptive capacity ability. As with the indicators of sensitivity, a bivariate correlation analysis was performed to identify individual indicators that were highly correlated (see Table 10 in Annexure). The average of the highly correlated indicators was determined to ensure that they are represented but don't increase the overall weighting. Table 5 shows the selected climate coping/adaptive capacity indicators.

Table 5. The coping/adaptive capacity used in this study obtained from aggregating multiple contributing factors shown for each district in Malawi

District	Access to fridge/ freezer	Access to cleaner energy	Access to financing	Access to transport	Access to communication	Access to protected water source	Literate	Adaptive Capacity Index
Zomba City	53.42	90.31	100.00	100.00	100.00	100.00	99.07	100.00
Mzuzu City	53.13	82.38	92.18	81.25	92.40	66.41	100.00	90.64
Blantyre City	24.45	100.00	96.97	85.28	93.05	62.60	98.26	87.97
Lilongwe City	49.64	78.92	92.84	82.22	82.23	55.73	95.70	84.14
Likoma	16.30	43.74	50.61	43.61	76.14	6.87	92.65	51.83
Rumphi	45.56	14.16	37.34	34.86	47.86	8.40	90.44	45.58
Balaka	73.94	15.67	36.33	23.47	36.34	4.58	77.21	44.24
Karonga	59.24	17.87	31.43	24.58	43.68	14.50	87.47	43.95
Nkhata Bay	37.55	9.94	37.29	34.17	50.48	7.25	83.94	43.19
Mzimba	53.28	7.49	28.86	29.31	46.30	4.58	82.96	40.86
Chitipa	60.41	9.57	27.85	31.81	37.54	5.73	88.22	40.47
Blantyre	37.41	21.90	33.05	27.08	39.41	9.92	82.54	39.12
Salima	68.12	13.47	32.04	18.61	34.12	6.49	66.64	38.75
Mulanje	79.77	8.37	28.56	17.92	30.95	4.20	76.02	38.71
Mwanza	47.60	21.71	30.98	22.22	37.49	7.25	75.69	38.51
Phalombe	100.00	5.79	22.05	14.72	27.93	3.82	71.43	38.34
Chikwawa	79.33	12.65	25.48	13.89	32.11	7.63	63.03	36.95
Kasungu	58.08	8.24	26.59	22.22	35.73	4.96	75.78	36.68
Nkhotakota	55.17	12.96	27.80	18.47	37.75	6.49	71.23	36.12
Zomba	72.63	8.37	24.67	19.03	30.95	3.44	74.62	35.93
Machinga	80.35	8.37	23.92	14.31	29.79	2.29	62.71	35.91
Mchinji	75.98	8.56	24.22	16.67	31.00	2.67	71.97	35.36
Neno	45.56	10.76	26.39	18.75	33.77	3.05	76.95	35.32
Dowa	52.55	7.36	25.63	20.00	29.99	2.67	72.58	33.80
Chiradzulu	52.69	6.61	23.92	17.08	27.28	1.53	79.32	32.95
Nsanje	61.14	10.70	23.21	15.00	30.15	3.05	61.06	32.67
Thyolo	41.05	8.43	26.34	19.86	30.05	4.20	74.65	31.79
Mangochi	60.26	14.22	21.44	16.11	32.41	4.58	57.65	31.57
Ntchisi	39.30	5.35	21.90	17.50	30.60	1.53	73.47	30.47
Lilongwe	61.57	7.36	20.69	13.89	24.16	1.91	67.36	29.76
Ntcheu	43.38	8.43	19.68	16.53	28.64	1.91	73.27	29.55
Dedza	54.59	6.04	16.25	12.22	23.20	2.29	62.23	26.85

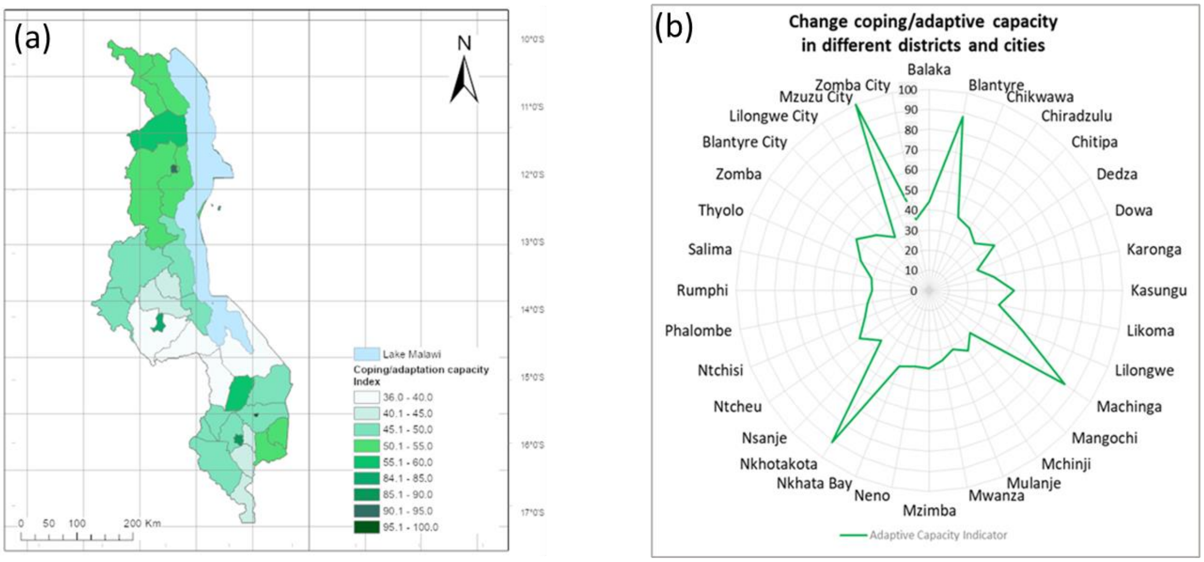

Figure 19: Climate coping/adaptive capacity in Malawi. (a) spatial map of the adaptive capacity index. (b) spider diagram for the climate coping/adaptive capacity index in Malawi's districts and cities.

As expected, the coping/adaptive capacity is the highest in the four cities (Figure 19). The coping/adaptive capacity in Zomba City is the highest relative to the other cities and districts, with four of the contributing drivers being the highest. Interestingly, ownership of a fridge or freezer was not ranked high in any of the cities, with Blantyre City ranked as the second lowest. The district with the highest for fridge or freezer ownership relative to other areas was Phalombe. Dedza also had the lowest coping capacity of all districts, with low access to cleaner energy, finance, transport, communication and protected water sources in relation to other districts. The individual drivers contributing to the high sensitivity and low coping capacity in Dedza are shown in Figure 20a and Figure 20b respectively.

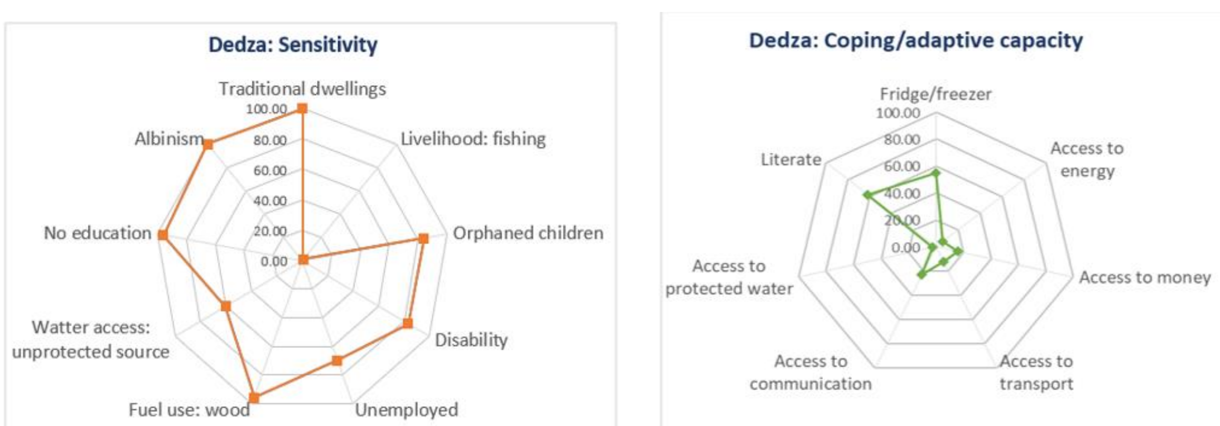

Figure 20. Dedza, the district with both the highest sensitivity and lowest coping capacity compared to other locations, showing the individual drivers of sensitivity and coping capacity components.

3.3.4 Overall Vulnerability assessment

There are several angles that need to be taken into consideration in order to generate a full climate impact vulnerability assessment. Since climate exposure alone is insufficient to fully explain the climate risk, social vulnerability which includes the socioeconomic characteristics affecting the proneness of certain populations to impacts of climate change and related risks must also be considered (de Sherbinin et al., 2019). Human health is another angle. The health of some members of society is affected by climate change impacts e.g., heat waves coupled with poor air quality and changes in the prevalence of vector-borne and non-vector-borne infectious diseases. Sensitivity to climate variability and change would be expected to be higher for those populations with poor basic living conditions such as overcrowding, malnutrition, and inadequate access to health services. Thus, the sensitivity of human population health to climate conditions is highest in Malawi, one of the developing countries, and more so among the poorest in Malawi communal areas. On the other hand, wealth also plays an important role in the climate vulnerability of a population. Wealth generally provides access to markets, technology, and other resources that can be used to adapt to climate variability and change. The proportion of economically active and inactive individuals in a population shows a rate of dependency in a population where a higher dependency ratio indicates that economically active individuals had many others to support, and resources for adapting to changes in climate would be more limited. If that population has a high literacy rate, then that implies better coping capacity.

Out of the total labour force of 6,614,065 persons, 5,389,463 (81.5 percent) were employed and 1,224,602 (18.5 percent) were unemployed (Malawi National Statistical Office, 2018). The unemployed were persons who during the reference period of seven days did not work even for an hour but were available for work. The Climate Social Sensitivity Index and the inverse of the Coping/adaptive Capacity Index were combined to derive a Social Climate Vulnerability Index. This index provides an indication of the general vulnerability to climate hazards of districts and cities in Malawi in relation to the area with the highest social vulnerability (Dedza). Figure 21a shows the spatial distribution of the Climate Social Vulnerability Index and the spider diagram in Figure 21b shows the Climate Social Vulnerability Index of each location in relation to its population.

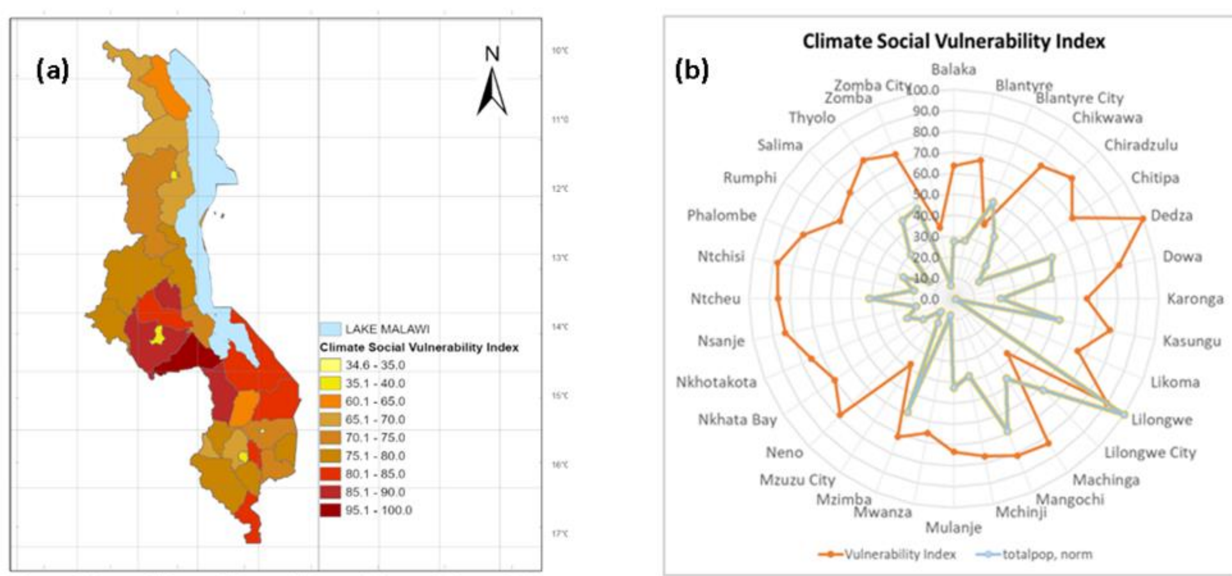

Figure 21: Climate change vulnerability in Malawi: (a) spatial map of the climate social vulnerability index; (b) spider diagram for the climate social vulnerability index comparing Malawi's districts and cities, showing the normalized population size for each location.

The Social Climate Vulnerability Index shows that, given the indicators used for characterizing sensitivity and coping/adaptive capacity, Dedza district had the highest Climate Social Vulnerability, followed by Lilongwe and Ntcheu district. **Figure** 21b also shows that the population size in the Lilongwe district was the highest compared to other locations and its population density was fifth highest. Dedza is ranked 7th in terms of population size and 11th in terms of population density.

3.3.5 Climate risk associated with vulnerability due to exposure to climate hazards

Combining socioeconomic and climate scenarios is being increasingly used for understanding the relative contributions of both changes in human factors (demography, economic development, urbanization) and climatic factors in generating future impacts. The exposure of communities to high temperatures and variability in precipitation of the baseline, as well as two of the four GWLs (2.0°C and 4.0°C) were considered. This allows us to understand if exposure to elevated temperatures, as well as high precipitation and periods of low precipitation (drought) is projected to increase in the future under these climate change scenarios, and if so, to find areas with larger projected changes. A subset of climate indicators was selected (see Table 3) to represent the exposure to climate change for inclusion in the Risk Assessment.

The exposure (climate hazards) data was at a higher resolution than the vulnerability data. The data for each selected climate hazard was thus spatially joined with districts and cities in ArcGIS Pro, using criteria to select the maximum of the values that was either within the boundary, or within a 30 km distance from the boundary. The distribution of the actual values of the selection of climate hazards for the three scenarios at each location is shown in Figure 22a-d. The value for each location represents the highest value within the boundaries and/or within 30 km from the boundaries of the particular location.

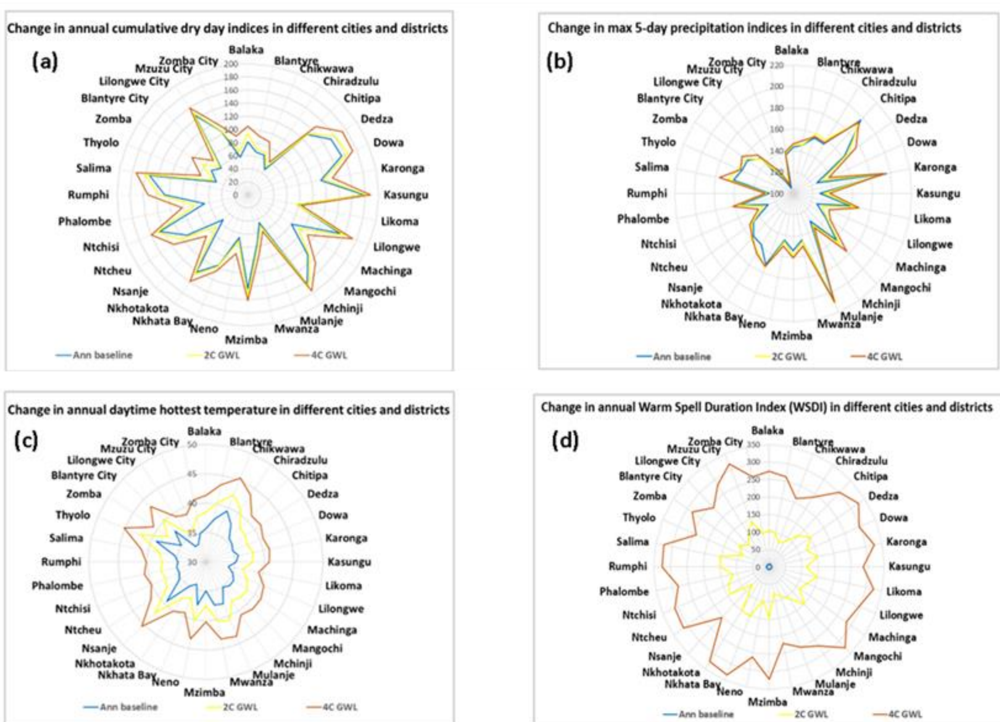

Figure 22:Change in the three scenarios (baseline, 2°C GWL and 4°C GWL) at each location for the four climate hazards selected for exposure assessment: (a) annual cumulative dry day (CDD) indices; (b) max 5-day precipitation indices; (c) annual daytime hottest temperature; and (d) annual warm spell duration indices (WSDI).

The selected exposure values were subsequently normalised, before being added to the climate social vulnerability index for each polygon. The resulting index was then normalised to derive a risk associated with exposure to each climate hazard. Risk associated with exposure to variability in precipitation has been characterised by cumulative dry days (dry days determine the length of the dry season) and maximum 5-day precipitation indices (extreme rainfall which may result in flooding) in Malawi.

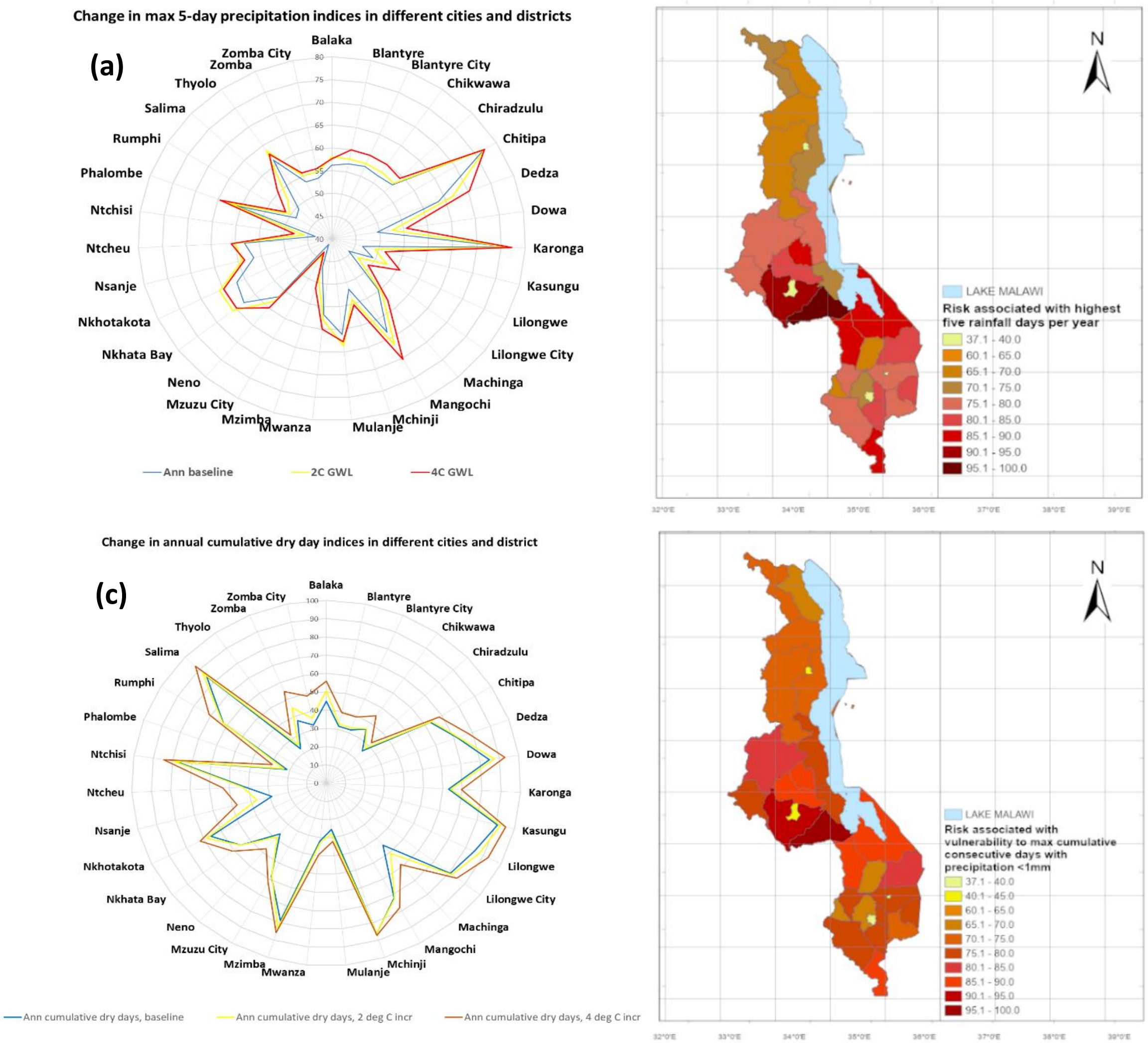

Figure 23: Exposure and climate risk associated with maximum 5-day precipitation indices and cumulative dry days in Malawi: (a, c) spider diagrams of the exposure associated with maximum 5-day precipitation indices and cumulative dry days; (b, d) spatial maps of climate risk linked to maximum 5-day precipitation indices and cumulative dry days for Malawi's districts and cities.

Figure 23a and b denote the exposure and risk associated with maximum 5-day precipitation indices and Figure 23c and d shows the exposure and risk associated with cumulative dry days. The highest exposure to maximum 5-day precipitation indices (Figure 23a) is found at Chitipa and Karonga. However, the highest risk is still in Dedza, followed by Lilongwe (

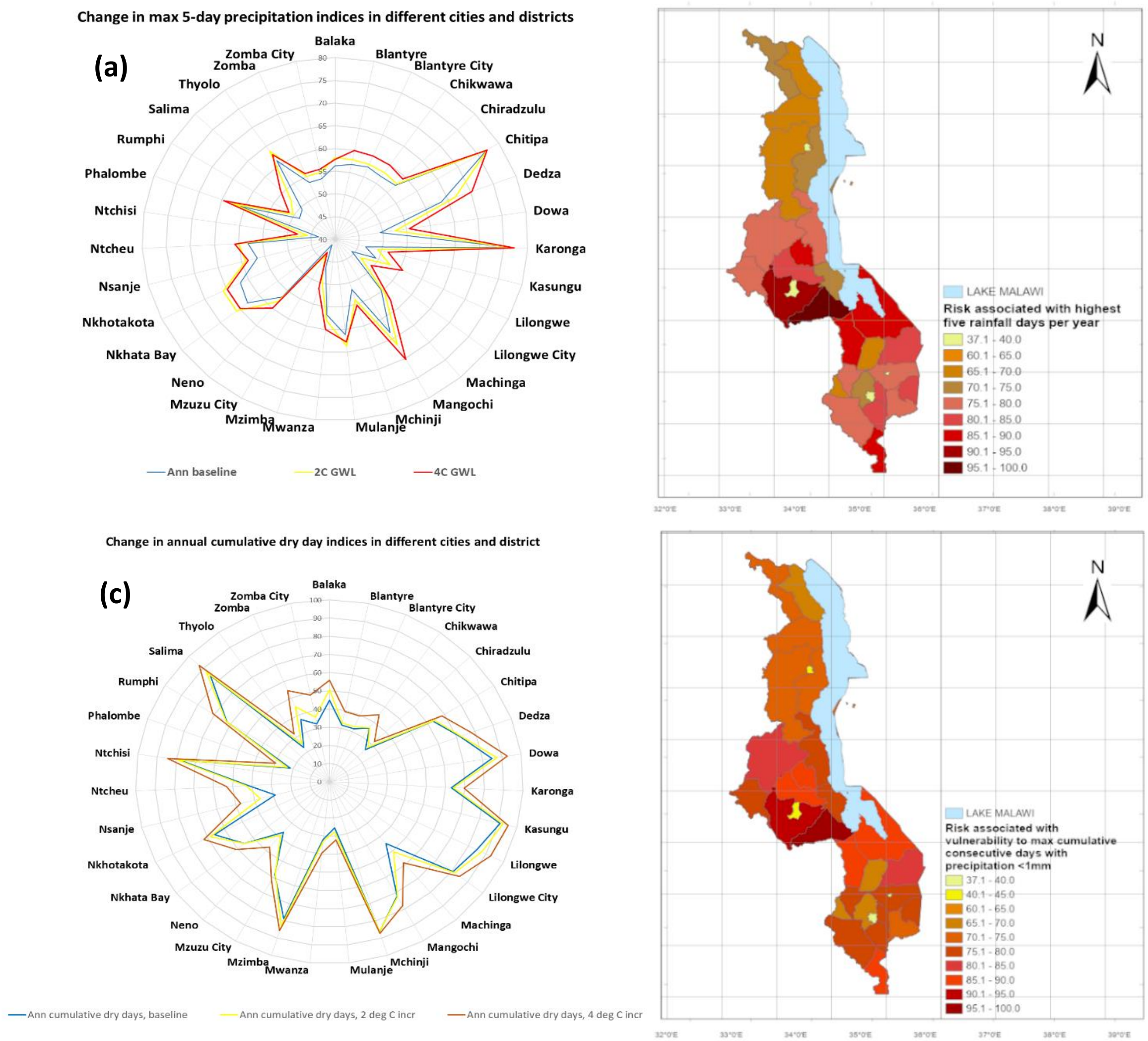

Figure 23b). The highest exposure to annual cumulative dry days is for the Kasungu district, followed by Lilongwe, Dowa and Salima. The highest risk was again at Dedza, followed by Lilongwe and Ntchisi. Figure 24a and b denote the risk associated with the maximum 5-day precipitation and Figure 24c and d show the risk associated with cumulative dry days, both as a spider diagram and spatial map.

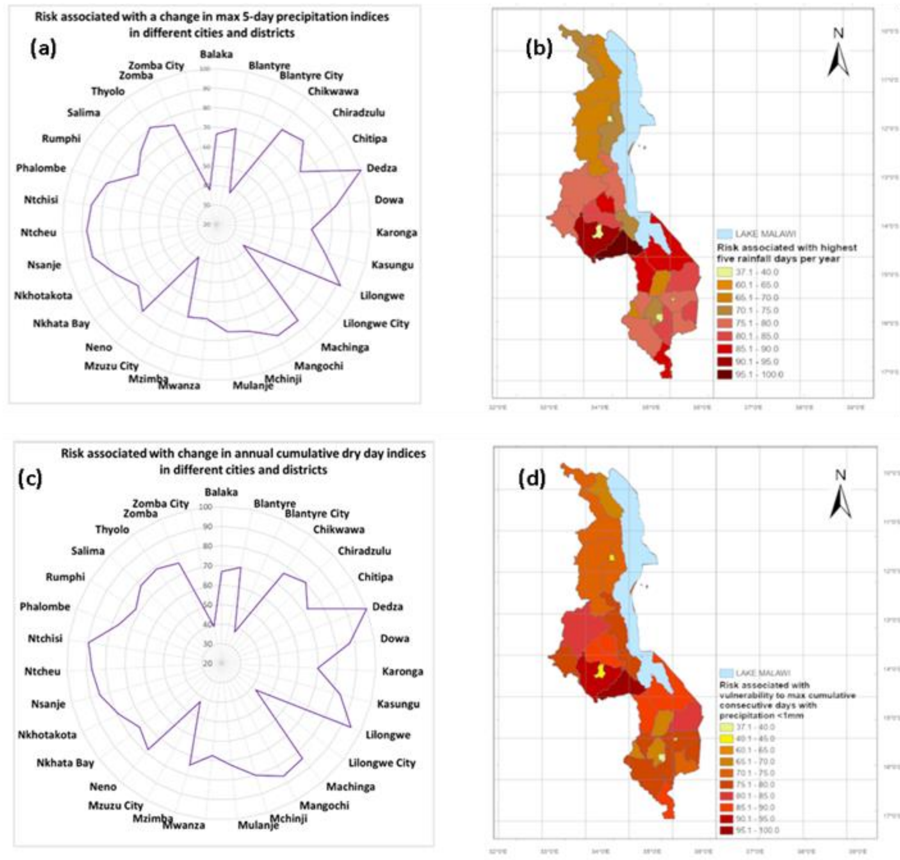

Figure 24: Climate change risk: (a) spider diagram and (b) spatial map of the risk associated with maximum 5-day precipitation indices and (c) spider diagram and (d) spatial map of the risk associated with cumulative dry days.

Risk associated with exposure to high temperatures has been denoted by the annual daytime hottest temperatures component, the average daily summer temperatures, as well as annual count of days contributing to “warm spells”, when the maximum temperature (TX) remains above its climatological 90th percentile (Warm Spell Duration index). Figure 25 shows the exposure and risk associated with the change in annual daytime hottest temperature as well as the change in annual WSDI.

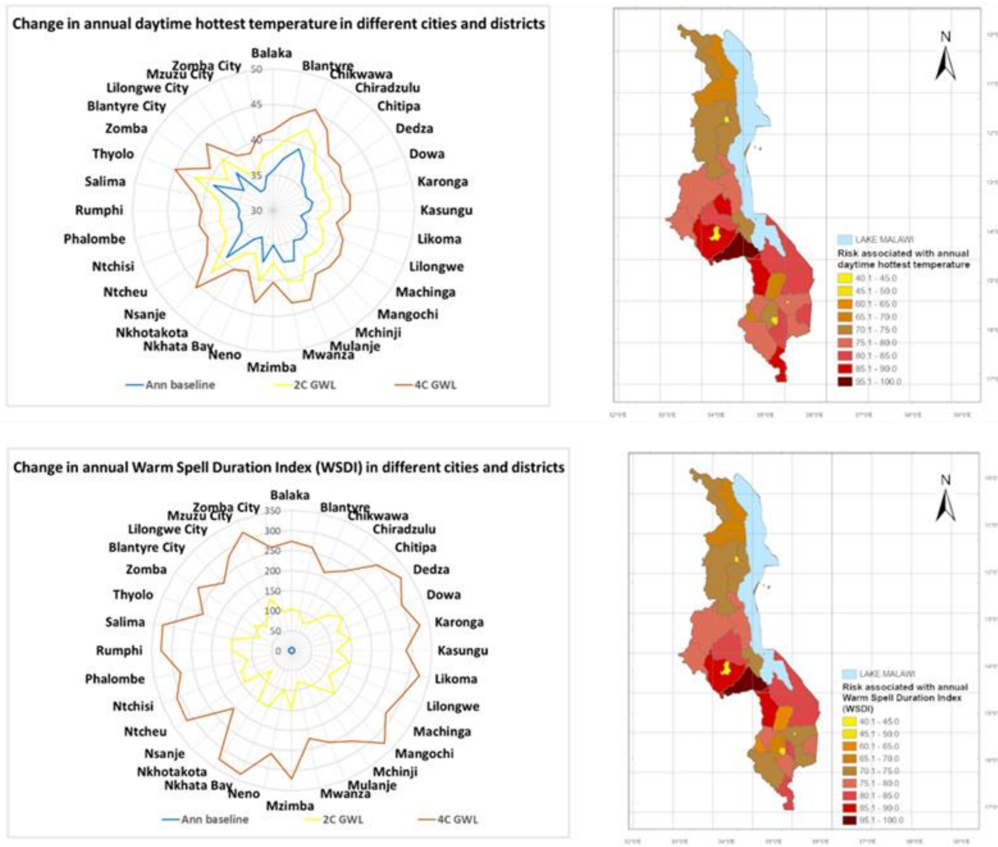

Figure 25: Exposure and Climate risk associated with annual daytime hottest temperatures (TXx) and warm spell duration (WSDI) indices in Malawi: (a, c) spatial map of the TXx and WSDI. (b, d) spider diagrams of exposure to the TXx and WSDI for Malawi's districts and cities.

Figure 26 denotes the risk associated with the change in annual daytime hottest temperature as well as the change in annual WSDI, both as a spider diagram and spatial map.

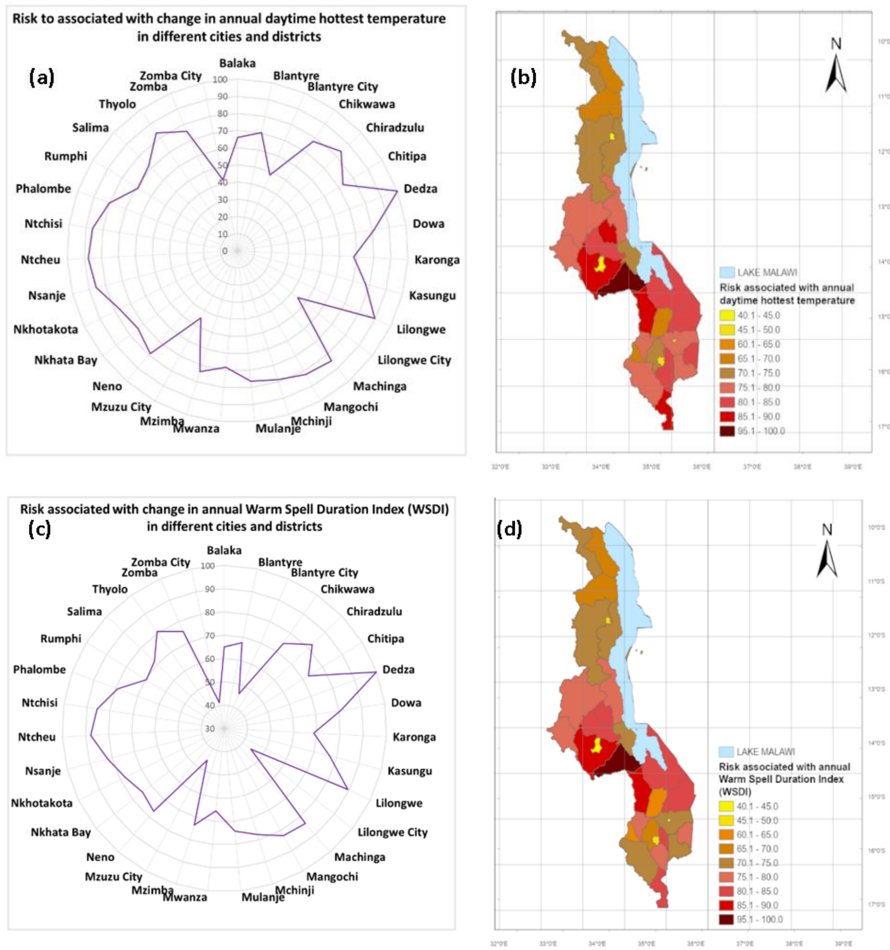

Figure 26: Climate change risk: spider diagram and spatial map of the risk associated with change in annual daytime hottest temperature (a and b), as well as the change in annual WSDI (c and d).

Summary

The socio-economic status in Malawi is complex with multiple interrelated factors. To improve the socio-economic status of Malawians, which may reduce their risk (particularly the vulnerability component) to climate change, there is still a need to put in measures that include investing in basic services such as healthcare, education, and clean water, as well as promoting economic growth and job creation. To address the historical and future climate risks in Malawi, several measures need to be taken. These include investing in climate-resilient infrastructure, such as water storage facilities and irrigation systems, as well as promoting sustainable agriculture practices that are less reliant on rainfall. This is because the study has shown that there will be an increase in drought tendencies and higher temperatures in the future with an increase in global warming. Many people are still without access to clean water. Efforts are thus needed to improve access to clean water and energy, which will help to reduce the country's vulnerability to climate change. As in other countries, the issue of the WEF Nexus in Malawi, need to be taken seriously to ensure the future security of these three sectors. The detailed discussion on the interdependencies and trade-offs linked to the WEF Nexus continues in the following *Section 4*. Finally, efforts need to be made to promote social inclusion and address poverty and inequality, which will help to build resilience and reduce the impacts of climate change on the country's most vulnerable populations. It has been shown here that Malawi is highly vulnerable to climate change, with a history of climate risks and future risks that are expected to increase such as droughts, heatwaves, and an increase in extreme heavy rain days in some districts. Addressing these risks will require a long-term commitment from the government, civil society, and the international community, and will require a focus on promoting climate resilience, sustainable development, and social inclusion. The government can start by incorporating the WEF Nexus approach in policies for some of its key sectors.

4 The perspective on climate risk and the WEF Nexus in Southern Africa

4.1 The WEF Nexus in Southern Africa

The WEF Nexus is a concept that refers to the interconnections and interdependencies between water, energy, and food systems (World Economic Forum, 2015). It recognizes that these three critical sectors are closely linked and that changes or challenges in one area can have significant impacts on the others. The connections between climate and WEF nexus are strong in southern Africa (Conway et al., 2015). Physical and socioeconomic exposure to climate is high in socioeconomically vulnerable areas and crucial priority sectors in the region, such as agriculture, energy and water. Hydropower comprises a major component of Southern African regional energy security, while irrigated agriculture and water for domestic use have requirements for water (Conway et al., 2015). Climate change and variability have influenced resource management in the region. There are extensive studies on seasonal climate forecasting in sub-Saharan Africa (MacKerron, 2004; Ziervogel et al., 2010). The Southern Africa Regional Climate Outlook Forum (SARCOF) provides likely conditions of seasonal climate, which is a rich source of information for integrating WEF nexus analysis and climate change impacts in the region from a seasonal timescale perspective. Conway et al. (2015) examined southern Africa's WEF nexus from the perspective of climate, considering national-level exposure of WEF production to climate variability in aggregate economic terms and analysed the relationship between interannual and multiyear climate variability and economic activity. The results showed the potential for seasonal climate forecasting in areas with high forecasting skills and socially and economically important nexus-related activities and described three key intraregional mechanisms for balancing nexus components. They concluded that water, energy and food are linked across different scales in southern Africa. The World Economic Forum identified climate change induced extreme weather events, mismanaged urbanisation, and food and water insecurity as some of the most likely and consequential risks currently facing decision makers (World Economic Forum, 2015).

Spatial interdependence is high and climate anomalies can produce regional scale effects. Climate change, combined with increasing demand associated with wider socioeconomic development pathways, urbanisation and population growth, will intensify linkages and or conflicts/trade-offs in the WEF nexus, particularly shorter-term pressures associated with climate risk from extreme climate events. A previous study over South Africa concluded that the WEF nexus approach is also useful for developing context-specific transformative pathways and informing WEF sector-inclusive climate adaptation strategies for climate risk and guidelines on improving livelihoods at a local level (Nhamo et al., 2020). Urbanisation in Southern Africa is estimated at double the size of the global average and the trend is expected to persist in future (Davis-Reddy et al., 2017). The estimated African population of 1.2 billion is expected to double to about 2.4 billion by 2050, a population growth rate which is higher than the world average (Davis-Reddy et al., 2017). This is likely to put enormous pressure on the finite water resources used in energy production, agriculture and water for domestic and industrial use. This is especially the case for Southern Africa where countries like Tanzania, DRC, Angola, Malawi and Zambia are expected to experience as much as five times increase in population sizes by 2100 (National Statistical Office, 2020). Such an increase in population alone will cause major shifts in the demand for food and dietary needs. Coupled with the negative effect of climate change projected for the region, it will have serious effects on food security as well as other securities in the energy and water sectors.

However, SADC has recently begun exploring opportunities for improved sectoral coordination in the WEF nexus to accelerate national investment and deal with climate risk in a holistic manner. National dialogues on the subject have been conducted across the SADC region, and Member States showed commitment to use an integrated approach in resolving challenges in the three WEF sectors. The initiative is being supported by the Global Water Partnership (GWP) (https://www.gwp.org/) with overall goal to support the transformation required to meet increasing water, energy and food security demands in the context of climate risk induced from climate change, urbanisation and population growth in the SADC region. Key aspects for support include creating an enabling environment that will drive cross-sectoral engagement, cross fertilisation and implementation of nexus investment projects that contribute to enhancing water, food, and energy security in the region following the aspects in the WEF Nexus conceptual framework, an example which is given in Figure 27.

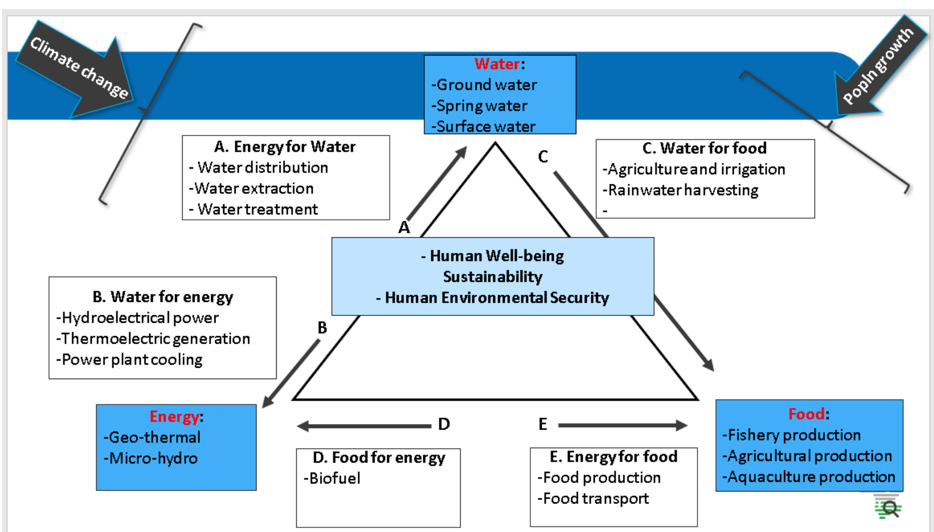

Figure 27. Water, Energy and Food security (WEF) Nexus conceptual framework showing the interdependencies of the WEF sectors under climate change risk and population growth. ***Source: Edited from the Research Unit for Humanity and Nature Water-Energy-Food Security Nexus***

Figure 27 shows a conceptual framework for the WEF Nexus, depicting the interdependencies of the WEF sectors under climate change risk and population growth. The end goal of the WEF Nexus as shown in the figure is human wellbeing. In the previous chapters, it has been highlighted that most countries in the SADC region are at risk of water scarcity through a decrease in rainfall and very high temperatures in the future. This is happening against the backdrop of a projected increase in population growth and urbanisation in almost all the countries in the region. This combination has the potential to increase the demand for this inadequate water supply for irrigation (food security), hydropower and water for domestic and industrial use. One arm of the WEF Nexus is the “Energy for Water”. The idea here is that energy is needed in the water distribution, water extraction or even water treatment done for water provision for domestic and industrial use. On the other hand, there is also “Water for Energy” and “Water for Food” under the WEF nexus which involves the water required for energy generation and irrigation, respectively. Here, the significance is that water is needed for hydropower generation, thermal power plant cooling and thermoelectric generation, while at the same time water is needed for agricultural irrigation and rainwater harvesting.

There is also another arm which interconnects energy with food where energy is needed to power irrigation farming, fishing cold chain, food transportation and agrifood processing, while at the same time food production might be needed for energy through biofuels used in many countries to blend with petrol. As can be seen in Figure 24, all these WEF Nexus interdependent arms are affected by climate change and population growth through an increase in demand for the dwindling water resources in the region. Thus, it is of extreme importance that when planning anything which talks to the future security of the WEF sectors, the interdependence, synergies, trade-offs and possible conflicts be taken into consideration. It will also be very advantageous if policies in the three WEF nexus are made to talk to each other or interlink so that conflicts due to the finite supply of water is minimised. Focusing on the WEF nexus from a climate services and climate adaptation viewpoint could support these actions. A SADC WEF Nexus Community of Practice does exist (Dashboard - SADC Community of Practice (wefnexus.org)) but currently has limited ability to inform effective and systematic decision-making to help curb the impacts of climate change and population growth on the WEF sectors. There is a need for the Member States to ramp up efforts to implement the WEF Nexus approach in their climate change response strategies and plans.

It is noted that the main connecter and pillar for the WEF Nexus is the availability of water. The current state of the water resources and related infrastructure development in the SADC region is a cause for concern when compared to other regions in the developed world. In terms of water availability, an estimated total of 2 300 km^3/year of renewable water resources is available to the 260 million SADC population (Aquastat 2011) where the current level of abstraction is only 44 km^3/year. Of this 44 km^3/year abstraction, 5% is used by industry, 18% for domestic use while 77% is used for irrigation (Aquastat 2008). Out of the total population, 39% of people have no access to enough, safe drinking water and 61% don’t have adequate sanitation services (SADC, 2011). On the agricultural and food security side, of the potential 50 million hectares of irrigatable land available in the region, only 3.4 million hectares (7%) was irrigated as of 2010 (SADC 2011). The following sub-sections describes the three WEF sectors in the context of the WEF Nexus.

4.1.1 Water Sector

The availability of water resources is at the epicentre of future climate change impacts (Davis-Reddy et al., 2017). Africa still has acute gaps in the provision of reliable and quality climate services related to water with only 27% of Africa countries providing this service. Almost half a billion people in Africa still have no access to basic safe drinking water and a quarter of a billion people are projected to be affected by high water stress by 2030 resulting in about 200 million people being displaced (WMO, 2022)). The presence of displaced people may then contribute to increased population density, create overcrowded areas, and contribute to the growth of informal settlements. In SADC, some countries like Zimbabwe, Malawi, South Africa and Lesotho are already water stressed, resulting in limited water, food and energy resources. With the SADC population projected to double by 2040 and with 70% of freshwater being from shared water resources, there is a possibility of future water-based conflicts especially in the dry southwestern parts of Southern Africa (Field et al., 2014). Another important point is that the population distribution and economic growth in the region does not follow the same distribution as the availability of water resources, e.g. Mozambique, Angola and Zambia which are less developed countries have more water resources than the economically developed South Africa, Namibia and Botswana (WMO, 2022). Thus, since currently, fresh water is from shared water resources, this might change in the future when those with water will try to retain most of it to cater for their growing population and urbanization. Therefore, there is a need for WEF Nexus-based policies that incorporate these issues of inevitable water stress in the future which may lead to compromised water, energy, and food security.

Table 6. Areas under irrigation based on the river basin in Southern Africa (Source: FAO-AQUASTAT)

River basin	Area of river basin (1 000 ha)	Countries	Area under irrigation (1 000 ha)	Large dam capacity (> 1 billion m^3)
Zambezi	135 137	Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, Zimbabwe	250	231.9
Orange	89 637	Botswana, Lesotho, Namibia, South Africa	310	14.2
Rift Valley	63 759	Djibouti, Eritrea, Ethiopia, Kenya, Sudan, Tanzania, Uganda	250	3.5
Limpopo	40 186	Botswana, Mozambique, South Africa, Zimbabwe	250	13.5
Total for 4 basins	**328 719**		**1 060**	**263.1**

In terms of water capacity from dams in SADC, the four largest basins in Southern and parts of Eastern Africa have a large area coverage of more than 330 million hectares (Table 6). These four basins have a total dam capacity of about 263 billion cubic meters servicing approximately 1 million hectares of irrigated land in the region. Therefore, any disturbances in the availability of water in these basins will consequently compromise food security in the region. This also applies to availability of energy because some countries in Southern Africa are reliant on hydro power electricity. Table 19 (in Annexure) is showing the main dams in the region, the catchments in which they are, their capacity and their main use in terms of whether they are used for irrigation (I), hydropower (H), water supply (S) or flood control (F).

Figure 28 shows the decrease in the total renewable water per capita in several countries within Southern Africa from the 1980s to 2012, with a rapid decrease in Madagascar and Democratic Republic of Congo. Unless measures are put in place, the scarcity of water may compromise water, energy and food security in the near future. One of the steps the SADC region can take in ensuring water security is by retaining more of the available renewable water for use in the region (by storing more water by constructing more dams) instead of letting it go to waste by flowing into the sea. Of the total available renewable water, the region retains 14% of it while the rest flows to the sea (SADC, Regional Infrastructure Development Master-Plan : Water Sector Plan). 34 of the dams identified in the SADC plan to be implemented between 2013-2021 by the SADC Regional body, they had a potential to increase (a) annual renewable water resources storage from 14% to 25%; (b) the area under irrigation from 3.4 million hectares to 10 million hectares; (c) hydropower generation from 12 GW to 75 GW; (d) access to water supply from 61% to 75% of the population; and (e) access to sanitation services from 39% to 75% of the population (SADC, Regional Infrastructure Development Master-Plan : Water Sector Plan). Therefore, with the projected scarcity of water in most parts of the region and the projected increase in population, this initiative may be significant in contributing to minimizing water related conflicts, trade-offs and encourage synergies between the water, energy and agriculture sector in line with the WEF Nexus. It should be noted however, that the construction of new dams should also receive careful consideration in the context of disadvantages, such as severe potential impacts on biodiversity, the displacement of communities and the flooding of agricultural land.

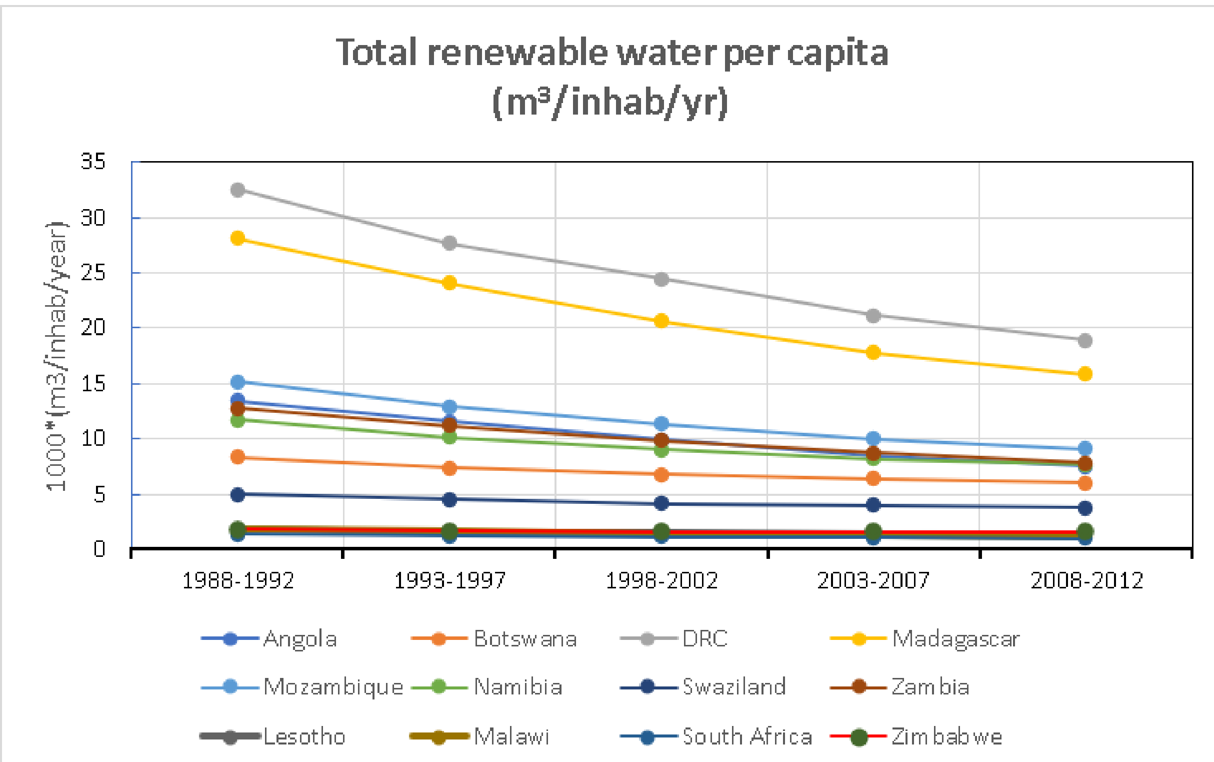

Figure 28: Water resources in Southern Africa represented by the total renewable water per capita in different countries.

4.1.2 Energy Sector

The energy resources mix found in the SADC region is composed of both traditional and renewable energy resources (Mabhaudhi et al., 2016). The primary energy sources used by countries include hydroelectricity, coal and natural gas, while a few use distillate fuel and wind energy, but the main energy used is coal (Table 7). With the current drive in the climate mitigation space to minimize greenhouse gas emissions, more countries are moving towards shutting down coal-powered stations and are investing in renewable energy. One of the key renewables which can be exploited more is hydro power, and it is currently the second-most used electricity source in Southern Africa (Table 7). However, climate projections suggest a decrease in rainfall in most parts in the region and a likely increase in evapotranspiration due to temperature increases. Therefore, with population growth, the demand for electricity for water, hydro-power energy and food production will increase and this might lead to water-related conflicts and warrant difficult trade-offs. Thus, incorporating the WEF Nexus in the policies which focus on the water sector, energy sector and agriculture sector, be it separately or in an integrated way, will go a long way in efficient water resource management which may reduce water-related conflicts and maximize the potential for synergies in the future. Wind energy and solar are two sources that have not been explored extensively in the region (Table 7). To minimize conflicts from an increase in demand for energy generated from hydro, countries can invest in other renewable energy options like wind and solar. This is very important since most catchments are projected to face a decrease in rainfall and the few catchments that are projected to experience an increase in precipitation may provide opportunities for hydro-electric power generation but at the same time, the related flooding may result in increased sediments reducing the catchment capacity.

Table 7. Southern Africa Electricity sources and generation capacity (MW) per country in 2014/2015. [Adapted from Davis-Reddy et al., 2017].

Country	Technology				
	Hydro- (MW)	**Coal (MW)**	**Gas (MW)**	**Distillate (MW)**	**Wind (MW)**
Botswana	0	732	160	0	0
Mozambique	2 573	0	0	151	0
Angola	1528	492	190	0	0
Malawi	351	0	1	0	0
South Africa	2 000	35 721	0	2 409	2 492
Lesotho	74	0	0	0	0
Madagascar	105	211	0	0	0
Namibia	348	132	0	21	0
Swaziland	61	9	0	0	0
D. R. Congo	2 442	0	0	0	0
Tanzania	717	0	585	78	0
Zimbabwe	750	1 295	0	0	0
Zambia	2 156	0	0	50	0
Mauritius	56	389	0	0	0
Total	**13 161**	**38 981**	**936**	**2 709**	**2 492**

4.1.3 Food Security and agriculture

In Southern Africa, agriculture is the biggest consumer of water compared to other sectors such as energy and water that are also big users of freshwater. Specifically, agriculture uses 70 to 80% of available freshwater resources (Malzbender & Earle, 2009). In terms of climate in the region, almost 75% of Southern Africa is in the arid to semi-arid zone and this is the case when most of the population in the region rely directly or indirectly on agriculture as their main source of livelihoods (Davis-Reddy et al., 2017). Agriculture strongly depends on either being rainfed or irrigated, both of which depend on rainwater. With most of the land being classified as arid to semi-arid, this contributes to the susceptibility of agriculture in the region to climate shocks such as droughts, floods, heatwaves and hailstones. With the latest IPCC Sixth Assessment report identifying southern Africa as a zone of the climate change hotspot regions now and in the future (Hoegh-Guldberg et al., 2018), agricultural yield may reduce with time. The region is projected to face mostly an increase in drought conditions, an increase in extreme heavy rain leading to floods and an increase in temperature (see Chapter 2 on climate hazards assessment).

Many countries in the region will face a wider gap between water supply and water demand. The changes in the supply side of water availability dynamics in the region will be due to the changes in climate. The projected increase in drought conditions and a general gradual decrease in rainfall coupled with the rapid increase in temperature leading to increased evapotranspiration will consequently result in a reduction of water supply. Furthermore, even in those areas in the region where an increase in rainfall is plausible, the rapid increase in temperature projected may still cause a decline in agricultural yield. As noted in the previous sections, some of the countries like Zimbabwe, Malawi, South Africa and Lesotho are already water stressed, a trend which is projected to continue into the future. It is estimated by the Food and Agriculture Organization (FAO) that the Southern African region may face a decrease in agricultural productivity of as high as 50% in the next decades because of water scarcity and insufficient irrigation. Specifically, a mean decrease in yield of 17% (wheat), 5% (maize), 15% (sorghum) and 10% (millet) is projected for Africa by 2050 (Knox et al. 2012) while the percentage of land suitable for maize crop is projected to decline by as much as 40% in the future (Figure 9; Dinesh et al. 2015).

Table 8. Area under large irrigation and the related dam capacity per country in Southern Africa
(Source: FAO-AQUASTAT Large hydroelectricity and hydro-agricultural schemes in Africa (fao.org))

	Area under irrigation		Dam capacity		
Country	**Total (*1000 ha)**	**Large schemes which are greater than 10 000 ha**	**Total (*billion m3)**	**Large dams which are greater than 1 billion m^3**	**Area of large schemes as % of total area**
Angola	80	-	4.5	4.1	-
Botswana	1.4	-	0.3	-	-
Congo DR	10.5	-	0.1	-	-
Comoros	0.1	-	-	-	-
Eswatini	49.8	-	0.6	-	-
Lesotho	2.6	-	2.8	2	-
Madagascar	1086.3	70	0.5	-	6
Malawi	56.4	-	-	-	-
Mauritius	21.2	-	0.5	-	-
Mozambique	118.1	50	64.5	59	42
Namibia	7.6	-	0.7	-	-
Seychelles	0.3	-	-	-	-
South Africa	1498	500	28.3	20.7	33
Tanzania	184.3	-	4.2	3.2	-
Zambia	155.9	20	99.8	98.9	13
Zimbabwe	173.5	20	99	95.4	11

Table 8 shows the area under irrigation and the dam capacity per country in Southern Africa. It shows that all the listed countries in the region have irrigation schemes, and most have dams for irrigation. Countries like South Africa, Zimbabwe, Zambia, Madagascar and Mozambique have large irrigation schemes of at least 10 000 ha in size. South Africa has the largest number (500) of these schemes followed by Madagascar and Mozambique with 70 and 50, respectively. This shows that a large amount of water is needed for these irrigation schemes (

Table 8). With the scarcity of water and population growth being projected, this may result in water conflicts or the need for trade-offs in irrigation hence compromising regional food security.

On the demand side, issues like the projected doubling of the SADC population by 2040, the increase in urbanization and an increase in economic development in the region will lead to a high increase in water demand for agriculture, hydropower and water for domestic and industrial use. For example, sub-Saharan Africa is estimated to have the highest increase in the consumption of meat and the second-highest consumption of milk compared to elsewhere in the world which will amplify the water demand for livestock production (Davis-Reddy et al., 2017). Thus, the combination of an increase in freshwater demand for food production and a decrease in the freshwater supply may result in water-related conflicts in the region. There is a need then for policies that incorporate the WEF Nexus in the design to try to minimize water-related conflicts and maximize synergies in the future. All three WEF sectors need water and with the gap between supply and demand for water widening, there is a need for strong holistic all-encompassing policies that address the availability of water for the WEF sectors in the future in Southern Africa.

4.2 Results of the WEF Nexus in Southern Africa Survey

A survey was developed with the objective to gauge the understanding of climate impacts, policy support, synergies and trade-offs in the water, energy and food security nexus. Understanding the WEF nexus in the context of climate services, climate hazards and climate change is an important building block for tailoring climate services and climate adaptation actions for maximum benefit. The survey was sent out to SADC National Hydrological and Meteorological Services (NHMS) as well as a list of the SADC WEF Nexus stakeholders. Out of all the stakeholders that participated, government institutions were the most represented. Overall, SADC member states that responded to the survey represented 50% of the region. All the water-energy-food security sectors were represented, hence the analysis from the survey gives a near-to-real picture of the WEF nexus in the SADC region.

There were 36.4% of the participants who highlighted that the WEF nexus is well established in their institutions and/or sectors while 54.5% pointed out that they had just heard about this nexus, but it is not yet being implemented in their respective sectors. This shows that more than 70% of the participants have just basic, or no knowledge of the WEF nexus. Thus, efforts to maximize on the synergies of the WEF nexus or to systematically analyse and holistically benefit from the trade-offs of the WEF Nexus has been minimal. The survey revealed that all SADC member states do have policies in place that focus on the different WEF sectors independently but not so much in an integrated manner. This shows that these sectors work in silos, hence there are no policies and plans focusing on at least two of the WEF sectors together. To address this, the SADC regional body has recently started the WEF Nexus dialogues. However, this initiative is in its infancy with member states still exploring the best ways to develop policies which focus on the synergies and trade-offs from the WEF nexus. Therefore, in future, there is high likelihood of policies which support the WEF Nexus at regional level or at least in some of the countries in the region.

Focusing on extreme weather events/hazards, the survey aimed to gain a better understanding of which hazards were perceived to affect which sectors more. The respondents indicated that the intra-seasonal dry spells, seasonal droughts, increases in temperature, and decreases in future rainfall (see Section 3) directly affect food security most in the SADC region. On the other hand, they indicated that the water and energy sectors in most parts will be more affected by the gradual increase in temperature and gradual decrease in rainfall. This is happening against the backdrop of higher temperatures than before resulting in crop failure thus compromising food security and sometimes water and energy security in the event of a multi-year drought. With the change in climate showing a future likelihood of a decrease in rainfall and an increase in temperature, this suggests a high chance of competing for food, water and energy resources. This is where robust policies need to be put in place considering the projected increases in population urban growth and lessening of water available for agriculture; energy and household/industrial water use.

In terms of current Policy, Financial and Operational support to enhance co-benefits in the WEF nexus in SADC, the respondents highlighted that there hasn't been a concerted effort to align policies of the WEF sectors. There is a need for support that, when given for a particular sector, will not substantially affect other sectors. For example, the support given to the agriculture sector to deal with dry-spells or drought shouldn't compromise the water available for domestic use or hydro power generation.

In summary, the SADC region has been identified as one of the world regions most vulnerable to climate change and its effects (IPCC, 2021). The current policies are for independent sectors, and it has been shown that this silo approach does not help when it comes to adaptation and mitigation of the effects of climate change. Substantial policy development work is needed within the context of the WEF nexus. Member states also require support to develop their National Frameworks on Climate Services, and significant capacity building is still required to enable users to understand the WEF nexus, its synergies and trade-offs and how they could come up with strategies to reduce the adverse effects of climate change.

4.3 In focus: The WEF Nexus in Malawi

The World Economic Forum (WEF) has been advocating for a holistic and integrated approach for managing the WEF Nexus to address the complex challenges arising from population growth, urbanization, climate change, and resource scarcity (WEF, 2011). The approach recognizes that these three essential resources are closely linked and that actions in one sector can have significant impacts on the others. Implementing policies and strategies that consider the WEF Nexus can lead to more sustainable and efficient resource management. In the context of Malawi, the WEF Nexus is of particular importance due to the country's high vulnerability to climate change (Section 3), limited natural resources, and high dependence on rain-fed agriculture. Applying the WEF Nexus framework in Malawi is of particular importance given the country's unique challenges and vulnerabilities. Its heavy reliance on rain-fed agriculture makes it susceptible to climate variability and change and related challenges such as droughts and floods. Additionally, Malawi faces energy access issues, particularly in rural areas, and water scarcity in some regions hence the country has various challenges related to water, energy, and food security. Next, the WEF Nexus components in Malawi are explored.

4.3.1 Water

Malawi's water resources primarily consist of lakes, rivers, and groundwater with the lake being the main source. Lake Malawi, the third-largest lake in Africa, plays a crucial role in providing water for various uses, including drinking, irrigation, and hydropower generation. However, the country faces challenges related to water scarcity and uneven distribution, especially during drought periods as highlighted in Section 3, since the country's water availability is highly dependent on rainfall patterns. The decrease in rainfall is also against the backdrop of the rapid increase in temperature hence compounding the water scarcity problem due to evapotranspiration. Climate change exacerbates these issues, leading to irregular rainfall patterns and reduced water availability. The riparian countries, Malawi, Tanzania and Mozambique contribute approximately 55%, 41% and 4% respectively to lake inflows using the 1960–2009 average (Bhave at al 2020). With the increase in demand in these countries due to increases in populations, urbanization, and economic development, this implies that inflow into Lake Malawi may be reduced in future hence may result in water-related conflicts. Thus, proper management and equitable distribution of water resources are essential to support agricultural activities, hydropower generation, and access to clean drinking water for the population.

4.3.2 Energy

The energy sector in Malawi is characterized by one of the lowest electrification rates in the world. Currently, the electricity rate stands at 11 percent with severe disparities between urban (42 percent) and rural areas (4 percent) (Kojima 2016). Over 90 percent of all households in Malawi still have no electricity (Sahai 2020). The energy sector in Malawi is heavily reliant on hydropower, with most of its electricity generated from hydroelectric plants. Specifically, over 90% of Malawi’s electricity generation and irrigation depend on Lake Malawi outflows into the Shire River (Bhave et al. 2020). This dependence on hydropower makes the country vulnerable to fluctuations in water availability due to climate variability. During periods of drought, energy production can be significantly affected, leading to electricity shortages and increased reliance on costly energy imports. Another problem is that the expanding population and lack of access to alternative energy sources imply that, with the absence of intervention, deforestation will continue at an increasing rate in the foreseeable future. Access to electricity and the reliability of the network are major constraints even for the private sector. A study by Mtilatila et al. (2020) projected that there will be as much as a 24% reduction in hydropower production during 2071-2100 under a business-as-usual climate scenario. Thus, the future development of hydropower energy plants should take into consideration the effect of climate change (highlighted in Section 3 in this report) to increase future energy security.

Procedures, time and cost to get connected to the electricity grid as well as the reliability of the electricity supply and the transparency of tariffs in Malawi are ranked extremely low (169 out of 190 countries) and below the Sub-Saharan Africa average (Sahai 2020). Considering the demand/supply of electricity in Malawi, the country has a total installed generation capacity which is lower than the demand. This is despite the country having more than 2,000 MW of hydropower potential (Kalowekama 2021, Sahai 2020). About 108 MW of emergency diesel generation capacity has been installed to assist with the supply deficit, although it came at a high cost of about US$0.42 per kWh and is negating the country’s efforts of carbon emissions reduction. However, to alleviate the challenge, the Malawi government with the help of the World Bank is putting up the flagship Mpatamanga Hydropower 350-megawatt project at an estimated total cost of 1.07 billion USD to contribute to reducing energy shortages and enhancing energy security (Kalowekama 2021, Sahai 2020). The proposed Mpatamanga project is on top of the priority list in the least cost-generation expansion plan prepared under the World Bank-supported Integrated Resource Plan. However, as much as the proposed Mpatamanga is a positive development for Malawi's energy circumstances, the issue of the WEF nexus needs to be seriously taken into consideration. This is considering that there will also be an increased demand for water for agricultural irrigation as well as for domestic and industrial use due to population growth and economic development.

4.3.3 Food security and agriculture

Agriculture is the backbone of Malawi's economy, employing a large portion of the population and representing about 30 percent of GDP, over 80 percent of total export earnings, and 85 percent of employment (Kandoole et al. 2017. Most agricultural activities depend on rain-fed systems, making them highly susceptible to climate variations. Prolonged droughts can lead to reduced crop yields, food insecurity, and economic hardships for rural communities. Extreme poverty is widespread as indicated in the climate risk part of Section 3. The current estimates using the international poverty line of US$1.90 per day indicate that 69.4 percent of the population was classified as being poor in 2017, and they largely depend on climate-sensitive rainfed agriculture (Kandoole et al. 2017). In the context of the WEF Nexus, the success of the agricultural sector is directly tied to water availability and access to energy for irrigation and post-harvest processing. Additionally, fluctuations in energy availability and energy prices can impact on the cost of agricultural production and distribution of food products. Rapid population growth increases the demand for food, putting additional strain on already limited water resources which is needed for irrigation. The same water will also be needed for water and energy to cater for the increased population and economic growth.

4.3.4 Summary

To achieve success in managing the WEF Nexus, it is essential for Malawi to involve various stakeholders, including government agencies, private sectors, civil society, and local communities, in decision-making processes and resource management strategies. Cooperation and collaboration among these stakeholders can help ensure a sustainable and secure future for water, energy, and food in the country. Some of the new as well as existing policies, as much as they need to be climate smart, also need to consider the WEF Nexus. They need to consider that with the increase in population, urbanization and economic growth projected, the demand for finite water resources will increase substantially. Water is needed for energy production, food production, industry, and domestic use.

Over the years, Malawi, in an effort to sustainably manage the country's natural resources and climate change strategies, has crafted policies, bills, and other national documents. These policies include Malawi's First Nationally Determined Contribution to the UNFCCC updated in July 2021; Malawi National Resilience Strategy 2018-2030; Malawi National Adaptation Programme of Action (2006); Initial National Communication to the UNFCCC (2002); Second National Communication to the UNFCCC (2011); National Meteorological Policy (2019); Malawi National Climate Change Policy (2013); National Climate Change Management Policy (2017); Draft Meteorological Bill (2022). However, this was done without the systematic and strong inclusion of the WEF Nexus in the context of climate change. This caveat was also highlighted in the FOCUS Africa Deliverable D6.2.

In conclusion, in Malawi water is crucial for agricultural irrigation, hydropower generation, and domestic use. The energy sector requires significant amounts of water, especially for hydroelectric power plants, while agriculture relies on both water for irrigation and energy for processing and transportation. The availability and management of these resources are interconnected, and changes in one sector can impact the others. As much as the Malawi government is trying to address the power supply deficit challenge by expanding the generation capacity of hydropower and the expansion of the grid, this needs to be done with the WEF Nexus in mind to minimize future related inter-sectoral and regional water-related conflicts. To ensure that the relatively new National Energy Policy and Renewable Strategy (2017-2030) work effectively in future, WEF Nexus issues needs to be considered. To attempt to address these challenges, Malawi can adopt an integrated approach that considers the interdependencies among water, energy, and food systems. It is essential that such a strategy also takes into account how climate change via diminished rainfall may impact on water availability for both the hydro-electric and agricultural sectors. This approach can include the development of strategies that promote sustainable agricultural practices, enhance water management, and improve energy access. Investing in renewable energy sources like solar and wind can help reduce the country's reliance on hydroelectricity and contribute to energy security.

5 Challenges and solutions of climate risk on the WEF Nexus in Southern Africa

5.1 Challenges

The analysis has shown that the Southern Africa region is experiencing high climate risk through adverse impacts of climate change, such as erratic rainfall patterns, increased frequency of extreme weather events, and rising temperatures. These challenges directly affect water availability, energy generation, and agricultural productivity. Thus, climate risk poses significant challenges to the WEF sectors in Southern Africa. The region is particularly vulnerable to the impacts of climate change due to its dependence on rain-fed agriculture, reliance on hydropower for electricity generation, and limited water resources. On the other hand, the region’s rapid population growth is increasing the demand for water, energy, and food, putting additional strain on already limited resources. Another challenge in the region is that inefficient water management practices are resulting in wastage and inadequate access to clean water, affecting both agricultural productivity and energy generation. This can lead to conflicts over resources. Competition for scarce water and land resources can increase tensions and conflicts among different user groups, including farmers, industries, and energy producers.

In the context of water, Southern Africa’s water resources are crucial for various sectors, including agriculture, industry, and domestic use. The region’s water availability is highly dependent on rainfall patterns, making it vulnerable to climate change, especially droughts. Proper management and equitable distribution of water resources are essential to support agricultural activities, hydropower generation, and access to clean drinking water for the population.

From the energy side, many countries in the region rely or plan to heavily rely on hydropower for their electricity generation. Most countries are moving towards renewable energy and reducing coal-powered electricity. In countries such as Malawi, close to 100% of the energy supply is from hydropower. However, as mentioned earlier, the region's hydropower generation is susceptible to fluctuations in water availability due to changing rainfall patterns. This vulnerability can potentially lead to energy shortages, now and in the future during periods of drought, which can have adverse effects on industries, agriculture, and overall economic growth. Diversification of the energy mix to include other renewable energy sources like solar and wind could help mitigate this dependency on hydropower. Section 2 showed that there is potential in Southern Africa to use solar and wind energy in the future.

For food security, Climate change-induced erratic rainfall patterns are having a big effect in the region since agriculture is the economic backbone of most Southern African countries, employing a large portion of the population. The success of the agricultural sector is directly tied to water availability and access to energy for irrigation and post-harvest processing. Additionally, fluctuations in energy prices can impact the cost of agricultural production and distribution of food products. On the other hand, insufficient and unreliable energy supply hampers economic growth and affects food processing and storage. Water scarcity affects agricultural production, energy generation, and access to clean water for households.

5.2 Possible opportunities and benefits from the WEF Nexus:

- Integrated Approach: To address the WEF Nexus challenges in Southern Africa, an integrated approach is essential. This involves considering the interdependencies and trade-offs between water, energy, and food systems when formulating policies and implementing projects. Policymakers need to develop strategies that promote sustainable agricultural practices, enhance water management, and improve energy access. For instance, decision-making processes should consider the impact of agricultural practices on water resources and energy requirements, and vice versa. Investing in renewable energy sources like solar and wind can help reduce the country's reliance on hydroelectricity and contribute to energy security.
- Diversification: Climate risk can drive the development of diverse economic sectors less dependent on water and thus less vulnerable to climate impacts, reducing overreliance on agriculture and hydropower. Reducing dependence on rain-fed agriculture and expanding irrigation systems can help mitigate the impact of droughts on food production, provided that water resources are not as yet fully allocated (e.g. to household demand, hydro-electricity and existing agricultural use) and can indeed be deployed to irrigation. Diversifying the energy mix by investing in renewable energy sources can reduce some countries in Southern Africa’s dependency on hydropower and decrease the vulnerability to fluctuations in water availability. Solar, wind, and biomass energy can provide alternative and reliable sources of power, especially in rural areas where electricity access is limited.
- Private and Public Partnerships: Collaboration between government agencies, private sectors, and international organizations is crucial to developing sustainable solutions for the WEF Nexus. It can facilitate technology transfer, knowledge sharing, and financial support for initiatives aimed at enhancing water, energy, and food security. For example, Chirambo, 2016 noted that the main challenge for Southern Africa to reach its potential in the use of other renewable energy is finance. Private and Public Partnerships can alleviate this challenge. Also, policymakers in the region may make the costs of renewable energy affordable by offering tax rebates on renewable energy products or raw materials.
- Renewable Energy Opportunities: Climate change encourages a shift towards renewable energy sources like solar and wind, which can provide sustainable alternatives to hydropower and contribute to reducing greenhouse gas emissions.

- Water Management Innovations: Climate risk assessment fosters innovation in water management practices, including rainwater harvesting, water recycling, and efficient irrigation systems, which can enhance water resilience in agriculture and other sectors. Also, enhanced water storage and management infrastructure can help mitigate the impact of variable rainfall patterns and reduce the risk of water scarcity during dry periods. Building reservoirs and small-scale water storage facilities can improve water availability for irrigation and hydropower generation. Benioff et al. (2012) identified several water-management-related adaptation strategies that can be followed in the region such as contingency planning for droughts and floods; water conservation; river-basin planning and coordination; making changes in the construction of infrastructure; and using inter-basin water transfers.
- Adaptive Agriculture: Doing climate risk assessments may prompt the adoption of climate-smart agricultural practices, such as drought-resistant crops and agroforestry; conservation agriculture; and efficient water management techniques like rainwater harvesting and drip irrigation to improve resilience and adaptability to changing climatic conditions. Promoting climate-resilient agricultural practices can enhance food security while reducing the pressure on water resources and energy.
- Regional Cooperation: As climate change impacts are transboundary, Southern African countries may be prompted to collaborate on cross-border management of shared water resources and renewable energy projects. Thus, addressing climate risk in the WEF Nexus requires cross-border collaboration, encouraging regional integration and cooperation in resource management and disaster response. Many water sources in the region are shared among countries. Collaborative approaches and agreements for transboundary water management are vital to ensure equitable and sustainable utilization of shared resources.
- Economic Diversification: Carrying out climate risk assessment can drive the development of diverse economic sectors less dependent on water and less vulnerable to climate impacts, reducing overreliance on agriculture and hydropower. Diversifying the energy mix by investing in renewable energy sources can reduce some countries in Southern Africa's dependency on hydropower and decrease the vulnerability to fluctuations in water availability. Solar, wind, and biomass energy can provide alternative and reliable sources of power, especially in rural areas where electricity access is limited.
- Enhanced Awareness and Preparedness: Climate risk assessment heightens awareness of the interconnectedness of the WEF Nexus and the urgency to develop adaptation and mitigation strategies which can lead to better preparedness for future challenges. Raising awareness among the general public about the importance of the WEF Nexus and its impact on their daily lives can foster a culture of resource conservation and responsible consumption.
- Water-Energy Efficiency Measures: Encouraging water and energy efficiency measures in agriculture and industries can lead to significant resource savings. For instance, implementing energy-efficient irrigation systems and promoting water recycling in industries can reduce both water and energy consumption. This can be informed by research and data collection which should be highly promoted in the region. Investing in research and data collection related to water resources, energy demand, and food production can provide valuable insights for evidence-based decision-making and long-term planning.
- Cross-Sectoral Coordination and Governance: Improving coordination among relevant government ministries, departments, and agencies is essential for effective management of the WEF Nexus.

Establishing a multi-stakeholder platform to address the interdependencies between water, energy, and food can lead to more informed and balanced decision-making.

- Sustainable Land Use and Forest Conservation: Preserving and sustainably managing forests and natural ecosystems is crucial for maintaining water sources and regulating water flow, which, in turn, supports agricultural activities and hydropower generation.

5.3 Summary

In conclusion, climate risk assessment presents both significant challenges and potential benefits to the Water-Energy-Food (WEF) Nexus in Southern Africa. As a region highly vulnerable to the impacts of climate change, Southern Africa faces complex interdependencies among water, energy, and food systems, making it crucial to address climate-related challenges with integrated and holistic approaches. The challenges arising from the climate risk assessment include water scarcity, food insecurity, energy shortages, conflicts over resources, ecosystem degradation, and economic losses. These challenges threaten the region's socio-economic development, food security, and access to clean energy and water resources. Without effective mitigation and adaptation strategies, the WEF Nexus in Southern Africa could face severe disruptions, affecting livelihoods and exacerbating existing vulnerabilities.

However, there are potential benefits that can be harnessed from climate risk assessment results. The need to diversify energy sources can drive investments in renewable energy technologies, offering opportunities for sustainable and climate-resilient energy solutions. Climate challenges can also stimulate innovations in water management and agriculture, promoting efficient use of resources and climate-smart practices. Moreover, the shared nature of climate risks can encourage regional cooperation and collaborative management of transboundary water resources and renewable energy projects. To address climate risks on the WEF Nexus in Southern Africa effectively, policymakers, governments, and stakeholders must prioritize integrated resource management, sustainable land use, and ecosystem conservation. Investing in climate-resilient infrastructure, promoting climate-smart agriculture, and enhancing adaptive capacity at local and regional levels will be crucial.

Additionally, public awareness, capacity building, and strong governance structures are essential for fostering cooperation and participation among communities and stakeholders. By adopting a proactive and collaborative approach, Southern Africa can build resilience to climate change impacts, ensure sustainable development, and safeguard the water, energy, and food security of its populations. Ultimately, successful management of the WEF Nexus in the face of climate risk requires a long-term commitment to sustainable development, climate adaptation, and regional cooperation, ensuring a more secure and prosperous future for the people of Southern Africa.

6 Discussion and conclusion

The water-energy-food security nexus has emerged as a critical issue in Southern Africa, where the region faces the challenge of ensuring reliable and sustainable access to water, energy, and food amidst changing environmental, economic, and social conditions. Southern Africa is characterized by high levels of water scarcity, variability in precipitation, and a high dependence on hydroelectric power, which may lead to increasing competition for limited water resources between the energy and agricultural sectors. This competition, combined with climate variability and climate change, poses significant risks to water, energy, and food security in the region. The WEF nexus approach is based on an understanding of the synergies and trade-offs between water, food and energy resources. It provides a multidisciplinary platform for stakeholder engagement to improve resource use and sustainable development. Understanding the WEF nexus in the context of climate services, climate hazards and climate change has an important role to play in tailoring climate adaptation actions for maximum benefit. WEF nexus and climate services are necessary complements when there are shared constraints in nexus resources that have noticeable climate change impacts and that are used across economic sectors. Climate services provision in Southern Africa, a key component of the FOCUS Africa project, has an opportunity to promote and raise awareness about the climate risk in the region and factoring the WEF Nexus approach in climate sensitive sector plans especially for the future.

Under the FOCUS-Africa project, the socio-economic benefits of the climate services being developed are also considering water-energy-food nexus interactions, while opportunities for enhancing the use of tailored climate services across sectors are being explored. This includes, e.g., common climate services needed for the water and food security sectors or the use of climate projections to understand impacts of climate change on energy production and food production. Understanding of the perceptions of impacts and priorities of climate hazards and climate change on different sectors is also being explored e.g., how do practitioners perceive the impacts of dry spells on crop farming as opposed to energy production and where would priorities for action fall? In addition, many of the case studies in the project provide opportunities to better understand conflict and opportunities for synergies between sectors using the different climate services being developed. Here in this report, we covered the specific area on the WEF Nexus which include assessing current and future climate vulnerability and risk through analysis of climate change impacts, climate sensitivity and the adaptive capacity of systems in the water, energy, and food security nexus. Population growth and a substantial change in climate projected for Southern Africa combined with a significant percentage of the population that is already highly vulnerable to climate change impacts, were considered in this report which brought the principles of climate risks and WEF nexus together. Specifically, the report covered the assessment of climate risk on the WEF Nexus in Southern Africa.

Water security is critical for the functioning of all economic sectors in Southern Africa, including agriculture, energy production, and industry. Here, it was noted that water scarcity in the region is a pressing issue, as most of the countries in the region experience droughts and water scarcity, which has been further exacerbated by increases in temperature. Moreover, the region's reliance on hydroelectric power, which depends on water availability, further highlights the need to ensure water security in the region. Energy security in Southern Africa is also important, as the region's growing population and economic development are contributing to increasing demand for energy. Despite having a huge potential for hydropower energy, the region still faces challenges related to energy access, affordability, and reliability. This was clearly exemplified in the case of Malawi where about 90% of households are still without access to electricity. This is particularly true in rural areas and for marginalized communities, which often lack access to modern and clean energy sources. Despite having a considerable portion of irrigatable land in the region as highlighted and with a significant amount of fresh water being lost to the sea, food security is also still a critical issue in Southern Africa. Food production systems in the region are already under stress due to the impacts of climate change, which include increased frequency and intensity of droughts and floods. Moreover, food production is also constrained by limited access to water and energy, which affects productivity and leads to increased costs hence bringing the issue of the WEF Nexus to the core.

The WEF nexus in Southern Africa is complex and multi-dimensional and requires an integrated approach that considers the interconnections and interdependencies between these sectors. This can be achieved through coordinated policies and strategies that ensure sustainable access to water, energy, and food, while also considering the impacts of climate change and the need for resilience. Ensuring water, energy, and food security in Southern Africa is critical for sustainable development and poverty reduction in the region. The region's heavy reliance on rain-fed agriculture, dependence on hydropower for electricity generation, and limited water resources make it particularly vulnerable to the impacts of climate change. An integrated approach that recognizes the interdependencies between these sectors can help to address the challenges and risks associated with the water-energy-food nexus. Such an approach requires political will, strong institutions, and effective governance structures that promote sustainable and equitable access to resources in a coordinated manner. In this report, the challenges presented by climate risk in Southern Africa include water scarcity, food insecurity, energy shortages, conflicts over resources, ecosystem degradation, and economic losses. These challenges have the potential to exacerbate existing vulnerabilities, adversely affect livelihoods, and impede socio-economic development in the region.

On the other hand, the results from the climate risk assessment also presents opportunities for positive change. It can drive the need for diversification in the energy sector, leading to investments in renewable energy sources and greater energy security as was highlighted extensively for Malawi in this report. Additionally, findings from the climate risk assessment can incentivize the adoption of climate-smart agricultural practices, innovative water management techniques, and ecosystem-based approaches, enhancing water and food security while fostering environmental sustainability. Climate-smart agriculture and effective integrated water resources management is particularly crucial for the Southern African circumstance identified in this report such as the projected increase in drought conditions, amplified temperatures and the region already being agro-centric.

The report also highlighted that to effectively address climate risks in the WEF Nexus, Southern African countries must prioritize cross sectoral adaptation and resilience-building measures. This involves investing in climate-resilient infrastructure, promoting sustainable land and water management practices, and fostering regional cooperation for shared resource management. Moreover, stimulating public awareness about the climate risk on the WEF Nexus is essential for promoting a culture of conservation and responsible resource use among particularly communities. Education and engagement can empower individuals and local stakeholders to actively participate in sustainable development efforts and contribute to climate resilience. By recognizing and addressing the challenges while seizing the opportunities presented from a climate risk assessment, Southern Africa can create a more sustainable and secure future for its water, energy, and food systems and secure its future in the WEF sectors. Regional collaboration, innovative solutions, and long-term planning will be crucial in building resilience and adapting to the changing climate, ensuring the well-being and prosperity of the region's people and environment.

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Annex

Table 9. Large dams of at least 1 billion m^3 by river basin in Southern and Eastern Africa

River Basin	Status	Name of dam	Dam located in: river	Dam located in: country	Dam properties: Capacity (billion m3)	Height (m)	Use*
ZAMBEZI	Existing	Kariba	Zambezi	Zambia, Zimbabwe	188	128	H
		Itezhitezhi	Kafue	Zambia	4.925	70	H
		Cahora Bassa	Zambezi	Mozambique	39	171	I, H, F
		Many small dams are located in Zimbabwe, mainly for irrigation purposes					
	Planned	Series hydropower cascade dams on mainstream Zambezi (Batoka Gorge, Devil's Gorge and Muputa Gorge					
ORANGE	Exisiting	Bloemhof	Vaal	South Africa	1.264		I, S
		Gariep (H. Verwoerd)	Orange	South Africa	5.674		I, H, S
		P.K. Le Roux	Orange	South Africa	3.237		I, H
		Vaal	Vaal	South Africa	2.122		
		Katse (LHWP)	Malibamatso	Lesotho	1.95	185	H
	Planned	Mashai Dam (3.3 BCM), Tsoelike Dam (2.22 BCM) and Ntoahae Dam in Lesotho within framework of the Lesotho Highlands Water Project (LHWP)					
		Due to Lesotho's commitments through the LHWP, its water resources will have reduced from 5.23 BCM per yr to 3.03 BCM per yr in 2020					
		LHWP transfers 2.2 BCM/yr water to South Africa (Vaal River), while providing Lesotho with facilities to generate its own electricity					
LIMPOPO		Mapai	Limpopo	Mozambique	11.2	65	I
	Existing	Masingir	Elefantes	Mozambique	2256	48	I,H, F
		Many smaller dams are located in the Limpopo basin in South Africa, mainly for irrigation					
	Planned	In South Africa plans exist for water transfer from Incomati to Limpopo, Usutu to Limpopo, and Orange to Limpopo					
		- In Botswana plans exist for north-south water carrier from Shashe river to Notwane river (both located in the Limpopo basin)					
CONGO	Existing	Inga 1	Nkokolo/Congo	DRC		50	H
		Inga II	Nkokolo/Congo	DRC		58	H
		Due to lack of maintenance during the civil war, these dams are heavily silted and operate on only 30% of their capacity					
	Planned	Inga III on the Nkokolo/Congo, with a height of 60 m, for hydropower					
		Grand Inga on the Congo, with a height of 150 m, for hydropower					
RIFT VALLEY	Existing	Koka	Awash	Ethiopia	1.9	42	I, H
	Planned	Turkwel	Turkwel	Kenya	1.645	155	I
SAVE	Existing	Kyle	Mutirikwi	Zimbabwe	1.425	67	I
	Planned						
INCOMATI	Existing	Corumana	Sabié	Mozambique	1.273	46	I, H, F
	Planned	Driekoppes Dam in Komati River in South Africa and Maguga Dam (0.332 BCM) in Komati in Swaziland					
CUNENE	Existing	Gove	Cunene	Angola	2574	58	I, H
		The Gove Dam Also provides water to Namibia for water supply to population					
	Planned	Epupa Dam between Angola and Namibia for hydropower with capacity of 7.3 BCM					

Data source: FAO, 2012. AQUASTAT database- [Accessed 14 June 2023], https://www.fao.org/3/bc815e/bc815e.pdf

Table 10.Results of bivariate correlation – green shows a positive correlation and red an inverse correlation

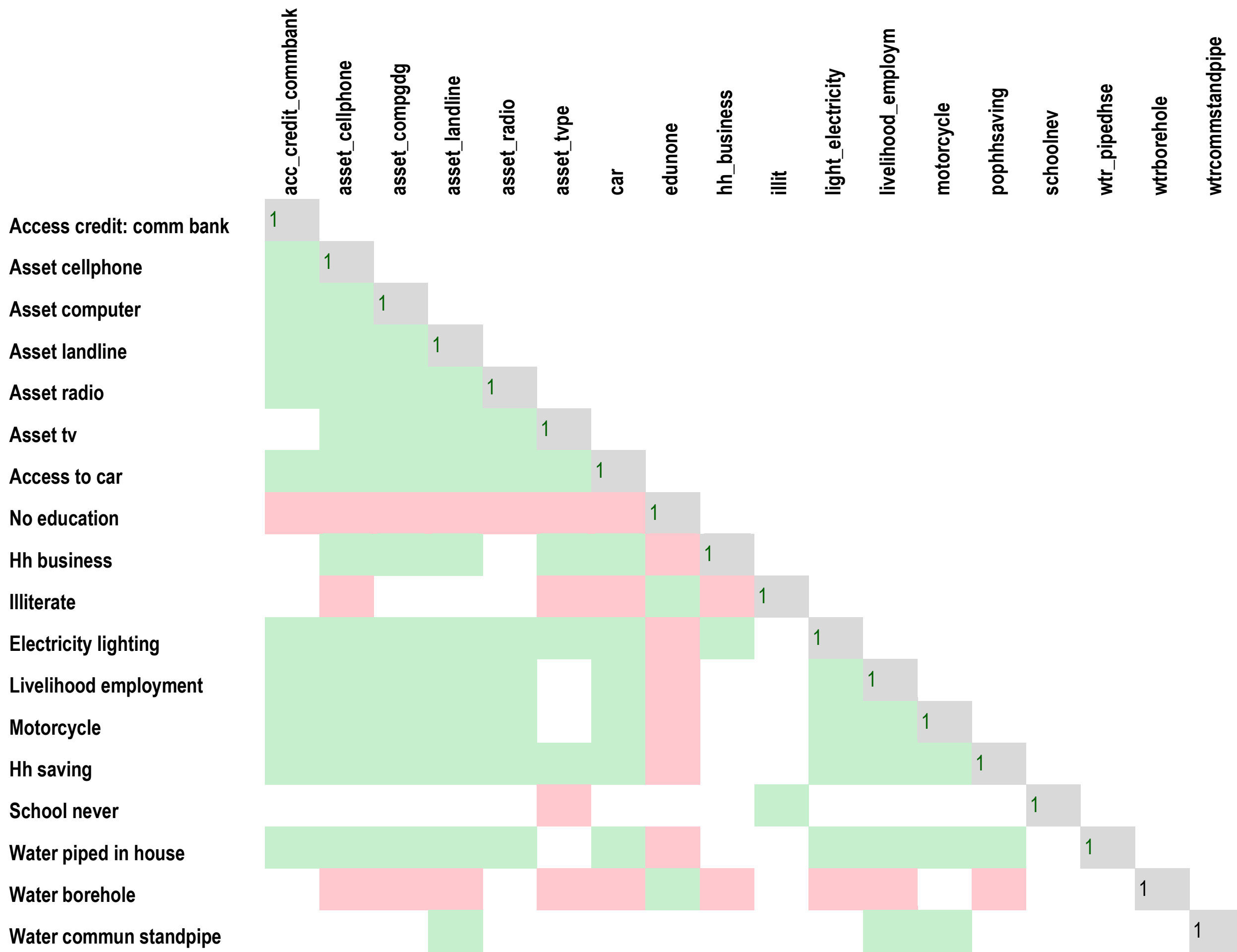

Table 11. Exposure Indices for cumulative dry days, temperature (combining hot temperatures and dry days) and high precipitation as well as an index combining all the individual indices. The three highest values of each individual indicator is shown in bold.

Name	cdd_Annbsl	Cum dry days Index	cwd_ann	precip_ann	prec_summer	prec_winter	r20mm_ann	rx5day_ann	Precipitation Index	tmax_ann	tmax_Summer	tmax_Winter	tmean_ann	tmean_Summer	tmean_winter	Txx_ann	wsdi_ann	High Temperature	Climate hazard index
Balaka	80.8	45.5	12.1	1088.0	968.4	120.0	14.6	143.3	60.2	28.7	30.3	27.2	28.2	29.8	26.6	35.7	7.9	92.5	76.9
Blantyre	66.2	37.3	13.1	1147.0	988.1	159.7	14.6	146.0	63.3	29.5	31.2	27.8	28.9	30.7	27.2	37.4	7.9	95.2	76.0
Blantyre City	57.4	32.3	13.1	1147.0	988.1	159.7	14.3	146.0	63.3	29.5	31.2	27.8	28.9	30.7	27.2	37.4	7.6	95.0	74.0
Chikwawa	65.4	36.8	12.4	1202.0	998.3	204.3	16.5	155.8	66.4	**31.1**	**32.9**	**29.3**	**30.5**	**32.3**	**28.7**	**39.4**	7.6	100.0	78.9
Chiradzulu	46.1	26.0	13.1	1202.0	998.3	204.3	16.5	155.8	66.5	29.8	31.6	27.9	29.2	31.0	27.3	37.7	7.6	95.8	73.1
Chitipa	129.4	72.9	**22.6**	**1591.0**	1091.0	**520.7**	**25.9**	**196.3**	88.5	29.7	31.0	28.4	29.2	30.5	27.9	35.7	7.5	94.9	99.4
Dedza	153.1	86.2	15.9	1380.0	1242.0	138.4	20.9	161.8	75.9	29.2	30.5	27.8	28.7	30.1	27.3	35.4	7.1	93.2	99.1
Dowa	**155.4**	87.5	12.1	1007.0	955.5	55.9	13.4	126.1	55.7	28.5	29.9	27.2	28.0	29.5	26.6	35.0	7.3	91.4	91.1
Karonga	113.9	64.1	18.2	**1591.0**	1070.0	**520.7**	**25.9**	**196.3**	87.8	29.7	31.0	28.4	29.2	30.5	27.9	35.7	7.5	94.9	95.8
Kasungu	**177.6**	100.0	15.0	1083.0	993.5	129.7	12.6	127.0	60.6	28.2	29.5	27.0	27.6	29.0	26.3	35.2	7.5	90.7	97.5
Likoma	76.4	43.0	**19.3**	1581.0	**1283.0**	297.2	22.7	158.8	86.3	28.4	29.8	26.9	27.9	29.3	26.4	33.9	6.9	90.4	85.3
Lilongwe	153.1	86.2	12.4	1059.0	990.1	69.1	13.4	126.1	58.2	28.5	29.9	27.2	28.0	29.5	26.6	35.0	7.5	91.5	91.6
Lilongwe City	145.8	82.1	11.9	962.0	904.8	57.2	10.1	113.2	52.8	26.8	28.1	25.5	26.2	27.6	24.8	33.2	6.6	85.8	85.7
Machinga	80.8	45.5	12.5	1041.0	959.6	93.1	14.3	139.4	58.0	28.7	30.3	27.2	28.2	29.8	26.6	35.7	**8.0**	92.6	76.1
Mangochi	129.7	73.0	15.9	1380.0	1242.0	138.4	20.9	161.8	75.9	29.2	30.5	27.8	28.7	30.1	27.3	35.7	7.8	93.6	94.1
Mchinji	**163.6**	92.1	12.9	1124.0	1064.0	69.1	15.3	131.4	62.0	28.2	29.5	27.0	27.6	29.0	26.3	35.2	7.6	90.7	95.0
Mulanje	46.1	26.0	14.7	**1822.0**	**1446.0**	376.0	**29.5**	**209.2**	100.0	29.8	31.6	27.9	29.2	31.0	27.3	37.7	8.0	96.0	86.1
Mwanza	74.0	41.7	12.3	1112.0	1005.0	122.1	15.4	144.7	61.9	29.5	31.2	27.8	28.9	30.7	27.2	37.4	7.6	95.0	77.1
Mzimba	142.8	80.4	16.1	1368.0	1182.0	224.6	19.8	153.6	76.1	29.2	30.6	27.9	28.7	30.2	27.3	34.9	7.4	93.3	96.9
Mzuzu City	105.0	59.1	15.1	1099.0	874.8	224.6	9.5	105.4	59.7	26.7	28.1	25.3	26.1	27.5	24.6	33.2	6.6	85.4	79.3
Neno	66.2	37.3	12.1	1088.0	968.4	122.1	14.6	144.7	60.3	29.5	31.2	27.8	28.9	30.7	27.2	37.4	7.9	95.2	74.8
Nkhata Bay	115.3	64.9	**19.0**	1581.0	1161.0	**429.6**	22.1	172.0	86.8	28.7	30.0	27.3	28.2	29.6	26.8	34.1	7.1	91.4	94.4
Nkhotakota	141.6	79.7	17.8	1523.0	**1326.0**	266.3	23.0	157.8	85.0	29.2	30.6	27.9	28.7	30.2	27.3	34.9	6.5	92.9	100.0
Nsanje	53.3	30.0	12.4	1202.0	998.3	204.3	16.5	156.4	66.5	**31.1**	**32.9**	**29.3**	**30.5**	**32.3**	**28.7**	**39.4**	7.3	99.8	76.2
Ntcheu	111.1	62.6	12.3	1088.0	968.4	120.0	14.6	148.0	60.3	29.2	30.5	27.8	28.7	30.1	27.3	35.4	7.9	93.6	84.0
Ntchisi	145.8	82.1	13.4	1099.0	1012.0	86.9	13.5	127.2	60.3	29.0	30.4	27.6	28.5	29.9	27.1	34.9	6.5	92.3	91.1

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Name	cdd_Annbsl	Cum dry days Index	cwd_ann	precip_ann	prec_summer	prec_winter	r20mm_ann	rx5day_ann	Precipitation Index	tmax_ann	tmax_Summer	tmax_Winter	tmean_ann	tmean_Summer	tmean_winter	Txx_ann	wsdi_ann	High Temperature	Climate hazard index
Phalombe	67.1	37.8	14.7	1286.0	1079.0	206.7	16.3	155.5	70.8	28.4	29.9	26.8	27.8	29.4	26.2	35.0	**8.0**	91.3	77.5
Rumphi	127.0	71.5	17.8	1221.0	1007.0	234.9	12.6	124.1	67.2	28.3	29.7	26.8	27.7	29.2	26.3	34.8	7.5	90.7	89.0
Salima	153.1	86.2	15.9	1380.0	1242.0	138.4	20.9	161.8	75.9	29.2	30.5	27.8	28.7	30.1	27.3	35.4	7.1	93.2	99.1
Thyolo	52.1	29.3	13.1	1202.0	998.3	204.3	16.5	155.8	66.5	**31.0**	**32.7**	**29.2**	**30.4**	**32.2**	**28.6**	**39.2**	7.6	99.6	75.8
Zomba	67.1	37.8	14.7	1286.0	1079.0	206.7	16.3	155.5	70.8	28.4	29.9	26.8	27.8	29.4	26.2	35.0	**8.0**	91.3	77.5
Zomba City	58.6	33.0	12.1	1028.0	935.6	93.1	13.7	136.6	56.9	28.0	29.6	26.4	27.5	29.1	25.9	34.9	7.7	90.3	69.9