Understanding responses to climate-related water scarcity in Africa

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Abstract

Water scarcity is a global challenge, yet existing responses in the Global South are failing to cope with current shocks and stressors, including those attributable to climate change. In sub-Saharan Africa, the impacts of water scarcity threaten livelihoods and wellbeing across the continent and are driving a broad range of adaptive responses. This paper describes trends of water scarcity for Africa and outlines climate impacts on key water-related sectors on foodsystems, cities, livelihoods and wellbeing, conflict and security, economies, and ecosystems. It then uses systematic review methods, including the Global Adaptation Mapping Initiative, to analyse 240 articles and identify adaptation characteristics of planned and autonomous responses to water scarcity across Africa. The most common impact drivers responded to are drought and participation variability. The most frequently identified actors responding to water scarcity include individuals or households (32%), local government (15%) and national government (15%), while the most common types of response are behavioural and cultural (30%), technological and infrastructural (27%), ecosystem-based (25%) and institutional (18%). Most planned responses target low-income communities (31%), women (20%), and indigenous communities (13%), but very few studies target migrants, ethnic minorities or those living with disabilities. There is a lack of coordination of planned adaptation at scale across all relevant sectors and regions, and lack of legal and institutional frameworks for their operation. Most responses to water scarcity are coping and autonomous responses that showed only minor adjustments to business-as-usual water practices, suggesting limited adaptation depth. Maladaptation is associated with one or more dimension of responses in almost 20% of articles. Coordinating institutional responses, carefully planned technologies, planning for projected climate risks, and integrating indigenous knowledge will help to address identified challenges of water scarcity towards more adaptive responses across Africa.

Keywords: Water scarcity; planned adaptation; autonomous adaptation; local and indigenous knowledge; Global Adaptation Mapping Initiative; Africa.

1 Introduction

Around four billion people worldwide are currently living with water shortages (Tzanakakis et al., 2020). Falkenmark et al. (1989) estimated the average (global) renewable water need per capita per year to be 1700 m^3. Countries whose renewable water supplies fall below this amount were considered as experiencing 'water stress'; between 1000 and 1700 m^3 per capita per annum, the country faces 'water deficit/shortage'; 'water scarcity' occurs when the water supplies drop below 1000 m^3 per capita per annum (Naik, 2017). In Africa, water scarcity is largely due to the unequal distribution of water (Gunasekara et al., 2014; le Blanc and Perez, 2008). For example, in Northern Africa, the annual groundwater recharge is only 144–350 m^3 per person, while other sub-regions range from 2400 to 9900 m^3, far above the average requirement for human needs (Herbert and Döll, 2019; Naik, 2017). Estimated local water requirements for food production are over 2,000m^3/person/year in sizeable parts of Africa, against an average of almost 650m^3/person/year in Europe and North America (Liu et al., 2017). Changing rainfall patterns, declines in precipitation and runoff, and increased evapotranspiration rates attributable to climate change are the most likely physical drivers of future water scarcity (Gan et al., 2016; Markonis et al., 2021): a situation that will be exacerbated by human drivers like population increase (Ahmadalipour et al., 2019).

In Africa, agriculture is the largest water-use sector, with large populations dependent on rainfed-agriculture (Busby et al., 2014; Mabhaudhi et al., 2016). Rainfall volatility currently impacts about 93% of African agriculture (Besada and Werner, 2015). Projections indicate several parts of Africa are projected to suffer prolonged droughts and increased rainfall variability by 2025 (Dosio et al., 2019; Klutse et al., 2018) and water available for agriculture and domestic use will likely experience increasing constraints to access (Grasham et al., 2019b; Matchaya et al., 2019; Singh et al., 2018). Water scarcity, therefore, has severe implications for food security and human vulnerability across the continent (Niang et al., 2014; Williams et al., 2018).

Indicators from global assessments highlight Africa's critical water scarcity challenges and the fact that the continent is the second most arid after Australia (Besada and Werner, 2015; Dos Santos et al., 2017). Rapid population growth and urbanisation have resulted in additional pressures on domestic water resources and, together with increased agricultural demand land use change, will likely remain dominant drivers of water scarcity on the continent; Africa's population is projected to double by the 2050s (Liu et al., 2017; Niang et al., 2014; Tabutin and Schoumaker, 2020). In the early 1990s, only eight African countries were estimated to be suffering from water scarcity (Naik, 2017), yet by 2017, an estimated 785 million people globally lacked access to safe and affordable water for domestic use, 40% of whom lived in Sub-Saharan Africa (SSA) (UNICEF and WHO, 2019). By 2030, about 250 million people may experience high water stress in Africa, with up to 700 million people displaced as water stress becomes locally impossible to cope with (Groth et al., 2020; Mpandeli et al., 2020; Naik, 2017).

Water scarcity has multiple dimensions of cause and effect and is further complicated by competition and trade-offs between sectors (Mpandeli et al., 2018; Rosa et al., 2020). The complexity of sector-specific risks affected by water scarcity, exemplified most clearly in the water-energy-food nexus, can create 'wicked' problems that confound the utility of trade-offs in planning responses (Nhamo et al., 2018; Romero-Lankao and Norton, 2018). Competition for water from agriculture, fishing, tourism, energy, and industries, for example, is increasing and threatening livelihood systems across Africa (Liu et al., 2017). These challenges will likely increase as demands for domestic, industrial, and agricultural water rise sharply, potentially by 40%, within the next decade (UNDESA, 2017). The integrated nature and multidimensionality of water usage demonstrates that responses to water scarcity are a critical component of effective adaptation with important co-benefits for other sectors directly or indirectly affected by water scarcity (Horne et al., 2018; Mugambiwa and Tirivangasi, 2017; Owen, 2020).

Water scarcity is a key theme for scholarship on water sector adaptive capacity (Siders, 2019). This is not surprising as responses to water scarcity can enhance or constrain development pathways affecting adaptation to climate change (Gajjar et al., 2019; Rao et al., 2019a). Yet leading empirical scholarship on adaptation lacks multi-sectoral evaluation of responses to water scarcity (Vincent and Cundill, 2021). We therefore need a broader understanding of the types and efficacy of responses in the sectors and geographies affected by water scarcity, particularly in Africa, the most affected and most exposed of the continents (Siders, 2019; Vincent and Cundill, 2021).

Based on the needs here outlined, this paper synthesises current knowledge about water scarcity in Africa, and on the variety of responses. We first calculate trends of water scarcity, highlighting what we now understand of the historical, current and projected hydrological context of water scarcity and its spatial distribution across this continent. We then contextualise these trends by providing an overview of the range of impacts that water scarcity has had on Africa's agriculture, cities, livelihoods and wellbeing, security, economies, ecosystems; sectors expected to be increasingly at risk (Field et al., 2014; IPCC, 2019b). Finally, a review of the literature identifies and assesses current responses to water scarcity in Africa. The paper concludes by identifying promising adaptation strategies from both planned and autonomous approaches to address future water scarcity. Their efficacy is evaluated in light of the need for responses to water scarcity that simultaneously reduce risk and vulnerability, develop resilient social systems, improve the environment, increase economic resources, and enhance governance and institutions (Owen, 2020).

2 Materials and methods

A mixed methods approach was used to synthesise current knowledge of trends in water scarcity in Africa, the range and types of past responses to water scarcity, and highlight promising responses to water scarcity that can inform future adaptation pathways.

First, we used the Falkenmark Water Stress Indicator to identify trends in water scarcity in Africa to show changes in population exposure through time (Falkenmark et al., 1989; Falkenmark and Rockström, 2006). We then used the EM-DAT disasters data set to identify the number of people affected by severe droughts in Africa, highlighting the geographical spread of these over the past few decades, plausibly as a result of climate warming. EM-DAT records a drought disaster if local capacity overwhelmed, necessitating a request to national or international level for external assistance caused by an extended period of unusually low precipitation that produces a shortage of water for people, animals and plants (EM-DAT and CRED, 2020) (see Supplemental Data 1).

To show current and projected trends in water scarcity, we calculated the Standardised Precipitation-Evapotranspiration Index (SPEI) for the entire continent. This is calculated over a 12-month running window from the method of Vicente-Serrano et al. (2010) where PET is calculated using the Penman-Monteith formulation recommended by the FAO (Allen et al., 1998) (See Appendix F for climate models used). All models were resampled to 0.5 degree with bilinear interpolation for ensemble comparison. Standardized precipitation evapotranspiration index (SPEI) can be modified with the actual evaporation (SPAEI). While both capture relevant features of drought (Homdee et al., 2016), SPAEI has been shown to be more meaningful in water-limited areas whereas SPEI is generally more suitable in energy-limited areas (Rehana and Monish, 2020). Most CMIP-6 models report actual evaporation (evspsblpot, a key boundary condition for the atmospheric model) whereas comparatively few models report potential evapotranspiration (evspsblpot).

To perform the qualitative analysis of responses to water scarcity, we used the Global Adaptation Mapping Initiative (GAMI) and a systematic literature review to assess evidence from the peer-reviewed literature about Africa between 2013 and July 2020. GAMI provides a global stocktake of human adaptation-related responses to climate-related changes that were documented in the peer-reviewed literature between July 2013 and Jan 2020 (Berrang-Ford et al., 2020). It used bibliographic databases including Scopus, PubMed, Web of Science Core Collection, and Google Scholar to assess 48,316 scientific documents on adaptation published within this period (Berrang-Ford et al., 2020). GAMI combined a novel typology for assessing empirical research documenting human adaptation globally with systematic-review and machine-learning approaches to identify and synthesize 1,682 articles (Berrang-Ford et al., 2020). The breadth of GAMI's stocktake is unmatched in terms of quantity of articles identified, screened and coded, highlighting its potential value to capture the breadth of the vast literature on adaptation on Africa (Fischer et al., 2020; Lesnikowski et al., 2020). After Asia (34%), Africa recorded the second highest number of adaptation articles identified by GAMI, accounting for 32% of the total GAMI database (Berrang-Ford et al., in review). Further, 34% of GAMI articles concerning Africa included evidence of risk reduction, indicating the potential utility of the data set for assessment and pathway development (Lesnikowski et al., 2020). It identified 518 articles indicating adaptation actions in Africa (Fischer et al., 2020; Lesnikowski et al., 2020), from which we extracted a sub-set of 151 articles, selecting those articles tagged as 'Africa' and 'responses to drought' OR 'responses to water scarcity' for synthesis of evidence on responses to water scarcity from all sectors covered by GAMI: namely water and sanitation; poverty, livelihoods, and sustainable development; food, fibre, and other ecosystem products; cities, settlements, and key infrastructure; health, well-being, and communities; ocean and coastal ecosystems; terrestrial and freshwater ecosystems (Siders et al., 2020).

A further review of the literature identified responses to water scarcity that were excluded by the climate change and water sector focus of GAMI to capture broader responses to water scarcity including those associated with governance or tourism sectors. Peer-reviewed articles were identified through Web of Science, Google Scholar and Scopus between January 2013 and July 2020 using the following search string: Topic=(water AND Africa), Abstract=(drought AND response OR adapt*), Topic=(adapt*), Region=(Africa), Country=("Country_Name(s)"). The review included publications written in English and excluded non-human responses to water scarcity. It identified 280 articles which were then screened to leave 138 articles. These articles were combined with the GAMI articles. Articles with less than one paragraph about response and 49 duplicates were excluded to give a total of 240 articles for review (see Supplementary Data 2).

Articles were then assessed for their content on responses to water scarcity considering the geographic focus, inclusion of local knowledge and indigenous knowledge, who is responding, what responses are documented, what is the extent of the adaptation-related responses, and whether or not responses are reducing risk? (see Appendix A for detailed coding instructions and definitions and Appendix B for categories of types responses to water stress in Africa used in the analysis). Special attention was given to articles indicting adaptation that explicitly confronts inequality, injustice and inequitable power dynamics in responses to water scarcity (Owen, 2020).

It is difficult to know whether absence of adaptation reporting reflects a lack of adaptation activities or a lack of reporting in the peer-reviewed literature (Berrang-Ford et al., 2019; Biesbroek et al., 2018; Williams et al., 2021). The dominance of English-language publications favours anglophone Africa in the GAMI database. Despite such limitations, the focus on peer-reviewed literature aligns with the assessment needs of large climate and water assessments such as those of the IPCC that make judgements based on scientific consensus, making their findings easily translatable for policy and practice.

3 Results

We first present an overview of trends of water scarcity, highlighting the historical, current and projected hydrological context of water scarcity and its spatial distribution across in Africa. We then provide an overview of the range of impacts that water scarcity has had on Africa's sectors increasingly at risk from water scarcity. Then, we present the results of a review of the literature to identify and assesses the range of responses to water scarcity in Africa.

3.1 Water scarcity in Africa

Population growth is the dominant factor affecting water availability when computed using the Falkenmark Index. Localized population growth in northern South Africa, around Lake Victoria, in Ethiopia, and in many parts of west Africa has caused category changes in water availability that have exposed a growing number of people to both scarcity and absolute scarcity (Fig. 1).

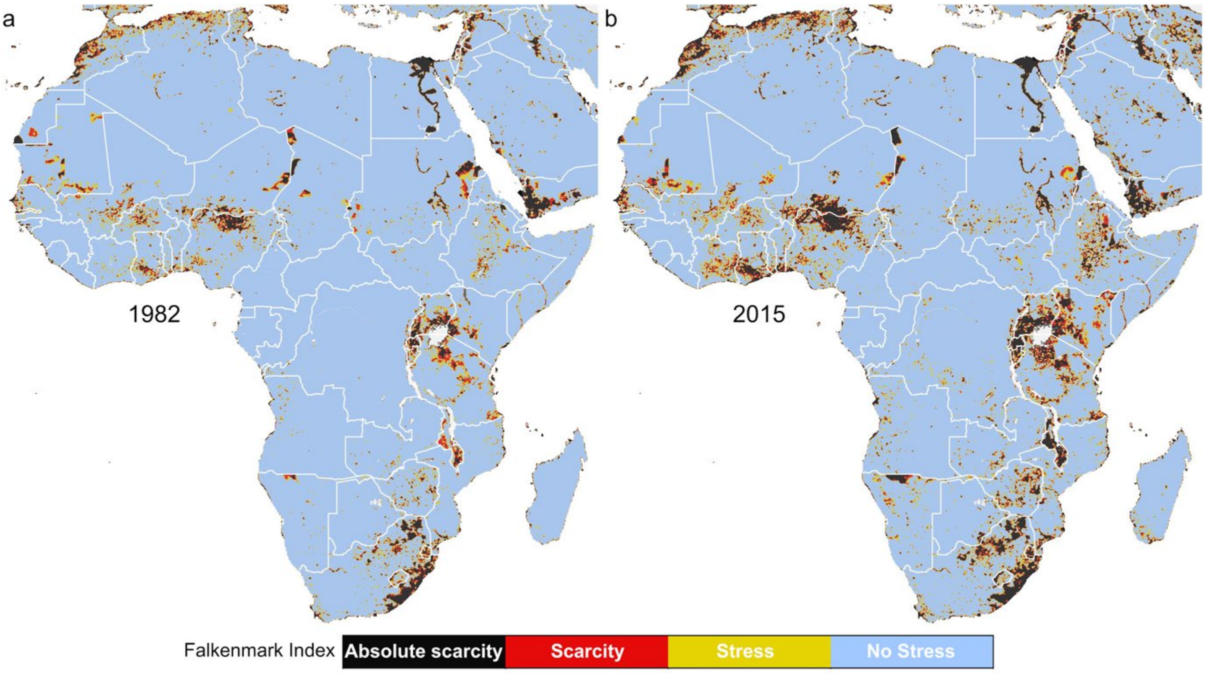

Figure 1: Population exposure to water stress in **Africa.** Recent changes in the Falkenmark Index over Africa (Falkenmark et al., 1989). Total surface and subsurface water flow taken from the NASA FLDAS model (McNally et al., 2017) and population estimates taken from the JRC's Global Human Settlement Layer (Clark et al., 2016).

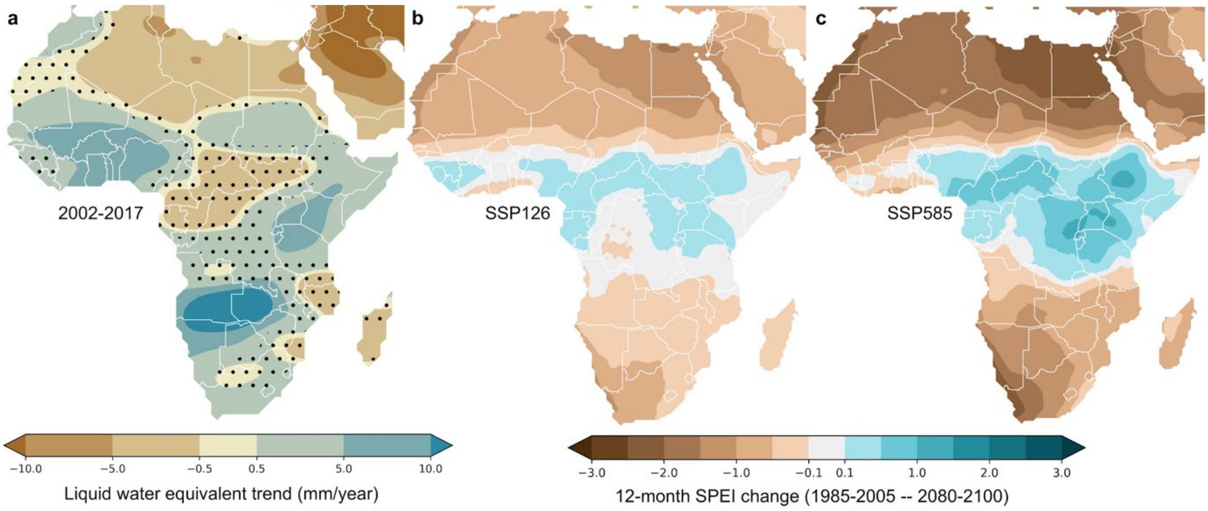

Figure 2: Recent mean drying/wetting trends in Africa and projected future changes in meteorological drought. (a) liquid water equivalent trends based on GRACE (Swenson, 2012) satellite observations (gravitational anomalies). Stippling indicates no significant trend (p0.05). (b-c) Projected changes in the 12-month Standardised Precipitation-Evapotranspiration Index (SPEI) from 23 CMIP6 models (Eyring et al. 2016) comparing 1985-2005 to 2080-2099 for (b) SSP126 and (c) SSP585 (O'Neill et al., 2016) (See also, Fig. D.1 for projected changes in mean atmospheric water balance, and Fig. A.1 for model agreement on wetting under SSP585). Decrease in SPEI indicates more drought susceptibility.

Extreme droughts and heatwaves, both of which are projected to intensify under climate change, can decrease crop production due to more variable rainfall and soil moisture

(D'Odorico et al., 2018). For example, declining trends in rainfall in some regions of North Africa are projected to continue in a warming world (Seif-Ennasr et al., 2016). This trend restricts groundwater recharge, exacerbates groundwater salinization and groundwater depletion (Hamed et al., 2018), and increases the risk of reduced soil moisture (Petrova et al., 2018). Figure 3 illustrates significant wetting trends that have been observed in parts of Central East Africa, West Africa and southern Angola, and Zambia and significant drying trends. Future climate change will exacerbate drought susceptibility for most of Africa, with more CO_2 plausibly aggravating the impact. Strong increases in precipitation under warming, especially near the equator, reduce drought risk for a narrow band of latitudes but does not outweigh the increased potential evapotranspiration under warming for much of the continent. Even strong mitigation measures (SSP126) are projected to lead to mild increases in drought susceptibility for much of Africa.

Elevated CO_2 increases the occurrence of extreme wet years and extreme dry years in climate models where general wetting trends are projected. In Central Ethiopia for example (Figure 3, panel a), CO_2 forcing drives a mean increase in SPEI (Figure 2, panel c). Yet drought severity also increases; the number of months below -1.5 tripling in the last 50 years of the time series compared to the first 50 years. This will likely have an impact on the severity of water scarcity extremes as drought magnitude of -2 or greater was not observed at this location in the historical simulation but appears 10 times in the second half of the century in this climate model realization.

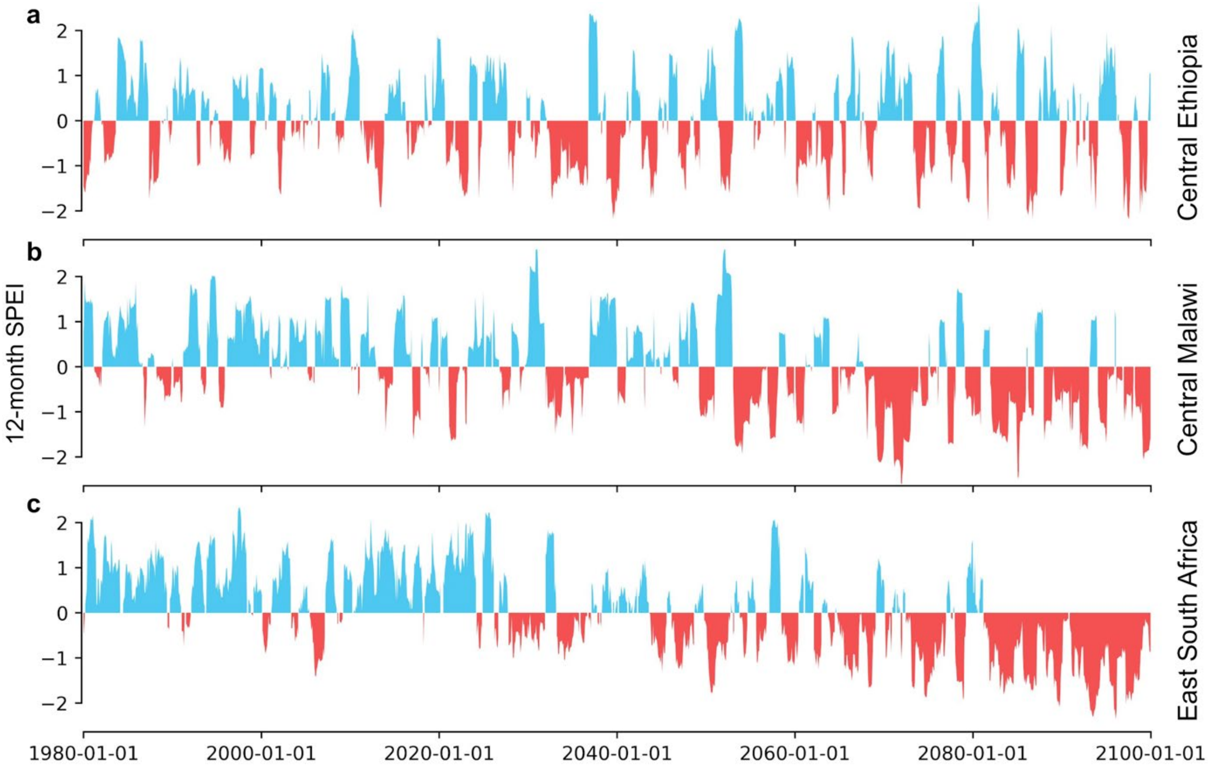

Figure 3: Projected changes in extremes - meteorological drought progression across selected locations for high-end climate change (SSP585). 12-month SPEI across 3 selected grid cells for the ACCESS-CM2 climate model.

Other areas are projected to see little increase in mean precipitation and to experience stronger drought trends. Permanent or near permanent meteorological drought develops around the end of the century as you move away from the equator. This behaviour of extremes is generally consistent across climate models (see Appendix F, Fig. F.1-5 for more climate model examples).

3.2 Sectoral impacts of water scarcity in Africa

Here we briefly outline the impacts of water scarcity foodsystems, cities, livelihoods and wellbeing, security economies and ecosystems. The vignettes of impacts of water scarcity on these key sectors contextualise the detailed section on responses identified in the systematic review and presented thereafter. Figure 4 presents an overview of the population affected by national level drought disasters in Africa 2000-2020.

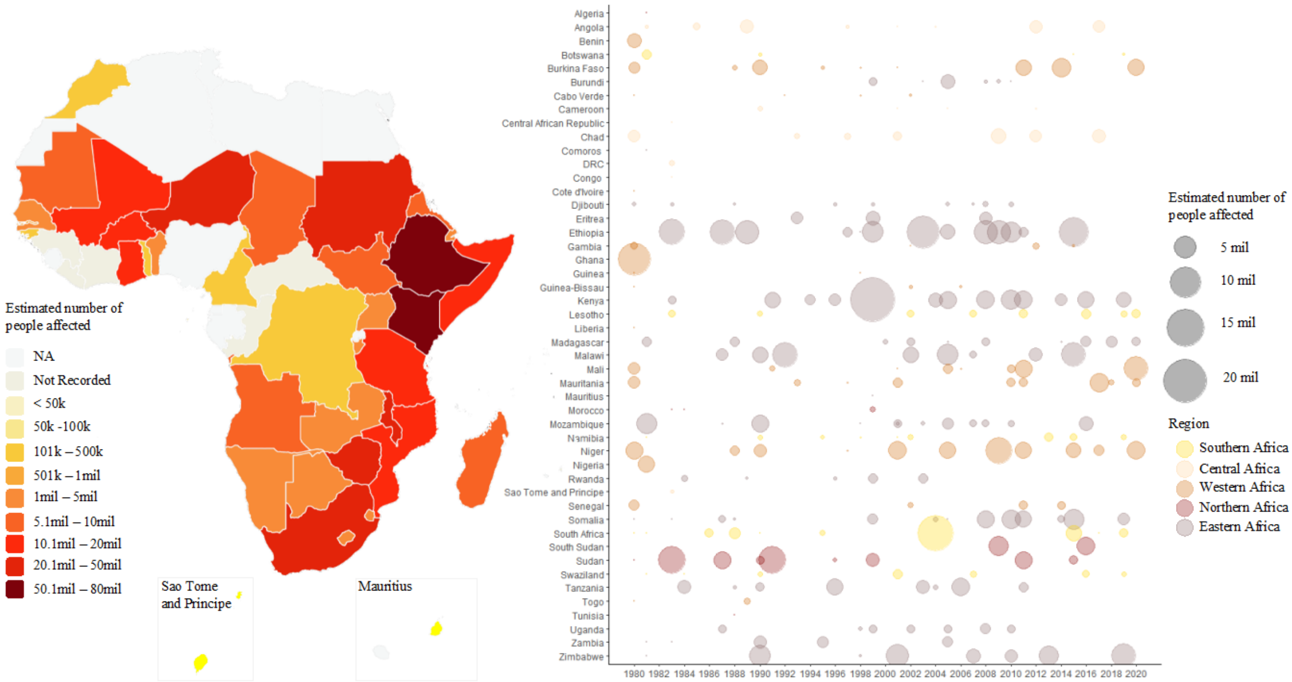

Figure 4: Population affected by national level drought disasters in Africa 2000-2020 (EM-DAT and CRED, 2020).

Although it is difficult to directly estimate the social and economic impact of droughts (Enenkel et al., 2020), the EM-DAT database on natural disasters estimates that over 256.3 million people were affected by severe drought in Africa between 2000 and 2020 (EM-DAT and CRED, 2020, see Supplementary Data 1). Although accounting for only 11% of frequency of natural hazard events within this time period, droughts caused 46% of all deaths – the most attributed to a single natural disaster type in Africa (EM-DAT and CRED, 2020).

3.2.1 Impact of water scarcity on foodsystems

Agriculture is the largest water-use sector in Africa and globally (D'Odorico et al., 2020). Water withdrawal for agriculture accounts for at least 60% of total water use in a majority of African economies, with 10 countries exceeding 90% (FAO and AQUASTAT, 1999). Agriculture is dominated by rainfed crops, making Africa economies particularly vulnerable to hydrological anomalies (FAO, 2018; FAO and ECA, 2018; FAO, 2020). Farmers are already feeling the effects of climate change on crop production through changes in precipitation variability (Kouressy et al., 2019; Sultan et al., 2019) and livestock fodder availability (Sloat et al., 2018; Stanimirova et al., 2019). For example, two thirds of farmers surveyed in Nigeria correctly noted a reduction in (and delayed onset of) early growing season rainfall and identified this as a major cause of yield losses in recent years (Ayanlade, 2016; Ayanlade and Ojebisi, 2020). Unreliable rainfall and prolonged drought have caused severe shocks to productivity in the

Maradi Region of Niger, significantly affecting the agro-pastoralist communities' livelihoods (Ado et al., 2019). Pastoralists are also perceiving changes in water availability and report more erratic, reduced rainfall and more frequent, prolonged droughts (Kimaro et al., 2018; Sanogo et al., 2017).

3.2.2 Impact of water scarcity on cities

Urban water supplies are unsafe and intermittent across the continent. Urban households experience chronic shortages in drinking water and frequent water rationing, with unplanned/informal urban settlements receiving less water than planned ones (Abubakar and Zumla, 2018). Few peer-reviewed studies on drought risks for urban dwellers have been carried out in Sub-Saharan Africa (Grasham et al., 2019a). Yet, a common proxy for low water quality can be seen in human health indicators such as cholera. Although cholera is usually associated with rainfall, it is also widely experienced during periods of droughts when water is collected from substantially contaminated ponds and streams (Grasham et al., 2019a). Given such contextual exposures and vulnerabilities, water scarcity in Africa needs to be understood within broader social and developmental contexts. Further, a lack of effective water delivery, especially under shock or stress conditions (Simpson, 2019; Simpson et al., 2019b), has led scholars to indicate management and governance failures as a leading causes of water scarcity (Muller, 2019; Rugemalila and Gibbs, 2015).

3.2.3 Impact of water scarcity on livelihoods and wellbeing

There is growing evidence suggesting that drivers of vulnerability to water scarcity include non-climatic drivers, such as age, income, and gender (Grasham et al., 2019a). Social capital, poverty, and gender depress women's agency and pathways to overcome water scarcity in rural areas (Pearson et al., 2015), particularly when household structures and social norms entrench patriarchal arrangements such as those of title and tenure (Rao et al., 2019b). As men are more likely to migrate away from water-scarce regions, women are often left behind without an adequately supportive social infrastructure (Rao et al., 2019b). The burden of water scarcity is felt hardest by the primary water collector in rural and urban contexts (Grasham et al., 2019a). For such reasons, water scarcity responses need to go beyond supply, technological, planning and management imperatives (Muller, 2019; Scheba and Millington, 2019; Vanham et al., 2018) to also consider their social capital, institutional, livelihoods and wellbeing dimensions (Nhamo and Agyepong, 2019; Ouweneel et al., 2020; Petrie, 2017; Simpson et al., 2020; Simpson et al., 2019c; Ziolkowska, 2016).

3.2.4 Impact of water scarcity on conflict and security

Many studies highlight a possible relationship between temperature, water scarcity and societal conflicts within Africa, manifesting as antisocial behaviour and violence (Chitonge, 2020; Gleick and Heberger, 2014; Regan and Kim, 2020). Water conflicts have increased among different sectors and users: agriculture, energy production, urban consumption, conservation, pastoralism and wildlife (Almer et al., 2017; Liu et al., 2017). The rise of social tensions in many dryland countries of Sub-Saharan Africa in recent decades has also led scholars to suspect a likely causal relation with environmental changes (Okpara et al., 2015; Selby and Hoffmann, 2014a; Selby and Hoffmann, 2014b). For instance, Lake Chad's shrinking (around 90% since the 1960s) has increased water and food insecurity, creating conditions for social conflicts and insecurity (Okpara et al., 2015). Similarly, in 2012, more than 100 Kenyans died in violence arising from water conflicts involving farmers and pastoralists (Gleick and Heberger, 2014). Warming trends since 1980 have elevated conflict risk in Sub-Saharan Africa by 11% (Carleton and Hsiang, 2016), and climate change may increase conflict risk across the region by 54% by 2030 (Burke et al., 2014).

3.2.5 Impact of water scarcity on economies

Water scarcity leads to increasing water costs per unit, affecting water access (Abubakar, 2019; Rusca and Schwartz, 2016). In addition, it is projected that high variability in Africa’s water basins could reduce hydropower revenue ranging between 5% and 60% by 2050 (Cervigni et al., 2015). This variability will amount to a projected three-fold increase in consumer expenditure for energy due to the dwindling production of hydropower (Cervigni et al., 2015). Revenues from the agricultural output are also projected to decrease by 10% to 20% by 2050, as irrigation capacity falls (Cervigni et al., 2015). These projections highlight the potential severity of the risk to economies and livelihoods in Africa from water scarcity.

3.2.6 Impact of water scarcity on ecosystems

Population growth has placed additional pressure on African ecosystems over the past century, with severe degradation in several countries (UNDP-UNEP, 2011). Unplanned and uncontrolled cropland expansion, cattle grazing, urbanization, and ineffective water management plans have severely degraded the natural landscapes and rivers within the Lake Victoria Basin, for example; biodiversity loss and water pollution have received most attention here (Hecky et al., 2010). A 57% increase in the irrigated agricultural sector has also resulted in a significant decrease in natural forests in south-eastern Africa and grasslands in eastern regions and the Sahel (Brink and Eva, 2009), which has had cascading effects for hundreds of millions of Africans who rely directly on ecosystem services to meet their essential needs.

3.3 Responses to water scarcity in Africa

The results of the systematic review of the evidence of human responses to water scarcity in Africa are presented below. First, the actors, targets and types of response to water scarcity are presented, highlighting the key actors and specific actions. A deeper analysis of response types is then provided in the following section examining the extent, depth, scope, speed and efficacy of types of response to water scarcity (see Appendix A for definitions). Finally, different types of responses to water scarcity are evaluated by presenting the evidence of risk reduction or maladaptation associated with each response type.

3.3.1 Distribution and types of response to water scarcity

Of 55 African countries, 33 (60%) have studies reporting on human adaptation strategies for coping with water scarcity; the most common are those involving responses to climate impact drivers, with drought and precipitation variability being the next most common. The leading 10 African countries with studies on human responses to water scarcity are Kenya, Tanzania, Ethiopia, South Africa, Niger, Uganda, Ghana, Malawi, Zimbabwe and Nigeria in that order. This trend aligns with the geographical distribution of adaptation scholarship in Africa noted elsewhere and is therefore more a function of active research than the proportional number of responses to water scarcity (Vincent and Cundill, 2021); 23 African countries have fewer than two articles identified here[i]. Actors responding to water scarcity are individuals or households (32%), local government (15%), national government (15%), civil society (sub-national 10%, national 8%), international or multinational governance institution (6%), sub-national governments (5%), other[ii] (5%) and private sector (3%).

Most planned responses to water scarcity target low-income communities (31%) with particular emphases on the most vulnerable within communities, such as women (20%), indigenous (13%), elderly (5%) and youth (5%). Many activities focus on coping strategies and sustaining living conditions such as food, shelter, and other livelihood activities. Very few studies target migrants, ethnic minorities or those living with disabilities.

Documented response types include behavioural and cultural (30%), technological and infrastructural (27%), ecosystem-based (25%) and institutional (18%). Behavioural and cultural responses mostly focus on subsistence and semi-subsistence farmers and the consequences of water scarcity on crop failure or livestock death, with livelihood diversification and migration a common response (for example, Schofield and Gubbels, 2019). Technological and infrastructural responses focus mainly on ways to access and conserve water (Bizikova et al., 2015), enhance farm productivity, and improve drought resilience of crops and animals (for example, Bedelian and Ogutu, 2017). Ecosystem-based responses include working with native species to protect soil, stabilize banks, protect against wind and fluvial erosion (for example, Kupika et al., 2019), and clear invasive species that destabilize ecosystems (for example, Richter et al., 2017).

Water management commonly includes forms of mulching that maintain in situ vegetative residues (for example, Feleke et al., 2016; Gebru et al., 2019). Institutional responses cover a variety of actions including: disaster management for droughts (and floods), water and groundwater management, increasing dam reservoir water storage, early warning systems, crops, food and seed storage systems, soil and crop research, water-user associations, water tariffs, water demand management policy, integrated coastal zone management, and the incorporation of risk reduction into development planning or zoning schemes (for example, Lesnikowski et al., 2013; Siders, 2019). Articles linking responses to water scarcity which concentrate on a particularly exposed or vulnerable developmental goal in Africa include food security (22%), poverty (17%), clean water and sanitation (12%), consumption and production (8%), health and wellbeing (8%), work and economic growth (8%), sustainable cities and ecosystem services (7%).

3.3.2 Scope and efficacy of types of response to water scarcity

Only 10% of planned water scarcity adaptation efforts have been implemented widely. Approximately 90% of the responses identified in the literature lack consistent coordination for implementation at scale across all relevant sectors and regions affected by water scarcity, and lack legal and institutional frameworks for their operation (Siders, 2019; Vincent et al., 2020; Ziervogel et al., 2019). This trend has many implications, one of which is that it undermines the role of agroforestry in building livelihood resilience to drought in many semiarid areas, as seen in Kenya (Quandt et al., 2017). A lack of coordination is particularly clear from the inconsistent engagement and acknowledgement of local and indigenous knowledge and practices which has led to inconsistent integration of these with formal risk reduction and adaptation strategies (Grey et al., 2020).

Almost 20% of responses are still in the early ‘planning or vulnerability assessment phase’, indicating that there has been limited coordinated implementation or only local ad-hoc implementation. For example, building an indigenous agropastoral adaptation framework to climate change in the North West Region of Cameroon (Azibo and Kimengsi, 2015), or ad-hoc uptake of rain water harvesting and saving technologies in Tharaka South, Eastern Kenya (Muriu-Ng’ang’a et al., 2017). Almost half the responses (47%) are in ‘the planning and early implementation phase’ in which there is widespread recognition among decision-makers of the need for response measures and there is evidence of at least some coordinated implementation, though measures are commonly still ad-hoc in their nature. For example, soil and water conservation in western Africa (Sietz and Van Dijk, 2015), recognition of the need to advance beyond coping responses to drought in The Gambia (Yaffa, 2013), and ad-hoc uptake of conservation farming across the continent (Ahmed, 2016; Kpadonou et al., 2017; Olaniyan, 2017; Swanepoel et al., 2018). Fewer than one fifth of responses (19%) demonstrate ‘expanding’ implementation where there is evidence that adaptation has become mainstreamed into decision-making processes and that responses demonstrate coordination and are as part of a coherent response strategy. Examples of expanding responses include integrated landscape restoration practices and rainwater harvesting and management in arid and semi-arid areas of Ethiopia (Woldearegay et al., 2018), and early warning systems of drought in East Africa (Funk et al., 2017; Nahayo et al., 2017; Zake and Hauser, 2014)

Most articles (73%) reported coping and autonomous responses that showed only minor adjustments to business-as-usual water practices, suggesting limited adaptation depth (for example, Azibo and Kimengsi, 2015). Business-as-usual coping and autonomous responses risk falling short of the IPCC definition of adaptation (IPCC, 2019a), instead respond to water scarcity in the short to medium term without planning explicitly for current and projected risks from climate change such as community managed storage and irrigation systems in Tunisia and Ethiopia (Alemayehu and Bewket, 2017; Ferchichi et al., 2017b), and reactive destocking and migration in Chad (Okpara et al., 2016).

One quarter of articles (25%) identified responses indicating ‘medium depth’ adaptation capacity, such as the expansion of existing practices rather than the development of entirely new practices: for example, replacement of traditional seed distribution systems in community seed fairs in Kenya which safeguard and promote local seed varieties better suited to the local climate (Amaru and Chhetri, 2013). Only 2% displayed high depth adaptation capacity: for example, observable transformation in response type from trial and error to a well-planned and participatory approaches, transition from soil and water conservation to water harvesting, extensions from small-scale to large-scale and landscape-level interventions, scaling from individual or isolated technologies to integrated and linked approach with technologies proven to be effective and climate-smart, and greater nuance in moving from blanket approaches to contextualised technology selection and implementation (for example, Amaru and Chhetri, 2013; Chisadza et al., 2013; Goulden et al., 2013; Woldearegay et al., 2018).

Most studies (71%) report limited scope for adaptation responses and are confined to local areas, such as a town, city or suburb, a catchment, or a handful of local communities within a confined sector, such as agropastoralists (for example, Kassian et al., 2016). A common relationship also exists between actions with limited scope and the use of local and indigenous knowledge (for example, Mashizha, 2019). For adaptation actions with 'medium scope', studies indicate that the ability to scale is contingent on the role of the State and the degree of its engagement with local actors (El Jihad, 2016). Only 3% of articles indicated adaptation actions with broad scope – that is, responses are implemented at a large scale and result in system-wide changes that might involve an entire organization, a country or large region, and a large population. In these cases, local knowledge is noted to be component to successfully scale to a broader scope (Dobson et al., 2015; Sietz and Van Dijk, 2015).

93% of adaptation actions indicate 'slow' and 'incremental change', emphasizing the generally slow pace of behavioural and cultural determinants of change, a trend also seen in urban areas (for example, England et al., 2018). Medium and high-speed responses are commonly top-down and include the development of infrastructure or institutional and governance reforms with ambitious goals like altering water-use behaviours through changes in the water tariff model (for example, Ouweneel et al., 2020; Simpson et al., 2019c).

3.3.3 Risk reduction and maladaptation of responses to water scarcity

61% of studies found that the responses to water scarcity reduced risk while about one third (35%) either showed no evidence or did not report on risk reduction. By linking knowledge of the local specifications of these drivers to regional and global patterns of vulnerability, our understanding of land-based adaptation could be significantly enhanced. In Chen and Davis (2014) for example, the rehabilitation of the ancient cascade water supply scheme increased both water availability and sustainability of water supply, highlighting the critical roles that local and indigenous knowledges can play in reducing contemporary risk. In general, the contextualised integration of scientific, technological and local knowledge is seen as the most effective means of risk reduction (for example, Ojoyi Mercy and Mwenge Kahinda, 2015; Opare, 2018; Quandt et al., 2017).

Almost one fifth (19%) of articles identified maladaptation associated with one or more dimensions of responses to water scarcity. Types of maladaptation in Africa are often related to environmental degradation, developmental challenges and systemic vulnerability (Antwi-Agyei et al., 2018; Magnan et al., 2016). Many autonomous actions are not consistent with (outmoded) governance and institutional frameworks, leading some actions to conflict with legal and governance directives (for example, Kassian et al., 2016; Matchaya et al., 2019; Ziervogel et al., 2019).

Migration responses to water scarcity in arid and semi-arid regions are associated with conflict and growing insecurity in receiving communities, increasingly gendered water access, increased divorce rates, and a loss of solidarity and skills (for example, Abubakar, 2019; Ngarava et al., 2019; Rao et al., 2019b). Water management responses have also been linked with unintended consequences of insecurity and conflict (for example, Okpara et al., 2015; Powell et al., 2017). Modification of food consumption to deal with drought-induced harvest losses can cause serious productivity, health and physical and mental development problems, especially in young children (for example, Godsmark et al., 2019; Yaffa, 2013). Increased access to groundwater through new technologies have often been associated with the depletion of groundwater (Comte et al., 2016; Ferchichi et al., 2017b; Houéménou et al., 2020). Unequal access to groundwater subsequently exacerbates disparities between farmers and affects their capacity to cope with water scarcity (Ferchichi et al., 2017a). Efforts to reduce poverty can also undermine other gains: for example, in Botswana owning fishnets strongly suggests a non-farm adaptation strategy, yet such a strategy can lead to overfishing (Nkuba et al., 2019).

4 Discussion

The following discussion reflects on our analysis of the literature and highlights the strengths and weaknesses of both ongoing and planned responses to water scarcity in Africa (see Appendix C for overview of examples of local responses to water scarcity in Africa). Then we synthesize and reflect upon the efficacy of identified responses highlighting, wherever relevant, their contributions to reducing risk and vulnerability, developing resilient social systems, environmental improvement, increasing economic activities and enhancing governance and institutions.

4.1 Planned adaptation to water scarcity

Africa showcases a range of global best-practice examples of water planning and management: for example, the urban wastewater management in Windhoek, Namibia (van Rensburg, 2016) and the growing distribution of drought-tolerant maize varieties in Kenya (Simtowe et al., 2020). Public investment in water infrastructure in Africa has generally favoured capital-intensive and infrastructure-focused projects, especially those aligned with high-profile political objectives, rather than (also) addressing governance and the root institutional causes of water mismanagement (Crow-Miller et al., 2017). As elsewhere in the world, common responses to water scarcity in Africa have traditionally involved building large dams with supply volume calculations guided by historical records of hydrological flow, projected consumption needs, and population growth (Muller, 2019; Tzanakakis et al., 2020). Yet, it is increasingly recognised that this approach is no longer sufficient to address current and projected water scarcity and may, in some instances, reduce water availability in particular areas instead of increasing it (Muller, 2020; Regan and Kim, 2020). Thus, design for supply needs to now incorporate interannual climate variability and longer-term projections of climate change and climate extremes (Jump et al., 2017; Schewe et al., 2019). For example, the informed planning for water resource management infrastructure on Benin's Ouémé River (Lawin and Tamini, 2019).

Questions about the appropriateness and environmental impact of large dams have led to their justification on novel grounds such as energy sovereignty, as demonstrated by Ethiopia's Grand Renaissance Dam and Tanzania's planned Rufiji Hydro project (Roussi, 2019; Siderius et al., 2021; Warner et al., 2019). These new perspectives are potentially compromising the goals of (transboundary) risk reduction, environmental, governance and vulnerability imperatives of effective adaptation as water planning is subordinated to political and national energy interests. As a consequence, water infrastructure managers face the challenge of re-negotiating political objectives while meeting both the material and organizational challenges of water supply and service delivery within a context of growing risk and scarcity (Cervigni et al., 2017; Lempert et al., 2015; Muller, 2020; Padowski et al., 2016; Sridharan et al., 2019). Governance and institutional challenges to planning for water scarcity are further compounded by of the few instances of participation of end-users and inclusion of broader stakeholders in centralised water planning and decision-making across the continent (Cornforth et al., 2021; Hellberg, 2019; Rugemalila and Gibbs, 2015; Taylor et al., 2021).

Global studies of agriculture have quantitatively demonstrated that efficient irrigation and soil management, water harvesting and storage, infrastructure improvements, crop management, and removal of alien invasive vegetation can all increase water use efficiency and enhance water availability during times of particular scarcity (Richter et al., 2017). In Africa, efforts to sustain agricultural production include expanding groundwater-fed irrigation, something that is historically common to North Africa (Kuper et al., 2017) and southern Africa (Cobbing and Hiller, 2019). Irrigation is used to counter crop losses through evapotranspiration and achieve maximum production in a particular growing environment (Ambika and Mishra, 2020; Mancosu et al., 2015). Nevertheless, intensive groundwater withdrawals to address acute water scarcity may increase the risk of groundwater depletion (de Graaf et al., 2019) and amplify the threat of saline intrusion in coastline areas from sea-level rise (Hamed et al., 2018; Ouhamdouch et al., 2019).

Infrastructural responses to future water scarcity, based on lessons learnt during the 2015-2018 Cape Town drought, have been developed and include investments in treated effluent systems (Kaiser and Eberhard, 2019). Wastewater reuse is now increasingly being recognised as a viable and appropriate measure for urban areas (CoCT, 2019; Currie et al., 2017; Drangert and Sharatchandra, 2017; Nagara et al., 2015). Recycling treated wastewater is prominent in the City of Cape Town's new Water Strategy as the city seeks to become a 'water sensitive city' by 2040 (CoCT, 2019; Kaiser and Eberhard, 2019). Cape Town's Water Strategy further includes desalination plants, water recycling, and adjustments in groundwater extraction to decrease redundancy in the water supply systems (Taing et al., 2019).

During Cape Town's worst drought on record (2015-2018), centrally-governed behavioural changes and a highly effective communications programme were credited for saving this city of four million people from running dry, by reducing water-usage by more than half (Madonsela et al., 2019). The city's average daily consumption dropped from approximately 1,200 million litres (ML) in 2015 to just 500 ML in 2018 (Muller, 2019; Taing et al., 2019). Restricting agricultural water use was supported by a range of government measures (such as punitive charges for high domestic water users) that were implemented to ensure compliance with the general need to significantly reduce consumption (Ouweneel et al., 2020). The Cape Town municipality also improved water infrastructure and management, monitoring, education, and communication (Rodina, 2019a; Rodina, 2019b). This integrated approach with both technological oriented actions and water governance system are adjudged as having been highly effective in promoting water conservation and dealing with extreme water scarcity.

4.2 Autonomous and informal responses to water scarcity

Most articles (73%) identified here report coping and autonomous adaptation actions that show little change from business as usual responses to water scarcity (for example, Azibo and Kimengsi, 2015).

Farming practices responding to water scarcity increasingly include the adoption of drought-tolerant crops that use less water and thereby mitigate against both water scarcity and food insecurity (Berhane, 2018; Hadebe et al., 2017; Mbogo et al., 2014). A recent success story highlights the potential for scaling-up the use of drought-tolerant maize varieties in Kenya (Simtowe et al., 2020). Conservation or regenerative agriculture can also improve infiltration and soil moisture retention through mulching and no-tillage approaches (Lal, 2015), which have seen a rapid uptake in Zimbabwe, Zambia, and Ethiopia (Rockström and Falkenmark, 2015) and extension most other SSA countries (Chomba et al., 2020).

Approaches that enhance soil moisture content are particularly important as most agriculture in Sub-Saharan Africa depends on moisture held in the soil (Rockström and Falkenmark, 2015). Collecting runoff, improving the infiltration, and managing land, water and crops across watersheds increases moisture from rain held in the soil (Bedeke et al., 2019; Leal Filho and de Trincheria Gomez, 2018a). Terracing such as Fanya-Juu terraces of Machakos, Kenya, and conservation tillage improves soil moisture retention, while rainwater harvesting tanks and other sub-surface storage types can improve small-scale agricultural productivity and resilience to drought (Bedeke et al., 2019; Leal Filho and de Trincheria Gomez, 2018a).

In Ethiopia's Tigray Region, indigenous water strategies such as percolation pits and ponds, check-dams, and deep trenched bunds have been successful at landscape restoration indicating their potential for larger scale environmental outcomes (Woldearegay et al., 2018). For arid and semi-arid areas of Kenya, sand dams have been used to augment subsoil rainwater storage for dryland agroecosystems. They support consistently higher vegetation biomass rates with vegetation able to recover more quickly after drought and enhancing resilience (Ryan and Elsner, 2016).

These rural responses include a range of local innovations and adoption of new technologies which align with customary responses (Apraku et al., 2018). Responses informed by local and indigenous knowledge (LIK) include early warning systems predicting seasons (Jiri et al., 2015; Nkomwa et al., 2014), rainwater harvesting practices (Makate, 2019; Mapfumo et al., 2016), stockpiling of grains, conservation farming practices like dry planting (Grey et al., 2020), as well as traditional preservation of food through sun drying, smoking and salting (Kamwendo and Kamwendo, 2014; Mugambiwa, 2018). Yet very little is known of the role LIK plays in urban responses to water stress (Mapunda et al., 2018) nor the adaptation limits of such practices, given the need to integrate projected risks with historically-informed LIK (Kettle et al., 2014).

Especially over the past few decades, as rural-to-urban migration rates have increased throughout Africa, the challenge of providing sufficient clean water to urban populations has increased sharply (Chitonge, 2020). The challenge is multidimensional and affected by both climate change and local developmental challenges such as governance, infrastructure development, finance, planning and management, which in turn affect the equitable access to water resources (Ahmed et al., 2016). Consequently, many African cities have a large informal water supply sector, particularly in peri-urban areas (Mapunda et al., 2018).

When considering autonomous responses to water scarcity, it is important to consider the range of both public and private actors and their variable adaptive capacities. Responses to the Cape Town drought (2015-2018) led to unprecedented uptake of greywater systems, rainwater harvesting tanks and boreholes to secure residents' water requirements (Simpson et al., 2019a; Simpson et al., 2020). These off-grid and autonomous strategies to secure household-level water supply transformed many water-access arrangements and the associated governance and tariff structure, undermining the municipality's financial sustainability (Ouweneel et al., 2020; Simpson et al., 2019c). The fight against future water scarcity in Africa will likely see further contestation between models of public and private water delivery. For those technologies which allow for decentralization and off-grid responses to water scarcity, the partial and gated nature of elite responses are likely to challenge centralized water distribution and governance arrangements (Simpson et al., 2019a). While municipalities or utilities need to recognize autonomous actors and their responses in the fight against water scarcity, planned responses need to accommodate and coordinate with their efforts in order to appropriately align private water supplier capacities with broader societal needs (Leal Filho et al., 2019).

This paper has some limitations. Firstly, it looked at the overall framework of water scarcity I Africa, without going deep into the sub-regional differences across the continent. Secondly, whereas it paid attention to the impacts of water scarcity in agriculture, it did not exam the consequences to crop varieties. Despite these constraints, the paper offers a comprehensive overview of the issues surrounding water scarcity in Africa, and draws attention to some of the issues which need to be considered, in order to systematically address it.

5 Conclusion

Water scarcity challenges in Africa are exacerbated by rapid population growth, widespread poverty, inequitable access, climate change, and a generally low capacity to develop and manage adequate water infrastructure. These challenges are multidimensional, with significant implications for the agricultural, human development, socio-economic, and ecosystem outcomes. Accounting for more than 80% of water use, it is especially important to address water scarcity in Africa's agricultural sector as it negatively influences food security and threatens millions of people's livelihoods. Yet responses in the literature have also displayed the importance of inter-sectoral and multi-level understanding of water scarcity and the interconnectedness of risk between various and sometimes competing users.

Centralized and top-down governance responses have not ensured equitable and sustainable water access to date. Planned approaches have promoted responses that are capital-intensive and infrastructure-focused, especially those aligned with high-level political objectives, rather than addressing root causes of water scarcity in Africa, particularly historical mismanagement, and the comparative lack of institutional capacity at the local level. Planned responses have also showed little recognition or integration of local and indigenous knowledge into scalable water practices. They further need to avoid creating new risks to water or compounding existing ones and thus being maladaptive.

Successful autonomous and local-level responses and development interventions in rural areas have been noted to include drought-tolerant crops which use less water, on-farm ponds, flood-based farming, more efficient low-cost irrigation technologies, and afforestation. Where these responses integrate risk projections, they are likely to be robust as adaptation options. In urban areas, treated wastewater reuse, rainwater harvesting, reverse osmosis desalination, and behavioural change are all promising adaptation strategies. Yet our analysis of the literature provided no evidence of the efficacy of autonomous responses at future global warming levels. In addition, there is limited understanding of the effectiveness of responses foregrounding local and indigenous knowledge in addressing projected risks outside historical ranges of variability.

These findings underscore the dangers of separating (or ring-fencing) responses to water scarcity from competing challenges to food security, urbanization, desertification, and human or state security. Addressing water scarcity can open new opportunities for African societies to foster socio-economic development and offer new perspectives regarding human health, agriculture, economy, peace, and regional stability.

The challenge for adaptation for the coming decade is to extend planned adaptation at the local level and better integrate projected risk of climate change and variability into local autonomous responses. This holds potential to help reverse current trends of water scarcity and achieve a more efficient, successful, and fair distribution of water resources across Africa.

Future work should focus the evidence limitations of policy (and top-down decision-making) in deploying technologies and responses to water scarcity in Africa and establishing the adaptation limits of responses to water scarcity at future global warming levels.

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Appendices

Appendix A: Coding and analysis of literature on responses to water scarcity in Africa

1.	**General**
	1.1. Description of topic summarized in document 1.2. Region(s) or geographic focus of adaptive responses documented 1.3. Sectoral focus of adaptive responses documented 1.4. Cross-cutting themes 1.5. Consideration of local knowledge 1.6. Consideration of Indigenous knowledge
2.	**Who is responding?**
	2.1. Who is engaging in adaptation responses? 2.2. Is there evidence that particular vulnerable groups are targeted in adaptation responses?
3.	**What responses are documented?**
	3.1. What types of responses are reported? Behavioural/cultural: Enabling, implementing, or undertaking lifestyle and/or behavioural change Ecosystem-based: Enhancing, protecting, or promoting ecosystem services Institutional: Enhancing multilevel governance or institutional capabilities Technological/infrastructure: Enabling, implementing, or undertaking technological innovation or infrastructural development. 3.2. What types of implementation tools are reported? 3.3. What climatic hazards are being responded to? 3.4. What aspects of exposure or vulnerability are targeted by adaptation responses? 3.5. What is the stated (or implied/assumed) link to reduction in risk?
4.	**What is the extent of the adaptation-related responses?**
	4.1. What is the *general stage* of response activities? Vulnerability assessment and/or early planning: The impacts of climate change are known as least indicatively (qualitative information), taking account of the uncertainty involved in climate change scenarios. There is some evidence of vulnerability assessment. There may be evidence that some adaptation measures have been identified and plans may be made for their implementation. There is limited evidence of implementation, or only small and ad hoc adaptation implementation. Adaptation planning and early implementation: There is widespread recognition among decision-makers of the need for adaptation measures. Impacts and vulnerability are well understood. Adaptation measures have been identified and there is evidence of at least some coordinated implementation, though measures may still be ad-hoc. Implementation expanding: There is widespread recognition and acceptance of the need for adaptation measures and coordinated planning. There is evidence that adaptation has been incorporated (mainstreamed) into decision-making processes. Implementation of adaptation measures are more likely to be coordinated as part of a coherent strategy than ad-hoc. Implementation widespread: Adaptation measures are implemented and coordinated consistently across all relevant sectors and regions, with adaptation planning standard practice and well-established within legal/institutional/cultural/social frameworks and norms. 4.2. Is there any information on who financed the response? 4.3. Is there any information on the costs of adaptation? 4.4. What is the *depth* of response activities? The depth of a response relates to the degree to which a change reflects something new, novel, and different from existing norms and practices. A change that has limited depth would follow business-as-usual practices, with no real difference in the underlying values, assumptions and norms. This would include responses that are largely based on expansion of existing practices rather than consideration of entirely new practices. In-depth change, in contrast, might involve radically changing practices by altering frames, values, logics, and assumptions underlying the system. This might involve deep structural reform, complete change in mindset by governments or populations, radical shifts in public perceptions or values, and changing institutional or behavioural norms). 4.5. What is the *scope* of response activities? The scope of a response typically refers to the scale of change. A small scope might refer to local initiatives, or activities restricted to particular neighbourhoods, communities, groups, or projects. Broad scope would refer to large-scale and system-wide changes that might involve an entire organization, a country or large region, and large population. While changes of small scope might involve isolated efforts, broad scope might be multi-dimensional, multi-component, and/or multi-level. Development of networks, inter-organizational coordination, and social relations within a response are more likely to lead to changes of broader scope) 4.6. What is the *speed* of response activities? The speed of change refers to the dimension of time within which changes are happening. A slow or incremental change might include small changes in incremental steps, or a series of small shifts. Faster change might involve rapid jumps or what might be called 'transformative' changes in terms of relatively sudden shifts in views, perceptions, attitudes, and norms)
5.	**Are adaptation-related responses reducing risk?**
	5.1. Is there any evidence that activities successfully reduced risk? There is moderate to substantial evidence that key indicators of vulnerability and/or risk have declined, as well as (qualitative or quantitative) evidence that adaptation efforts have contributed to these reductions. Evidence may be attribution-based or based on robust narratives and theories of change? 5.2. Are indicators or measures of 'success' identified? 5.3. Is there any consideration of risks or maladaptation associated with the adaptation responses? 5.4. Is there any reference to co-benefits?
6.	**Adaptation limits**
	6.1. Are limits to adaptation described? 6.2. Are these hard or soft limits? 6.3. Is there evidence to indicate whether responses approach, challenge, or exceed soft limits?
7.	**Assessing confidence in evidence**
	7.1. Are there any major methodological limitations? 7.2. Did the document provide sufficient information to answer all of these coding questions? 7.3. Comment on the quantity and quality of data upon which the findings are based. 7.4. Are the results relevant to a particular context only?

Appendix B: Documented range of types responses to water stress in Africa

RESPONSE TYPES	Count	Percentage	Details
Behavioural/Cultural	65	30%	Well management, soil water conservation, market gardening, Income diversification, Social networks (loans/remittance), migration (often rural to urban migration), traditional rainwater harvesting techniques, supplementary feeding, feed preservation, changing the reproduction season, keeping locally adapted breeds and destocking of goat flock size, transhumance, agroforestry, area closure, increase non-farm income, self-help micro-credit groups.
Technological/ Infrastructural	58	27%	New seed varieties or irrigation techniques, public infrastructure that address changes in water availability, drought-resistant and other varieties better suited to climate change, infilling eroded parts of a riverbank, change of water source to groundwater, boreholes, drip irrigation, rainwater harvesting
Ecosystem-based	54	25%	Water management, planting grass to stabilize the riverbanks, use living vegetation or the residues from harvested crops to protect soil from the wind, mulching, rotating crops grown in rows with cover crops such as grasses or legumes grown on the same field every other year
Institutional	39	18%	Disaster management for floods and droughts, water conservation, groundwater management, increasing dam reservoir water storage, early warning systems for crops, food and seed storage systems, soil and crop research, Water users association, water tariffs, water demand management policy, integrated coastal zone management, incorporating risk reduction into development planning or zoning schemes
	216	100%	

Appendix C: Examples of local responses to water scarcity in Africa

Response Type		Purpose	Location	Reference (exemplar)
Rural / Agricultural	Rainwater harvesting (basic: On-farm ponds / Rooftop catchments + Manual pumping + Low-cost drip irrigation)	Subsistence agriculture; Cultivating drought tolerant and low water use crops; Food security	Continent-wide; Machakos, Kenya	(Hadebe et al., 2017; Leal Filho et al., 2019; Leal Filho and de Trincheria Gomez, 2018b)
	Technological innovations and local calibration for rainwater harvesting • Geomembrane bag • Solar pumps • Treadle pumps • Motor pumps • Micro-irrigation	Commercial Rice and Maize Production; Subsistence Agriculture; Pastoralists; Food security	Ethiopia, Tanzania, Burkina Faso; Uganda; Kenya	(Gowing et al., 2018; Haddis, 2018; Kisekka et al., 2018; Lebel et al., 2015; Snelder et al., 2018; Songok et al., 2018; Stöber et al., 2018)
	Landscape restoration and water harvesting (percolation pits, afforestation, percolation ponds, check-dams, deep trenches with bunds)	Subsistence agriculture	Tigray Region, Ethiopia, Kenya	(Berhane, 2018; Ngigi, 2018; Oduor and Mabanga, 2018; Woldearegay et al., 2018)
	Smart subsurface / sand storage dams • Small earth dams + mechanised/ manual pumping + low-cost drip irrigation) • Natural alluvial aquifers and groundwater dams in seasonal sandy streams + mechanised/ manual pumping + low-cost drip irrigation	Water security	Kenya	(de Trincheria Gomez et al., 2018; Ryan and Elsner, 2016)
	Off-season small-scale irrigation • On-farm ponds • Shallow groundwater recharge with micro-catchment • Small earth dams • Rock outcrops + earth dams	Commercial and Subsistence Agriculture	Ethiopia, Zimbabwe, Kenya	(de Trincheria Gomez et al., 2018; Oguge and Oremo, 2018; Simane et al., 2018; Wuta et al., 2018)
	Flood based farming. • Spate irrigation; Alluvial dugouts; Soil bunds • Contour ponds; Finger ponds; Paddy ponds; Flood pastures. • Inundation canals; Flow division structures; Drop structures. • Depression agriculture	Fishery; subsistence agriculture; semi-subsistence agriculture; Drinking water and groundwater recharge; Timber fuelwood and leaf harvesting	Arid and Semi-arid regions (25 million hectares); N. Africa; E. Africa; Ghana; Eritrea	(Kool et al., 2018)
	Low-technology irrigation strategies • Subterranean micro-drip irrigation (Green River Principle); Furrows; Bottle drip	Horticulture	Kenya	(Stöber et al., 2018)
	Using road infrastructure as instruments for rainwater harvesting • Modified road design: Culverts; Converted borrow pits; Infiltration ponds/trenches; Gully plugs.	Underground water recharge; Soil moisture increase; Erosion/flooding control	Tigray region, Ethiopia	(van Steenbergen et al., 2018)
	Groundwater Extraction	Drinking; Household use; subsistence agriculture	Uganda	(Pearson et al., 2015)
Urban	Reverse Osmosis Desalination	Municipal	North Africa	(Gude, 2016)
	Virtual water trading	Municipal	North Africa	(Nagara et al., 2015)
	Reverse Osmosis Desalination (small scale)	Municipal	Swakopmund, Namibia	(Sorensen, 2017)
	Rainwater harvesting	Household use	Zimbabwe, Nigeria, and others	(Abubakar, 2018; Campisano et al., 2017)
	Greywater, rainwater, treated effluent systems	Household, business use	South Africa, and others	(Taing et al., 2019)
	Wastewater Reuse	Municipal	Windhoek, Namibia	(van Rensburg, 2016)

Appendix D: Projected changes in mean atmospheric water balance

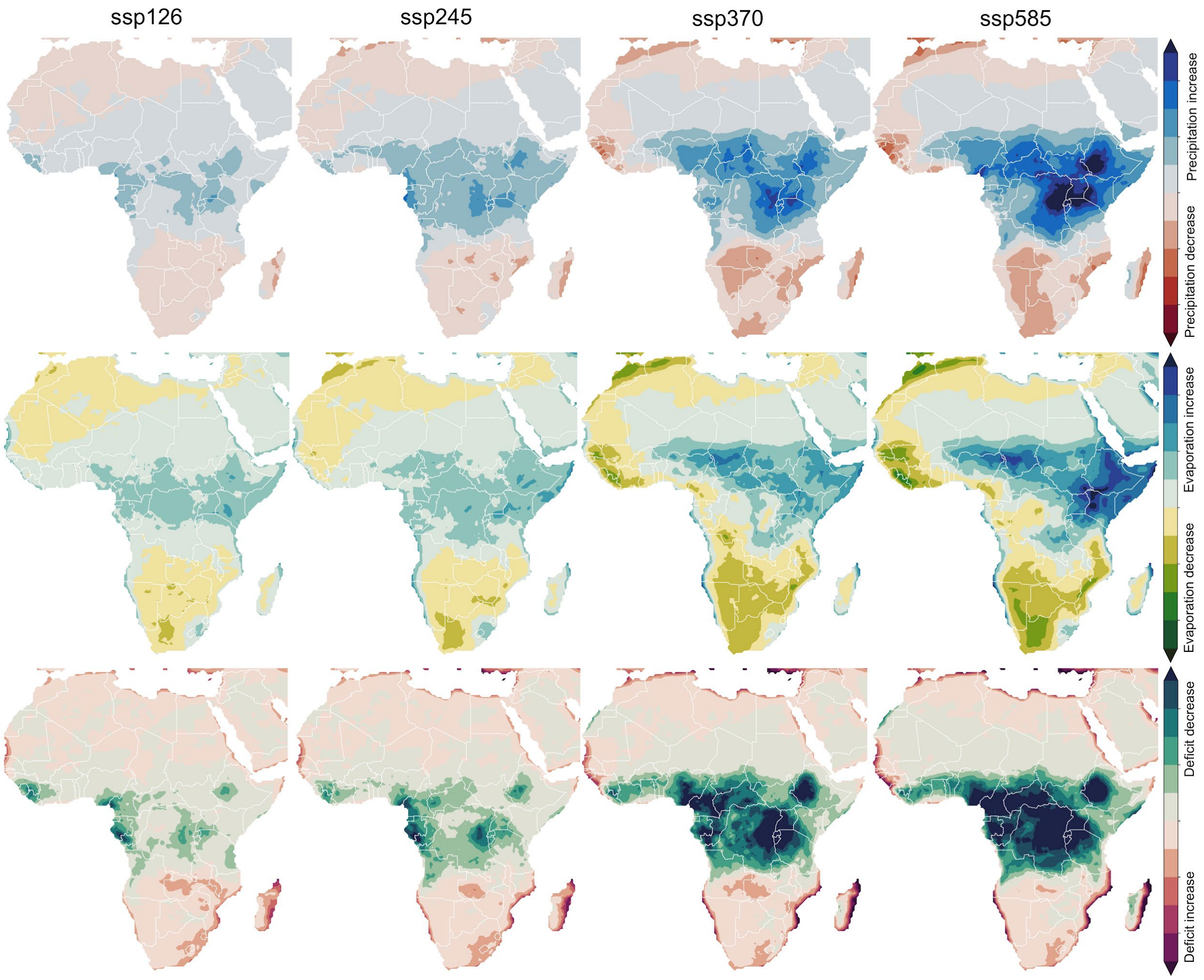

Fig. D.1: Projected changes in mean atmospheric water balance. Top row, change in precipitation (1985-2014) to (2070-2099), middle row, change in total evaporation, bottom row change in mean monthly deficit

Appendix E: Model agreement on wetting under SSP585

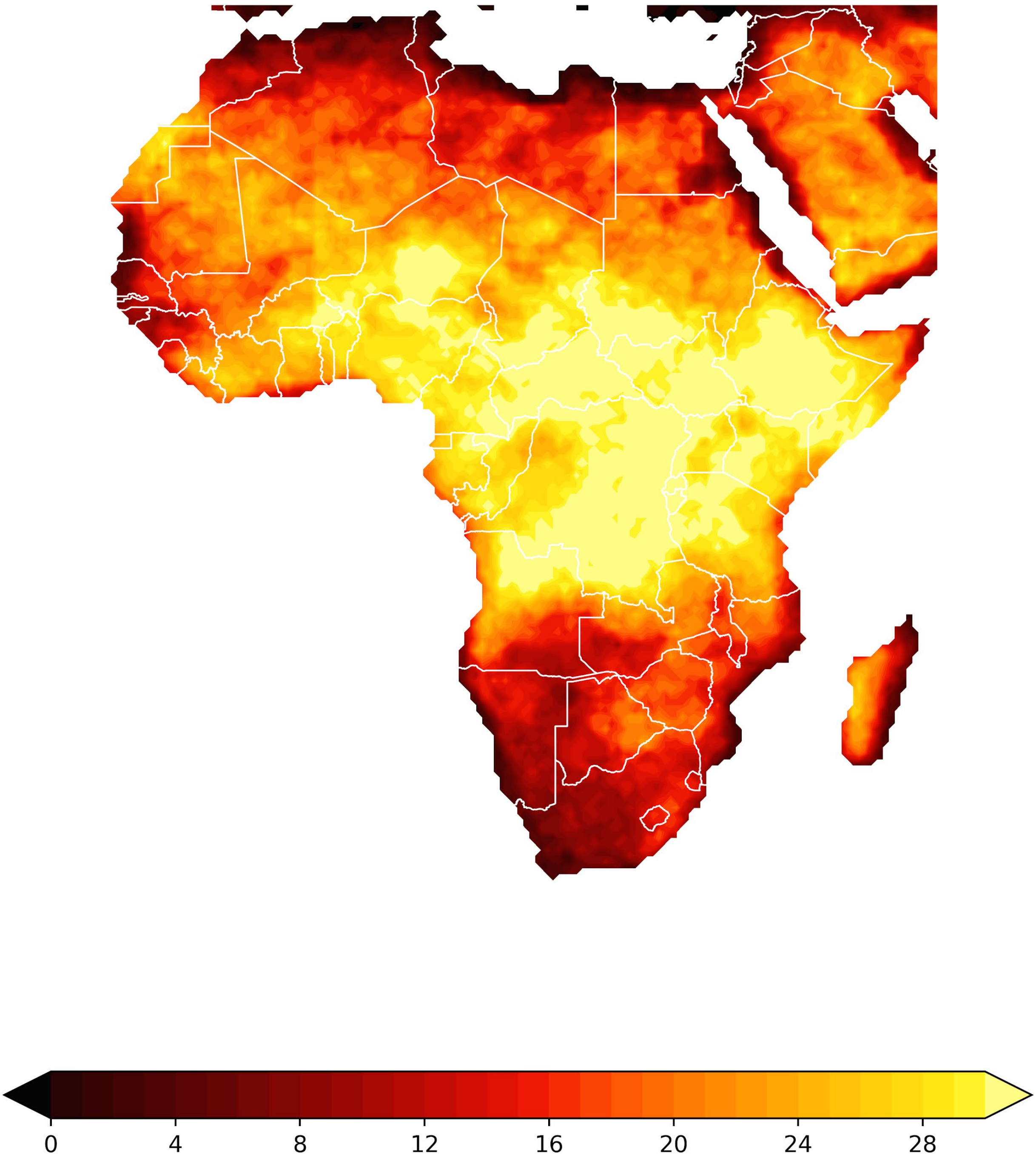

Fig. A.1: Model agreement on wetting under SSP585. Colorbar indicates number of models (out of 34 total) with projected wetting changes precipitation.

Appendix F: Projected meteorological drought progression across selected locations for high-end climate change model agreement

Climate models included: ACCESS-CM2, ACCESS-ESM1-5, CESM2, CESM2-WACCM, CMCC-CM2-SR5, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, CanESM5-CanOE, EC-Earth3-Veg, FGOALS-f3-L, FIO-ESM-2-0, GFDL-ESM4, GISS-E2-1-G, HadGEM3-GC31-LL, INM-CM4-8, INM-CM5-0, KACE-1-0-G, MIROC-ES2L, MIROC6, NorESM2-LM, NorESM2-MM, UKESM1-0-LL.

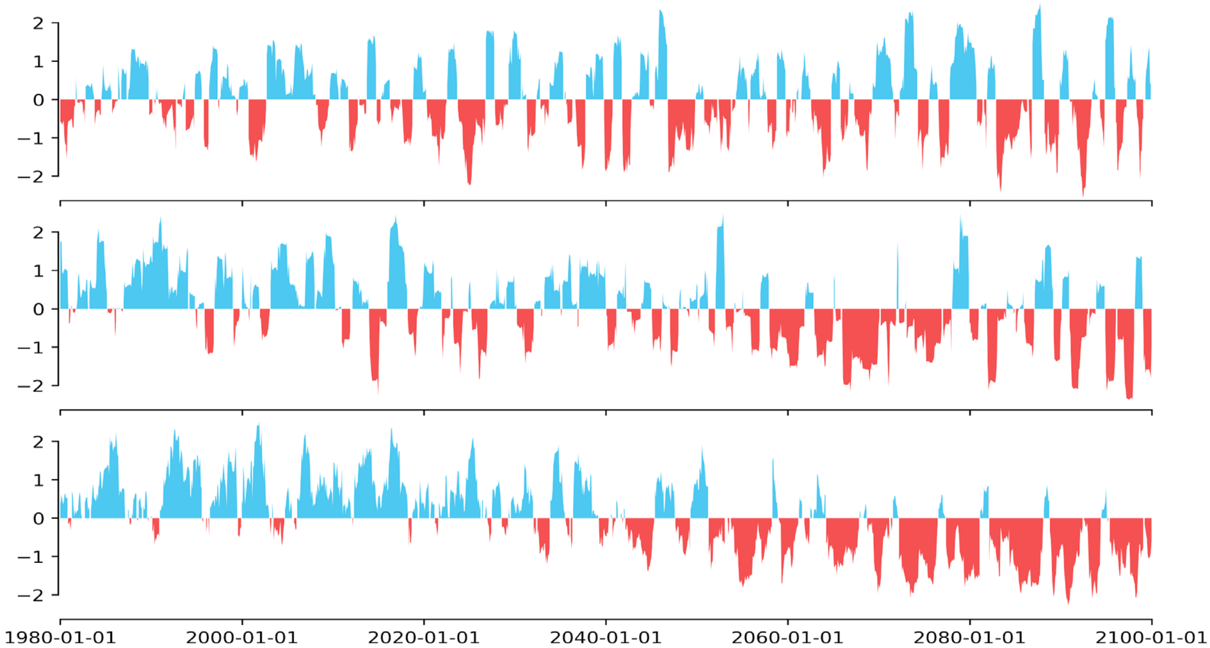

Fig F.1: Projected meteorological drought progression across selected locations for high-end climate change for central Ethiopia (top), central Malawi (middle) and eastern South Africa (bottom) ACCESS-ESM1 model.

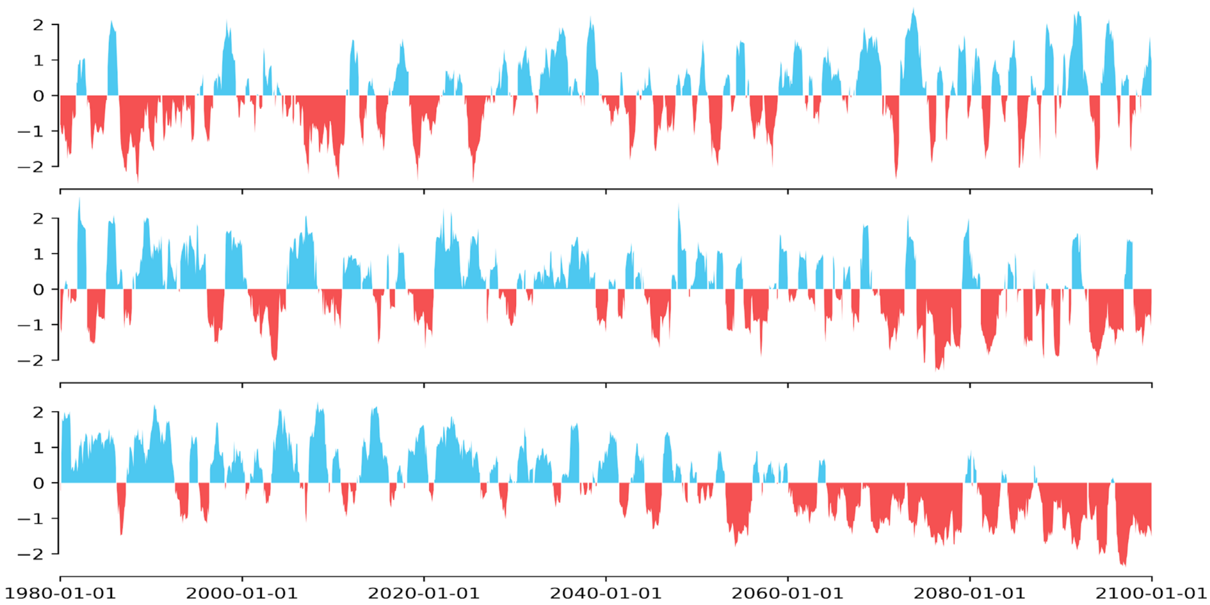

Fig F.2: Projected meteorological drought progression across selected locations for high-end climate change for central Ethiopia (top), central Malawi (middle) and eastern South Africa (bottom)EC-Earth3-Veg model.

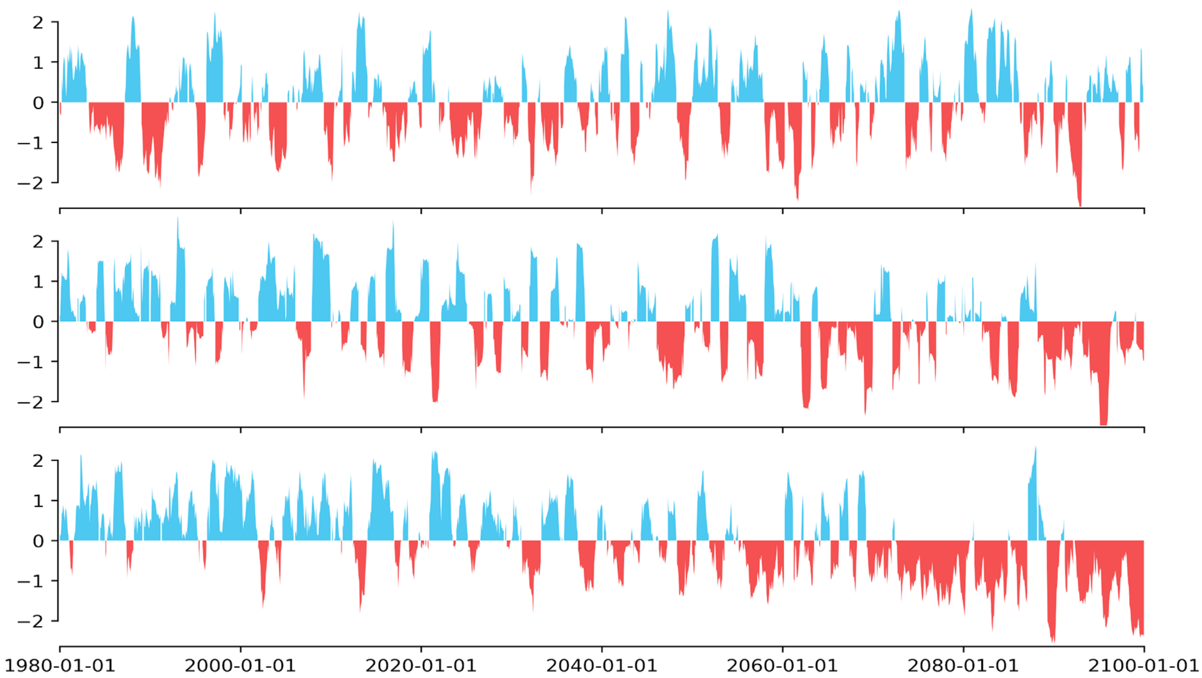

Fig F.3: Projected meteorological drought progression across selected locations for high-end climate change for central Ethiopia (top), central Malawi (middle) and eastern South Africa (bottom) MIROC6 model.

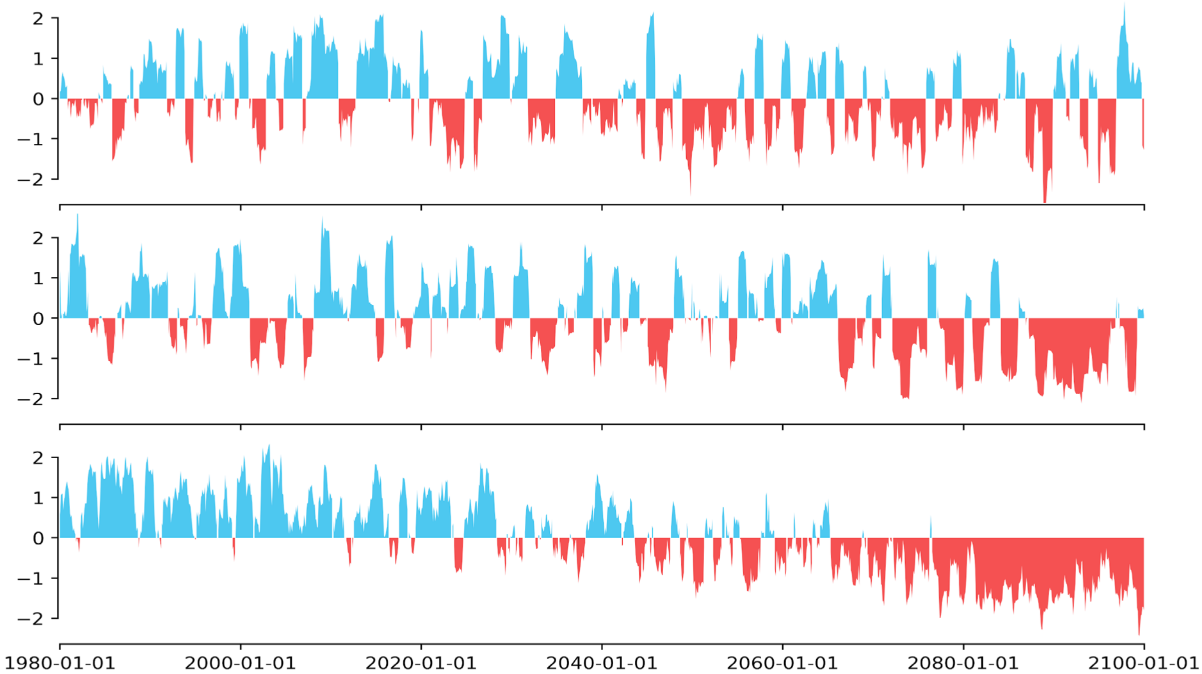

Fig F.4: Projected meteorological drought progression across selected locations for high-end climate change for central Ethiopia (top), central Malawi (middle) and eastern South Africa (bottom) CNRM-ESM2 model.

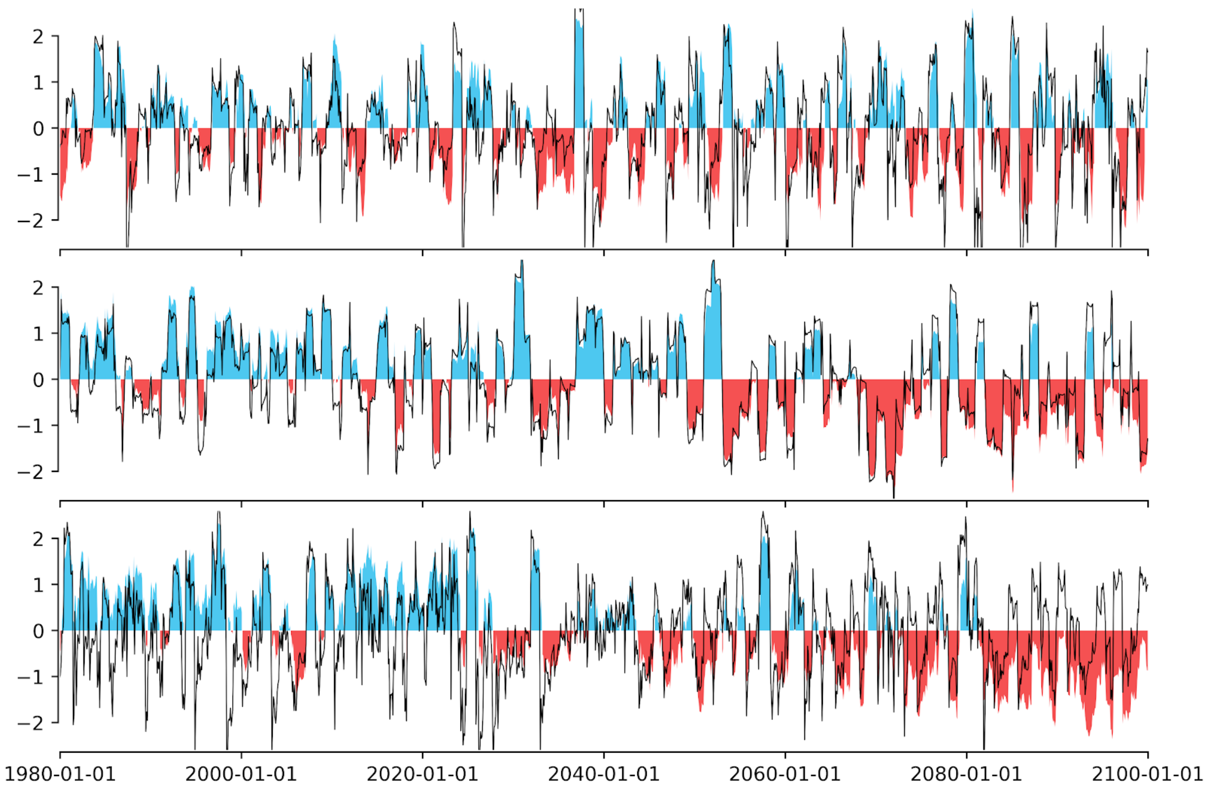

Fig F.5: Projected changes in extremes - meteorological drought progression across selected locations for high-end climate change for central Ethiopia (top), central Malawi (middle) and eastern South Africa (bottom) (SSP585). 12-month SPEI across 3 selected grid cells for the ACCESS-CM2 climate model with SPAEI shown in black.

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[i] African countries with less than 2 two peer-reviewed and English language articles on responses to water scarcity (2013-2020) are: Algeria, Mozambique, Angola, Burundi, Cabo Verde, Comoros, Congo, Cote d'Ivoire, Djibouti, DRC, Eritrea, Gabon, Guinea, Lesotho, Liberia, Libya, Madagascar, Mauritius, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia, Togo.

[ii] 'other' actors include: Universities and research communities, meteorological service departments, customary or traditional leaders, women's cooperatives, indigenous peoples, water user associations, multilateral development agencies (United Nations Development Programme's Community Water Initiative and Global Environment Facility's Small Grants Programme), agricultural extension agents, and sub-watershed committees.