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Drought risk for agricultural systems in South Africa: Drivers, spatial patterns, and implications for drought risk management

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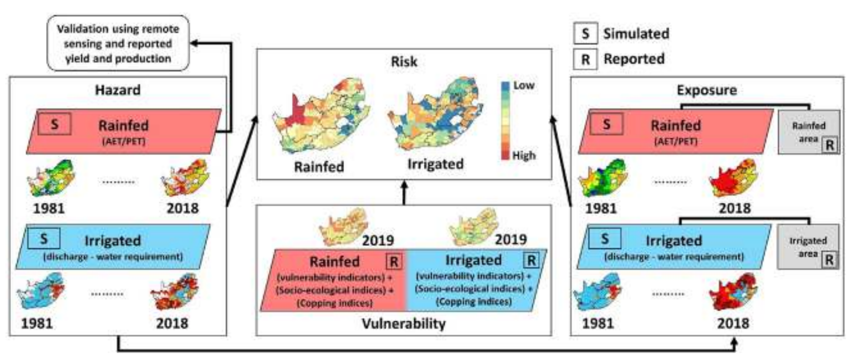
HIGHLIGHTS

- South Africa is highly susceptible to drought impacts on agriculture, given its high water reliance.
- Drought risk varies substantially between irrigated and rainfed agricultural systems.
- The most extreme drought for rainfed croplands is observed in Northern Cape, North West and Limpopo.
- Highest drought risk on time series for irrigated crops is across Limpopo and Eastern Cape.
- Our methodology to assess drought risk is transferable to other regions.

GRAPHICAL ABSTRACT



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ABSTRACT

The regular drought episodes in South Africa highlight the need to reduce drought risk by both policy and local community actions. Environmental and socioeconomic factors in South Africa's agricultural system have been affected by drought in the past, creating cascading pressures on the nation's agro-economic and water supply systems. Therefore, understanding the key drivers of all risk components through a comprehensive risk assessment must be undertaken in order to inform proactive drought risk management. This paper presents, for the first time, a national drought risk assessment for irrigated and rainfed systems, that takes into account the complex interaction between different risk components. We use modeling and remote sensing approaches and involve national experts in selecting vulnerability indicators and providing information on human and natural drivers. Our results show that all municipalities have been affected by drought in the last 30 years. The years 1981–1982, 1992, 2016 and 2018 were marked as the driest years during the study period (1981–2018) compared to the reference period (1986–2015). In general, the irrigated systems are remarkably less often affected by drought than rainfed systems; however, most farmers on irrigated land are smallholders for whom drought impacts can be significant. The drought risk of rainfed agricultural systems is exceptionally high in the north,

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Rainfed
Disaster risk reduction

central and west of the country, while for irrigated systems, there are more separate high-risk hotspots across the country. The vulnerability assessment identified potential entry points for disaster risk reduction at the local municipality level, such as increasing environmental awareness, reducing land degradation and increasing total dam and irrigation capacity.

1. Introduction

Drought is a recurrent feature of all climates and among the most complex, damaging, and least understood of all so-called "natural hazards" (Dai, 2013; Heim, 2002). It is generally defined as a period of abnormally low precipitation (compared with the long-term average climate of a given region), which is long enough to severely impact the hydrological resources (IPCC, 2014). This complex phenomenon often leads to major impacts on the environment, society and economy (Naumann et al., 2014a, 2014b), often with cascading effects. Moreover, with the added pressures of climate change, the frequency, severity, and duration of droughts will likely increase in many regions across the globe (Asadieh and Krakauer, 2017; Trenberth et al., 2014). The long-lasting impacts of droughts are felt in many sectors, including public water supply, energy production, tourism and agriculture, the last often being the most heavily affected sector (Dilley et al., 2005; UNDRR, 2019). This is more noticeable in countries with a large agricultural share of GDP or a large percentage of the labour force employed in agriculture, with the rural population particularly affected (Carrão et al., 2016). This demonstrates that the negative impacts associated with droughts are not only linked to the frequency, severity, and duration of drought events but also the degree of exposure, susceptibility and coping capacity of a given socio-ecological system (SES) (Meza et al., 2020a, 2020b). Furthermore, the combined impacts of climate change, accelerated population growth, and several declining socioeconomic factors will intensify drought hazards, exposure, and vulnerability in the long-term (Ahmadalipour et al., 2019). This highlights the need to understand and manage drought from a complex system perspective. It is necessary to consider climate and environmental drivers along with socioeconomic factors that determine how susceptible a community, region, system or sector is to drought and their capacity to cope.

Global assessments focused on drought risk of impacts on agriculture have shown that southern Africa is at particularly high risk (Carrão et al., 2016; Meza et al., 2020a, 2020b). South Africa is recognized as a drought-prone country (Baudoin et al., 2017; Gibberd et al., 1996; Jordaan et al., 2017a) that has experienced several "severe" drought events (as occurred in early 1980s and 1990s, the period 2014–16 (Baudoin et al., 2017), and the recent ongoing drought since 2018 (Mahlalela et al., 2020). During these years, environmental and socioeconomic factors in the agricultural system of South Africa were impacted by the drought, creating cascading pressures on the nation's agro-economic and water supply systems.

Agriculture is a core component of the economy and has major implications for job creation, food security, rural development and foreign exchange (National Treasury, 2003). The agricultural sector directly contributes 3% to the national GDP (DAFF, 2018; Schreiner et al., 2018), and indirectly (through manufacturing, textiles, food processing) at least 14% (WWFW (World Wide Fund for Nature), 2018). Approximately 8.5 million people (i.e. 14% of the population) are either directly or indirectly dependent on agriculture for employment and income (DAFF, 2018; Schreiner et al., 2018).

The agricultural sector in South Africa is composed of commercial farmers as well as subsistence farmers. These sectors experience drought risks differently. Historical root causes such as development support and economic reforms have favoured and benefited commercial farmers who are largely exporters (FAO, 1997), exacerbating the difference in coping capacity and socio-environmental susceptibilities between the two groups. Therefore, subsistence farmers have fundamentally different risk profiles and responses compared to the commercial farming sector (Thamaga-Chitja and Morojele, 2014). While commercial farming underpins South Africa's food security, subsistence farming provides income and food security on a household scale for much of the population. With the projected increase in the frequency, severity, and duration of droughts (WMO World Meteorological Organization, 2020), subsistence farmers growing rainfed crops are particularly susceptible to drought as they highly depend on climate-sensitive resources (Schreiner et al., 2018).

South Africa has extensive disaster risk reduction (DRR) legislation (e.g. the National Disaster Management Act, 2002), which has evolved over the decades (Vogel and Van Zyl, 2016). Thus, various policy documents, assessments and strategies for DRR have been compiled (e.g. the 2004 National Climate Change Response Strategy, the 2010 National Climate Change Response Green Paper, and the 2011 National Climate Change Response (Baudoin et al., 2017). Efforts to implement risk reduction approaches are also supported through global frameworks such as the Sendai Framework for DRR (UNDRR, 2015), and various reporting commitments to international organizations (e.g. UNFCCC, UNCCD). The South African National Disaster Management Framework (NDMF) clearly states the need for disaster risk assessments (drought in this case) as one of the key performance areas for any DRR strategy (Jordaan et al., 2017a, 2017b). However, the South African government has historically responded to drought with drought relief schemes that focus mainly on addressing the farmer's immediate needs rather than preemptively building resilience to possible future droughts (Ngaka, 2012; Jordaan, 2011).

There is significant literature in South Africa regarding the assessment of drought impacts on agriculture, e.g. at national level (Masupha and Moeletsi, 2020; Muyambo et al., 2017; du Pisani et al., 1998), quaternary catchment level (Magombeyi and Taigbenu, 2008) and regional level (Kamali et al., 2018). However, when assessing the risk of drought impacts specifically for agricultural systems, there is one assessment at national level (Schwarz et al., 2020), and there are only few studies at local level (Jordaan et al., 2013; Walz et al., 2018). Most of the drought risk assessments in South Africa still miss the connection between holistic consideration of socio-ecological vulnerability, exposure, and hazard from the local to the national scale. A comprehensive drought risk assessment is crucial to inform drought policies that foster proactive drought management (Sivakumar et al., 2014). So far a national drought risk assessment that integrates hazard, exposure and vulnerability to risk for irrigated and rainfed agriculture separately at the sub-national scale is lacking.

Distinguishing the risk components for irrigated and rainfed agriculture is important because: i) rainfall deficit is the main factor impacting drought hazard for rainfed systems while for irrigated systems, availability of irrigation water is more relevant, ii) spatial patterns of irrigated and rainfed systems and growing periods of irrigated and rainfed crops are diverse resulting in different exposure of irrigated and rainfed systems, iii) factors and weights affecting the vulnerability of the systems differ for irrigated and rainfed systems as the vulnerability levels may constantly change due to changes in farming systems and associated technologies, so that even in the same region vulnerability can vary greatly (Downing and Bakker, 2000).

Efforts to assess drought risk for agricultural systems at sub-national level for specifics regions in the world have increased over the past years (Chen et al., 2017; Deng et al., 2018; Han et al., 2016; Kamruzzaman et al., 2018; Ortega-Gaucin et al., 2021; Pei et al., 2018;

Zeng et al., 2019; Zhang et al., 2011); however, none of these assessments considered the inherent differences between irrigated and rainfed cropping systems. Frischen et al. (2020) analysed drought risk for irrigated and rainfed systems at the sub-national scale in Zimbabwe, however, the only differentiation in the methodology for each cropping system was considered at the exposure component while the hazard and vulnerability indicators were the same for both systems.

This paper aims at addressing the above gaps by conducting a sector-specific assessment of the drivers and spatial patterns of drought risk for rainfed and irrigated agricultural systems in South Africa in order to identify entry points for action. This is the first integrated drought risk assessment for South Africa at the sub-national level, which considers spatio-temporal consistent hazard-specific indicators, complemented by drought exposure and socio-ecological vulnerability factors – weighted by local experts - at the local municipality scale, specifically for irrigated and rainfed agricultural systems.

The paper presents a risk assessment based on a mixed-method approach, starting from the hazard assessment (Section 2.3), which is based on composite drought hazard indicators calculated for irrigated and rainfed crop systems separately using drought indices based on historical climate conditions (1986–2015). The exposed elements are described in Section 2.4 and were derived from a dataset differentiating irrigated and non-irrigated crops by local municipality. The vulnerability component was assessed through a composite-indicator based approach, where drought experts in South Africa weighted each indicator (Section 2.5). Then, the drought hazard, exposure and vulnerability information was compiled into a final drought risk assessment (Section 2.6), which resulted in integrated risk maps for both rainfed and irrigated agricultural systems, respectively (Section 3). Lastly, the paper discusses the results (Section 4) and identifies potential ways forward, including future research needs.

2. Data and methods

2.1. Case study region

South Africa is located in the southern part of Africa, spreading over 122 million ha with approximately 12% croplands (FAO, 2020a). The country is composed of nine provinces and has a wide range of climates from arid to subtropical, temperate, and mediterranean (Fig. 1) (Waldner et al., 2017). About 91% of South African territory is arid or semi-arid, with only 10% of the land generating half of the annual run-off (Le Maitre et al., 2018). The country has uneven rainfall distribution with a mean annual rainfall of 550 mm and annual mean temperature of 18 °C (FAO, 2020a). The potential annual mean evaporation for the

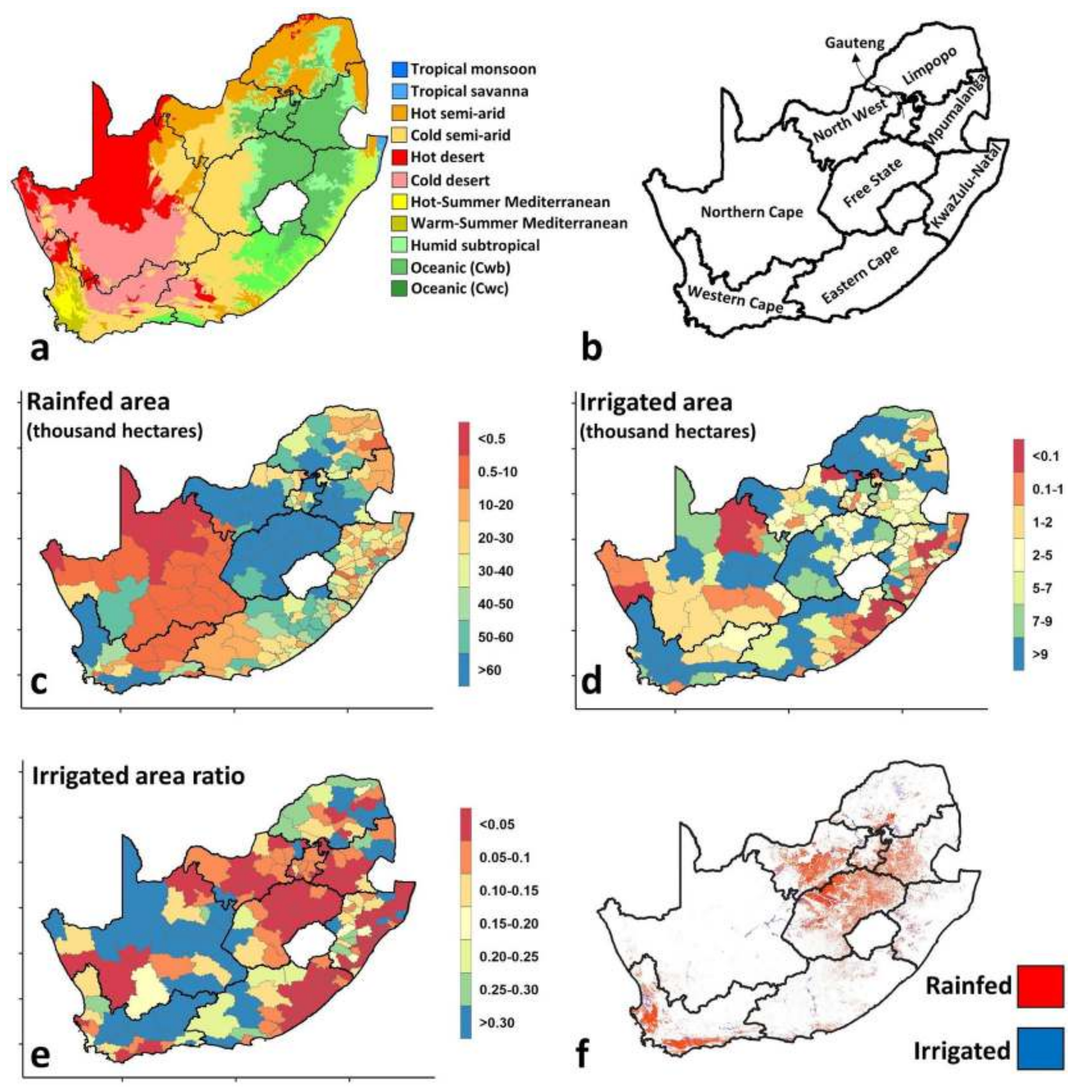

Fig. 1. a) Köppen-Geiger climate classification map for South Africa (1980–2006) (Beck et al., 2018). b) South African provinces. c) and d) Rainfed and irrigated areas per municipality, respectively. e) Ratio between irrigated and total agricultural area per municipality. f) Irrigated and rainfed agriculture in South Africa at pixel level. Maps are based on data from the national land use/land cover dataset 2018 (Thompson, 2019a, 2019b). Black lines indicate provincial boundaries.

whole country is about three times greater than its annual rainfall, 1800 mm per year (WWFW (World Wide Fund for Nature), 2018). According to the general household survey performed in 2018 almost 15% of the households were active in agricultural activities, of which more than 75% are involved in order to ensure an additional source of food (DALRRD (Department of Agriculture, 2020).

The agricultural economy comprises technically developed commercial farming on the one hand and more subsistence-based production in the remote rural areas on the other hand (Waldner et al., 2017). The dominant activities include: i) intensive crop production and mixed farming in areas characterised by winter and summer rainfall, ii) cattle ranching in the bushveld and iii) sheep farming in the arid regions (Waldner et al., 2017). Considering climate and soil properties, only 12% of the country is suitable for crop production; of which 22% is considered as high potential land in terms of production capacity (Waldner et al., 2017; WWFW (World Wide Fund for Nature), 2018).

In general, rainfed agriculture prevails in South Africa, accounting for the majority of the harvested area (Fig. 1) (Hardy et al., 2011). This means that only 1.35 million ha (8.5%) of the potentially arable land is irrigated (DAFF, 2019). Nevertheless, irrigated agriculture contributes 30% to agricultural production (FAO, 2020b). Irrigation application in South Africa can be permanent, supplementary, or occasional. Most of the commercial irrigation schemes are located in large river basins (e.g. Orange, Lower Vaal, Fish) and in the Western Cape region (FAO, 2016).

South Africa has been frequently affected by droughts in the last four decades. Major drought periods include 1982–1984, 1991–1992, 1994–1995, 2004–2005, 2008–2009, 2015–2016, and the most recent in 2018–2020 (Mahlalela et al., 2020; FAO, 2019; Walz et al., 2020; Unganai and Kogan, 1998). During those years, drought not only impacted the environment, but also the social and the economic systems. The 1992 drought affected around 250,000 people, with an estimated 50,000 job losses in the agriculture sector, and 20,000 additional jobs losses in related sectors (AFRA (Association for Rural Advancement), 1993). In 2007–2008, the South African government spent over R285 million (19 million US dollars) on drought relief measures for the agricultural sector, primarily on the purchase and supply of subsidised fodder depending on farms' sizes (Ngaka, 2012). Recent droughts such as the one in 2015–2016 revealed the cascading impacts of the drought. The BFAP (Bureau for Food and Agricultural Policy) (2016) reported that the area of maize planted for the 2016–17 season was 25% lower than the area planted in the 2015–16 season, which was reflected in the year-on-year declines in seasonally adjusted sectoral GDP. In addition to the direct impact on agriculture, general economic indicators pointed to an aggravated situation (e.g. input providers were hard hit due to the lack of purchasing power in the agricultural sector; given the suppliers' import propensity and the local currency depreciation (BFAP (Bureau for Food and Agricultural Policy), 2016)). Inflationary pressures resulting, inter alia, from drastic increases in food prices drove up interest rates, which had a negative effect on farming enterprises' debt servicing costs and further restricted access to credit in the sector (BFAP (Bureau for Food and Agricultural Policy), 2016).

Drought policy and strategies have included efforts from as early as the 1920s, concentrating on land use change, land reforms, soil management and agricultural practices (e.g. kraaling of stock) (Bruwer, 1993; Hassan, 2013). The most recent strategy towards drought is compiled in the National Development Plan which sets a vision of eliminating poverty and reducing inequality by 2030 (DALRRD (Department of Agriculture, 2020). However, a rethinking of drought governance is still required, which should look back in time and critically reflect on past drought experiences, perceptions and needs of drought risk reduction and how local context influences drought response (Baudoin et al., 2017; Vogel and Olivier, 2019). The government is still challenged to change the unbalanced land-ownership patterns while sustaining economic growth, food security and implementing effective drought management plans; as by 2018 according to the DALRRD (Department of Agriculture (2020) over 60% of South Africans did not have their land/property rights recorded or registered.

2.2. Risk framing and workflow

Following the IPCC (2014) definition, risk results from the interaction between hazard, with exposure of human and natural systems and the systems' vulnerabilities. In this paper, exposure is defined as the presence of agricultural systems that could be negatively affected by hazards. Vulnerability is the predisposition or propensity to be adversely affected by drought. It encompasses a variety of concepts and elements, including social-ecological sensitivity or susceptibility to harm and lack of capacity to cope (IPCC, 2014). Also, following the IPCC (2014) definition, susceptibility is understood as the likelihood of suffering harm in the event of a drought hazard process, and coping capacities refer to the use of available skills, opportunities, and resources to address, manage, and overcome adverse conditions in order to achieve basic functioning in short to medium terms. The workflow for the three risk components and risk aggregation is visualized in Fig. 2; the indicators and data sources for hazard, exposure and vulnerability are presented in Tables 1 and 2.

2.3. Hazard assessment

2.3.1. Rainfed hazard composite index

The rainfed hazard indicator was computed using the ratio between actual evapotranspiration (AET) and potential (PET) evapotranspiration of crops in the crop growing season for the period 1981–2018. AET refers to the amount of water consumed by a crop and evaporated from the soil under actual soil moisture calculated by performing a soil water balance in daily time steps, while PET assumes no limitation in crop water availability. The ratio is highly associated with crop yield and is widely used as a drought indicator for cropland (Peng et al., 2019). The Global Crop Water Model (GCWM) (Siebert and Döll, 2010a, 2010b) was employed to simulate AET and PET for specific crops grown in South Africa based on prescribed crop calendars and cropping patterns derived from the MIRCA2000 dataset (Portmann et al., 2010). The ERA5 global reanalysis (Hersbach et al., 2020) and ISRIC-WISE30sec v1.0 (Batjes, 2016) were used as the climate and soil input. The spatial resolution of GCWM's is five arcmin (8.3 km). Drought hazard in specific years was defined as deviation from the long-term mean condition in the reference period 1986–2015 (Meza et al., 2020a, 2020b). The annual hazard indicator for rainfed agricultural systems CH_RfAg_y was calculated as:

$$CH\_RfAg_y = 1 - \frac{AETy/PETy}{\overline{AET}/\overline{PET}} \tag{1}$$

where $AETy$ and $PETy$ are annual sums of actual and potential evapotranspiration of all cultivated crops in year y ($m^3\ yr^{-1}$). $\overline{AET}$ and $\overline{PET}$ are the long-term annual mean of actual and potential evapotranspiration ($m^3\ yr^{-1}$) in the reference period 1986–2015. Consequently, positive values of CH_RfAg_y represent conditions dryer than usual, while negative values indicate wet years. The long term hazard during the study period at grid level was computed as the frequency (percentile rank) of years in which the AET/PET ratio was at least 10% lower than the mean AET/PET ratio in the reference period 1986–2015 (Meza et al., 2020a, 2020b). A long-term hazard of 0.5 means therefore that in every second year the AET/PET ratio is lower than 90% of the long-term mean AET/PET ratio.

2.3.2. Irrigated hazard composite index

The irrigated hazard index $CH\_IrrigAg_y$ (-) is defined based on the annual difference between the water resource available for irrigation and irrigation water requirement. The water resource available for irrigation was simulated using the WaterGAP model

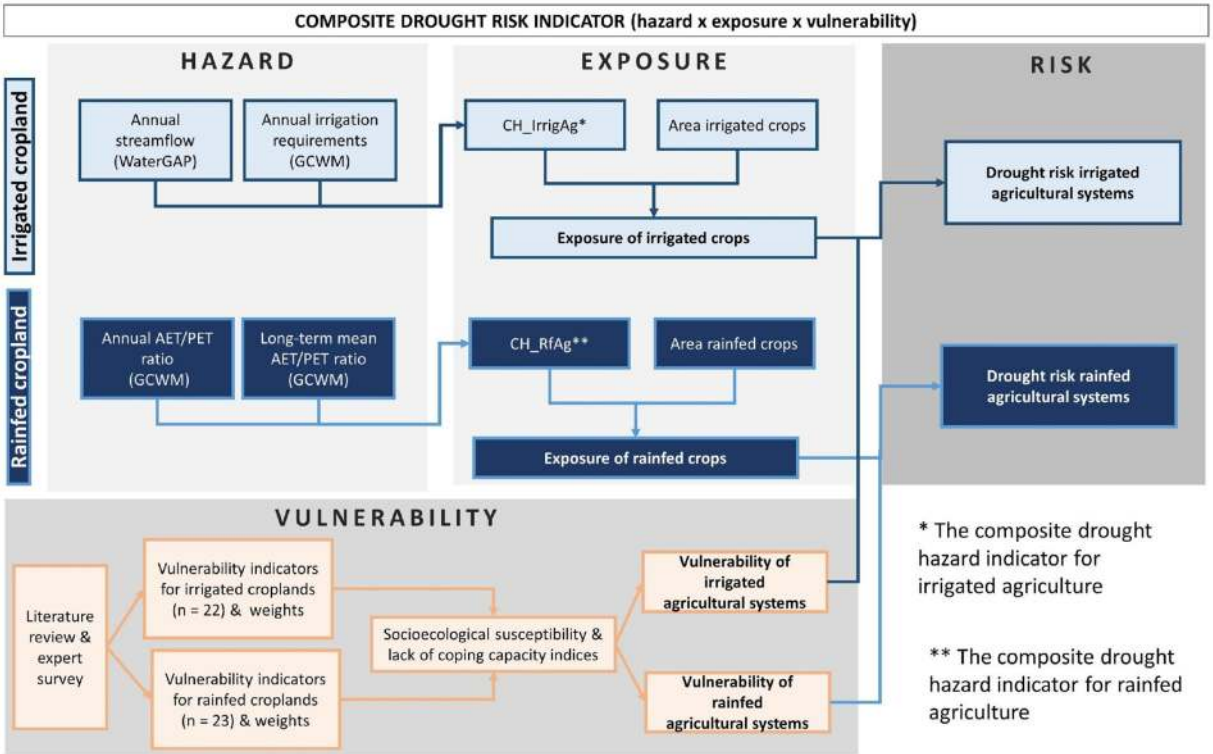

Fig. 2. Workflow for the drought risk assessment for irrigated and rainfed agricultural systems in South Africa. The workflow is explained in detail in Sections 2.3–2.6.

(Müller Schmied et al., 2020a, 2020b) as annual sum of discharge Q at a spatial resolution of 30 arcmin for the period 1981–2018. The irrigation water requirement IWR was simulated using GCWM as the volume of water needed to increase the AET of irrigated crops to their PET (Siebert and Döll, 2010a, 2010b). Drought hazard for irrigated crops $CH\_IrrigAg_y$ was computed for each year as:

$$CH\_IrrigAg_y = \frac{(Q - IWR)_{med} - (Q_y - IWR_y)}{Q_{med}} \quad (2)$$

where $(Q - IWR)_{med}$ is the median of the difference between discharge and irrigation water requirement ($m^3\ yr^{-1}$) in the reference period 1986–2015, Qy and $IWRy$ are discharge and irrigation water requirements in year y ($m^3\ yr^{-1}$), and Q_{med} is the median of the annual discharge in the reference period 1986-2015 ($m^3\ yr^{-1}$). Positive values of $CH\_IrrigAg_y$ indicate drought, while negative values indicate that the difference between water resources and water demand for irrigation is larger than usual (wetness). Both models (GCWM and WaterGAP) used the same soil and climate input data and the same simulation period (1981–2018). The outputs of GCWM (for crops grown in South Africa) were aggregated to 30 arcmin to match the spatial resolution used by WaterGAP. The long-term hazard for irrigated conditions at grid level was computed as the frequency of the years with an irrigated hazard index $CH\_IrrigAg_y$ of bigger than 0.5 meaning that the deficit in the annual difference between discharge and irrigation requirement exceeded half of the long-term median of annual discharge. A long term hazard for irrigated conditions of 0.2 means then that such a deficit occurs every 5 years.

2.4. Exposure assessment

Based on the drought risk assessment workflow (Fig. 2), agricultural land (irrigated and rainfed) was used to analyse drought exposure. The estimation of exposed agricultural land was based on the South African National Land Cover dataset 2018 (Thompson, 2019a, 2019b), from which irrigated and rainfed land were extracted as separate classes. The SANLC 2018 map has 20 m spatial resolution and was generated using multi-seasonal Sentinel 2 satellite time series data acquired during the period 01 January 2018 to 31 December 2018, 20 m spatial resolution and 90.14% accuracy (Thompson, 2019a, 2019b). Rainfed systems are mostly located in the North Eastern provinces, as well as in Northern and Western Cape (DAFF, 2018). The hazard indicators - CH_RfAg_y and $CH\_IrrigAg_y$ - were aggregated from pixel to municipality level as average of the pixel values, using the rainfed or irrigated area

Table 1
Hazard and exposure indicators used for the irrigated and rainfed assessment and the origin of the input data.

Risk component	Agricultural system	Indicator	Data source	Processed data
Drought hazard	Irrigated	Water availability Water requirement	WaterGAP (Müller Schmied et al., 2020a, 2020b) GCWM (Siebert and Döll, 2010a, 2010b)	Annual time series of the difference between discharge Q and irrigation requirement IR compared to the long-term (1986-2015) mean of that difference (Eq. (2)) Calculated for period 1981-2018
	Rainfed	Crop drought stress	GCWM (Siebert and Döll, 2010a, 2010b)	Annual time series of the deviation of the ratio AET / PET from the long-term (1986-2015) mean of that ratio (Eq. (1)) calculated for period 1981-2018
Exposed elements	Rainfed or irrigated	Area rainfed or irrigated in the local municipality	Thompson, 2019a, 2019b	National land use/land cover dataset 2018 (DEA, 2019) differentiating between rainfed and irrigated agriculture

Table 2
Final list of indicators used to perform the vulnerability assessment with expert weighting for irrigated and rainfed systems. The weights with a value close to 1 are highly relevant, whereas indicators with a value close to 0 indicate lower relevance. Only indicators with selected values were used for the respective vulnerability assessment (Irrigated, Rainfed).

Indicator	Direction	Data source	Expert weight irrigated	Expert weight rainfed
Social susceptibility				
Unemployment rate (%)	+	StatSA, 2011	1.00	0.91
Population with assistive devices and medication-Chronic medication	+	StatsSA census 2011 (Boundaries 2016) - Disability	0.95	0.76
Population with inadequate sanitation/sewerage/toilet services	+	StatsSA (Community survey 2016)	0.91	0.75
Population with environmental awareness by district	–	StatsSA (Labour Force Survey)	0.89	0.88
Dependency ratio (population at the age of 0-14 and > 65)	+	StatSA (Agricultural Household survey 2016)	0.88	0.79
Accessibility to high-density urban centers by travel time	+	Weiss et al., 2018	0.85	0.79
HH with alternative on farm income	+	StatsSA (Agricultural Household survey 2016)	0.84	1.00
People skipping a meal for five or more days in the past 30 days	+	StatsSA (Community survey 2016)	0.83	0.88
Population that have experienced violence and crime	+	StatsSA (Community survey 2016)	0.81	0.78
Debtors by municipality (%)	+	National Treasury (Balance Sheet) Municipal Finance Data Tables	0.73	0.95
Hydropower installed capacity [MW]	+	World Bank (Global Dams Database, 2020) and the Global Reservoir and Dam Database (GRanD)	0.71	No selected
Gender inequality (gender parity)	+	SatsSA 2016 Gender Series Empowerment	0.69	0.70
Population per municipality that rate the overall quality of the water services poor	+	StatsSA (Community survey 2016)	0.63	0.68
Population that has experience of crime - Theft of livestock; poultry and other animals	+	StatsSA (Community survey 2016)	0.63	0.61
Population with ill-health (mental) (%)	+	StatsSA (Community Survey 2007) - Disability	No selected	0.73
Environmental susceptibility				
Farm land ratio	+	StatsSA (Agricultural household survey 2016)	0.89	0.85
Land Degradation Index (LADA)	+	Department of Agriculture, Forestry and Fisheries, 2016 DAFF)	0.87	0.86
Clay content (0-2 micro meter) in (g/100 g) (w%) at depth 0-5 cm	–	Hengl et al., 2015	0.80	0.81
Maximum fertilizer application rate kg/h	–	Mueller et al., 2012 and West et al., 2014 for mineral fertilizer data and manure and atmospheric deposition.	0.79	0.74
Coping capacity				
Total dam storage capacity in million cubic meters	–	Lehner et al., 2011 for GRanD	0.87	0.70
Borrowed money from total municipality liability	+	National Treasury (Balance Sheet) Municipal Finance Data Tables	0.80	0.84
People that receive social grants	–	StatsSA (Welfare - Community Survey 2007)	0.75	0.85
Road density m/km2	–	GloBio (Global Roads Inventory Project (GRIP) dataset)	0.72	0.75
Area equipped for irrigation expressed as percentage of total area	+	FAO, 2020a, 2020b, 2020c	No selected	1.00

within each pixel derived from the SANLC 2018 dataset for weighting. From this point, the combined components of hazard and exposure are referred to as 'hazard/exposure'.

The simulated hazard/exposure for rainfed conditions was validated using the remotely sensed AET/PET ratio in the period 2001–2018. AET and PET values were extracted from the Moderate Resolution Imaging Spectroradiometer (MODIS) product (MOD16A2.006) which provides data at 500 m spatial resolution (Running et al., 2017). The dataset is derived from meteorological reanalysis data coupled with remotely sensed products of land cover and vegetation properties (Huang et al., 2017). The dataset was preprocessed based on the quality control layer, and pixels with low quality were excluded. The original data set provided the AET and PET in 8 days intervals, which were summed up to yearly values. The CH_RfAg_y was recalculated for model results and remote sensing observations considering the reference period 2001-2018 to account for the limited availability of remote sensing observations. Both datasets were aggregated to the municipality level considering the extent of the rainfed growing area in each pixel. The Pearson correlation coefficient was calculated between model and remote sensing driven CH_RfAg_y at the municipality level.

2.5. Vulnerability assessment

Drought impacts are often associated with drought hazard severity, but the degree of the impact is mediated by the vulnerability of the exposed agricultural system, i.e. its susceptibility and the (lack of) capacity to cope with drought events (IPCC, 2014; World Bank, 2019). While an array of methods for assessing vulnerability to natural hazards exists, indicator-based approaches are among the most common to represent the multi-dimensional nature of vulnerability (Hagenlocher et al., 2019; de Sherbinin et al., 2019). For this assessment, composite indicators were developed according to the impacted sector: i) irrigated agriculture and ii) rainfed agriculture, considering a wide array of environmental, social, and economic indicators.

Relevant indicators were identified through a combination of literature review and expert consultation. The review was conducted based on pre-defined search terms (Table S1) in Web of Science and Scopus. The selected articles (n = 17) were coded with MAXQDA software (VERBI Software, 2019) to extract suitable indicators. Later, these indicators were compared and complemented with the ones identified by Hagenlocher et al. (2019) in their review of existing drought risk assessments, and within South Africa at a local municipality level by Walz et al. (2018) and a quaternary catchment level by Jordaan et al. (2017a, 2017b). In total, 44 suitable indicators for rainfed and irrigated systems in South Africa were identified (Fig. S2).

To assess which of those 44 indicators are the most relevant for representing vulnerability of these two systems towards drought, an online expert survey was conducted as a joint effort with the National Disaster Management Centre (NDMC) of South Africa. A total of 33 experts representing all provinces of South Africa participated in this survey. They selected 36 relevant indicators for irrigated systems and 40 for rainfed (Fig. S2). These experts were from multiple sectors including academia (n = 4), private sector (n = 5), NGO (n = 1), government (n = 20), international organizations (n = 1) and others (n = 2). The final selection of relevant indicators for each agricultural system based on the survey results followed a two-step approach as proposed by the (European Commission, JRC, 2019): i) Indicators were kept if more than half of the experts considered them a medium-high or highly relevant and ii) *Z*-scores with a 95% confidence interval were used to ensure that there was high level of agreement among the experts. The data was then standardized to give each indicator a value between 0 and 1 in each category (i.e. not relevant, low relevance, low-medium relevance, medium high relevance and highly relevant). The average was then calculated by dividing the total number of replies given for each indicator by the total number of answers given for each indication. Indications with a value near 1 are extremely relevant, while indicators with a value near 0 are less relevant (Fig. S2).

Open-source data for the selected indicators was retrieved (Table 2, e.g. statistics from StatSA (2011, 2016a, 2016b); National Treasury (2019), World Bank (2019, 2020)) in order to ensure that the final results can be validated and reproduced in a different context - as recommended by Naumann et al. (2014a, 2014b). Following the methodological suggestions by Hagenlocher et al. (2018a, 2018b), Meza et al. (2020a, 2020b), Naumann et al. (2014a, 2014b), and OECD (2008a, 2008b), statistical operations were performed to prepare an indicator dataset to perform the vulnerability assessment (S1 & Fig. S1): i.e., i) imputation of missing data, ii) normality test, iii) outlier detection and treatment, iv) multicollinearity assessment, v) normalization and vi) expert weighted aggregation.

The selected vulnerability indicators were normalized to make them comparable. A linear min-max normalization was applied to create a range between 0 (lowest vulnerability) to 1 (highest vulnerability) (Beccari, 2016; Carrão et al., 2016).

The final step to build the composite vulnerability index (CVI) for each agricultural system (irrigated and rainfed) was the weighted arithmetic aggregation for each vulnerability component (SOC-ENV_SUS and lack of COP) based on the normalized indicators (Z_i) and the weights obtained from the expert survey (W_i).

$$\text{CVIIrrigated} = \sum_{i=1}^{n}(Zi * Wi) \qquad \text{CVIrainfed}\sum_{i=1}^{n}(Zi * Wi) \tag{3}$$

2.5.1. Reliability analysis

In order to increase the transparency on the data quality used to perform the vulnerability assessment, a metric to calculate the reliability of the data for each local municipality was developed. Following suggestions of the European Commission, JRC (2017) in their Index for Risk Management (INFORM) and Hagenlocher et al. (2018a, 2018b), the reliability metric included two dimensions i) average year of the data sources (recency) and ii) percentage of missing data across all indicators. Each dimension score was then normalized to a scale from 0 to 1, aggregated and averaged in order to have the final reliability scores. Where the tendency to 1 indicates that the vulnerability score for that particular local municipality is based on more reliable data, while the tendency to 0 indicates less reliable data (Supplementary material Fig. S3).

The reliability metric was computed separately for each of the two agricultural systems considered in this article (irrigated and rainfed).

2.6. Risk assessment

Drought risk, in any particular area, is composed of hazard, exposure, and vulnerability (IPCC, 2014). For this paper, hazard/exposure and vulnerability were combined through a matrix approach (Fig. S8). Two different drought risk assessments were performed - one for irrigated agricultural systems and one for rainfed systems - at the municipality level. Following methodological suggestions of the International Standard on Risk Norm ISO/IEC 31010 (IEC (International Electrotechnical Commission), 2019), Frigerio and De Amicis (2016) and Tung et al. (2019) the CVI and hazard/exposure for each agricultural system was classified into seven classes using equal intervals from the maximum, and then those classes were combined to obtain the final risk for each agricultural system (Supplementary material Fig. S8).

3. Results

3.1. Drought hazard and exposure of agricultural systems

Our results demonstrate a large variability in drought hazard and exposure among provinces and local municipalities. The most extreme drought hazard/exposure for rainfed conditions is observed in the North Cape, North West and Limpopo provinces during the study period (Fig. 3). On the other hand, the lowest hazard and exposure in the period 1981-2018 is computed for Kwazulu Natal province (Fig. 3). Western and central parts of Eastern Cape and Mpumalanga provinces also have a low level of rainfed drought hazard/exposure (Fig. 3). The time series analysis of drought hazard and exposure showed that 1992 and 2016 were the driest years during the study period under rainfed conditions (Figs. 4 and S4). The year 2000 and 2006 are classified as wettest years across South Africa (supplementary material (Figs. 4 and S4). The frequency of dry years for rainfed systems remarkably increased after year 2010.

In general, the irrigated systems are less often affected by drought than rainfed systems, with larger areas exposed to drought in Limpopo and Eastern Cape provinces of South Africa (Fig. 3). These areas have semi-arid to arid climates and are characterised with less annual precipitation than the rainfed growing areas of the country. For irrigated croplands, larger areas were affected by drought hazard/exposure since 2012, even in areas that have low share of irrigated croplands, such as north western municipalities in the Northern Cape (Figs. 3 and 5). Despite smaller areas of hazard/exposed irrigated land compared to rainfed areas, the impacts can be significant due to the number of affected people. Roughly about 230,000 irrigation farmers were affected, mostly smallholders often with very small plots for self-consumption (FAO, 2016). The highest hazard/exposure was found in years 2015-2016 and the lowest in year 2001 (Figs. 5 and S5).

The accuracy of simulated hazard/exposure for rainfed agricultural systems was tested by comparing modeling outputs with remotely sensed exposure data in the period 2001-2018 (Fig. 6). There was a strong correlation (0.5 to 0.9) between remotely sensed and simulated drought exposure for rainfed conditions for most of the municipalities across South Africa. The lowest correlation (0 to 0.2) was obtained in a limited number of municipalities mainly in KwaZulu-Natal and Eastern Cape provinces, which are largely covered by natural grasslands. The annual drought signal obtained by remote sensing may therefore deviate considerably from the conditions in the cropping period considered in the model.

Moreover, we assessed the relationships between annual drought exposure simulated for rainfed systems and yield/production reported at the country scale (FAO, 2021). The correlation coefficient among simulated drought exposure and reported yield and production anomalies were −0.32 and −0.41, respectively (Fig. S6) which means that drought resulted in lower yields and production. The model reproduced the drought for the years (1992–2015–2016) which showed the largest yield/production reduction. As a second analysis, we performed the assessment for maize production anomaly in South Africa in the period 1986 to 2018 and its relationship with the annual rainfed hazard/drought simulated for rainfed systems across five most important maize production provinces in South Africa (Fig. S7). The results showed a remarkable overlap between negative production anomalies and simulated drought hazard for all provinces, e.g. in years 1992-93, 2007, 2013 and 2016. In contrast, positive production anomalies were recorded in all provinces in years with low drought hazard such as 1991, 2006 or 2014 (Fig. S7). It is important to note that the FAO and regional yield/production data did not distinguish between rainfed and irrigated systems. Therefore, we expected even higher correlations when separate data would become available.

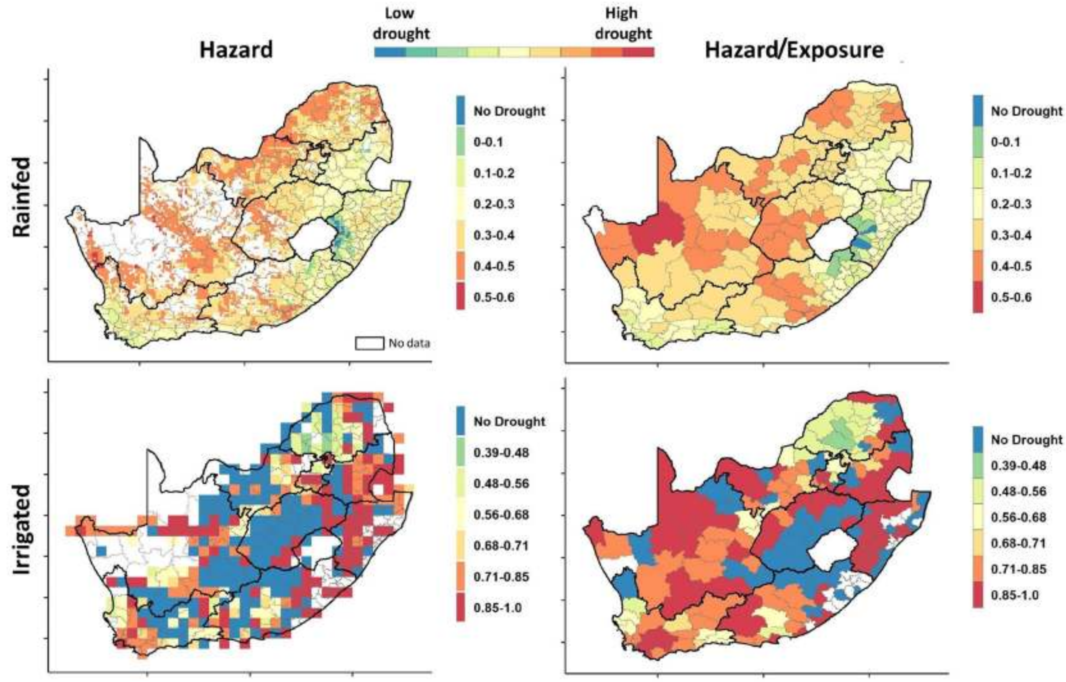

Fig. 3. Long-term drought hazard and combined hazard/exposure for rainfed (top row) and irrigated (bottom row) cropping systems across South Africa at grid and local municipality levels in the period 1981–2018.

3.2. Vulnerability and risk of rainfed and irrigated systems

The vulnerability assessment shows heterogeneity across the country (Fig. 7) for both systems. Our assessment highlights that crops under rainfed systems are more vulnerable to drought than irrigated systems. Several indicators contribute to the difference, but the most relevant are the lack of area equipped for irrigation, which affects the coping capacity of the system, followed by a low fertilizer application rate.

According to the experts (Table 2 and Fig. S2), the most relevant vulnerability indicator for irrigated systems is unemployment rate (%). This is also recognized as a relevant indicator by the scientific community in

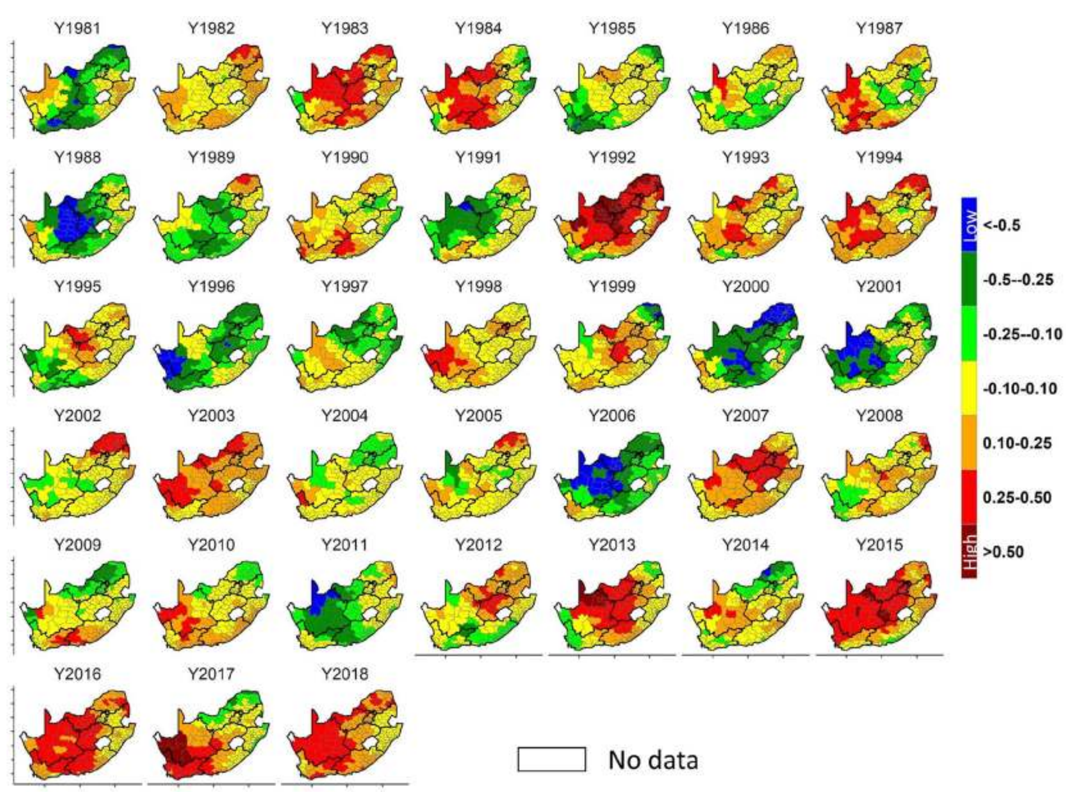

Fig. 4. Annual drought hazard/exposure for rainfed cropping systems across local municipalities of South Africa in the period 1981–2018.

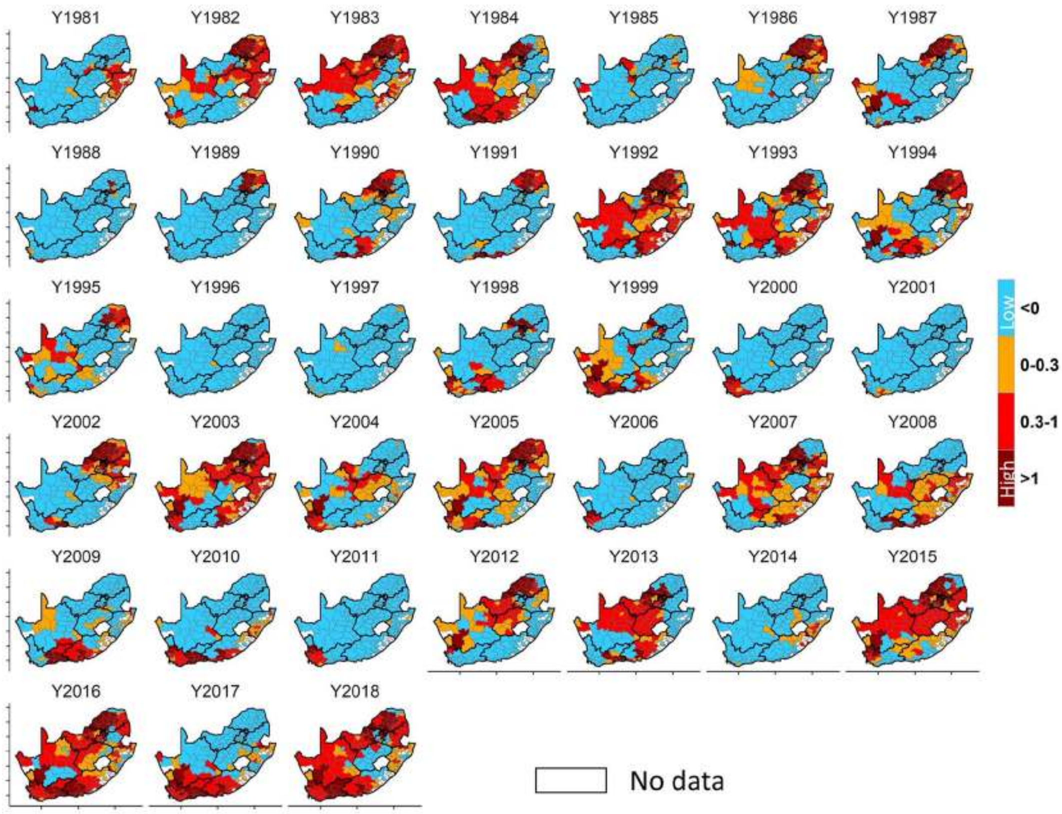

Fig. 5. Drought hazard/exposure for the irrigated cropping system across local municipalities of South Africa for the period 1981–2018.

the South African context as the country suffers from deep structural unemployment having a direct impact on poverty levels (Chibba and Luiz, 2011). Agriculture proved to be the best way to reduce rural poverty according to the rural development literature, besides, in most developing countries, agriculture and agriculture-related activities provide most of the rural employment (Machethe, 2004). Irrigation schemes have had great impact in South Africa, not only in food production but also alleviating poverty. One notable example is the one caused by the Great Depression by resettling of returning soldiers that reduced the unemployment rate in the country (FAO, 2016). Irrigated agriculture employs between 10% and 15% of the total agricultural workforce (DWA, 2002).

The most relevant indicator for rainfed systems according to the experts (Table 2) is the percentage of households with an alternative to farm income. Low harvests threaten the households that only depend on their farm income (~97%); this could result from a drought period that requires compromising their entire livelihoods. Having an alternative income may increase their coping capacities as they do not depend solely on the agricultural income derived from crop sales.

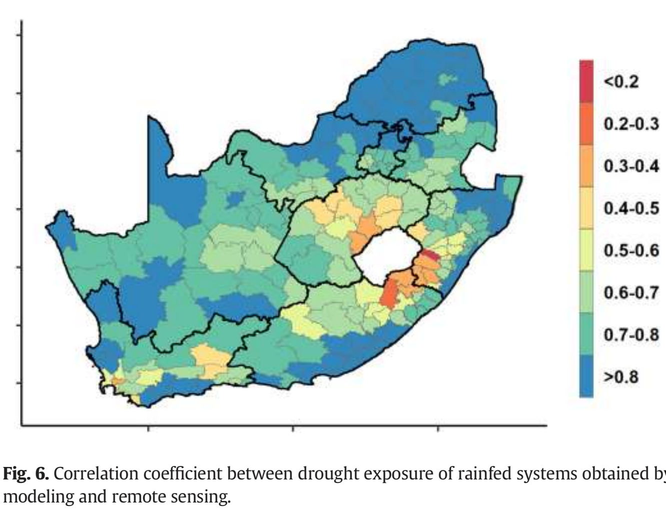

Fig. 6. Correlation coefficient between drought exposure of rainfed systems obtained by modeling and remote sensing.

The experts assigned to the two indicators "population with assistive devices and medication (disability)" and "total dam storage capacity" high weights for irrigated systems but much lower weights for rainfed systems. In contrast, the indicators "households with alternative farm income" and "debtors" received high weights for rainfed systems and much lower importance for irrigated systems.

The vulnerability maps display high values particularly on irrigated systems for the Western Cape municipalities and for rainfed agricultural systems in KwaZulu-Natal. Our findings underline that determining factors of vulnerability vary depending on the sector which is susceptible to the negative impacts of drought. For instance, the main indicators which shape the vulnerability for irrigated systems and are potential entry points for the drought risk reduction is the lack of environmental awareness, poor water quality, and low total dam storage capacity. In the South African context this is due to the limited access to extension services (e.g. geographically remote farmers tend to have little network coverage), and very limited financial resources to invest in technologies or utilities. Resulting in a lack of accessible, relevant, and practical information to share, as well as few or no opportunities to expand the irrigation farmers' capacities (FAO, 2020b).

For rainfed agricultural systems, the key indicators shaping the socio-environmental susceptibility and the coping capacities of the local municipalities are the small fertilizer application rate, the lack of area equipped for irrigation, and land degradation. This last indicator is relevant for both systems; land degradation is linked to different factors in the context of agricultural systems in South Africa, one of them is the lack of environmental awareness that led to unsustainable farming practices (Rother et al., 2008; Schulze, 2016).

The drought risk assessment highlights its context-specificity and how different communities of a country experience different levels of

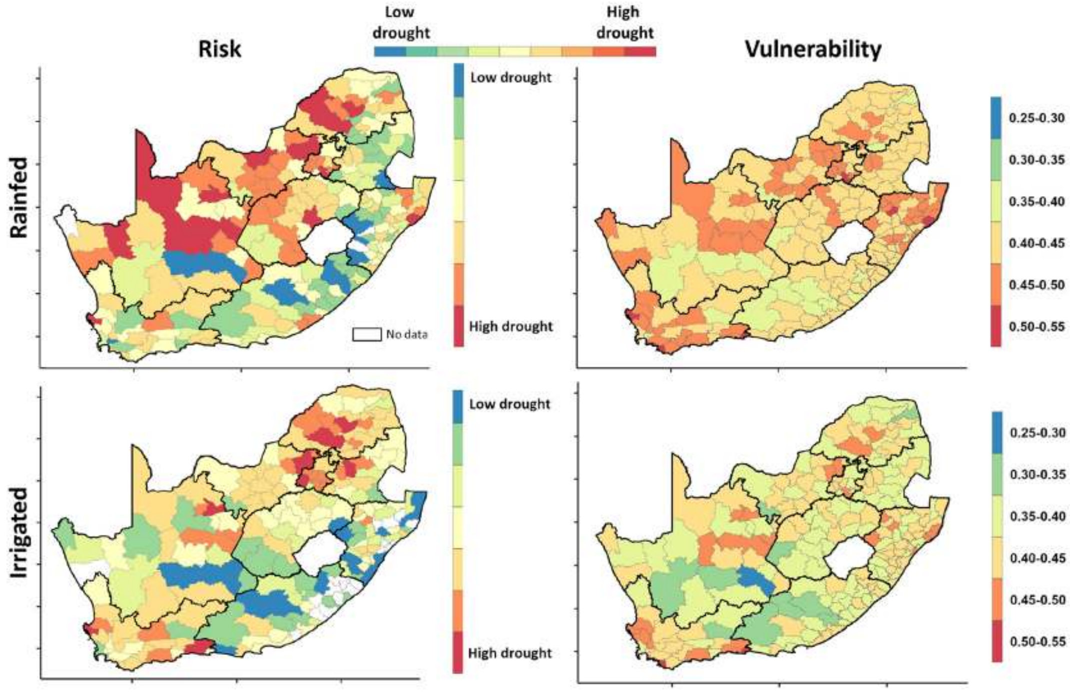

Fig. 7. Drought vulnerability and risk in South Africa at local municipality level for rainfed (top row) and irrigated agriculture (bottom row). Tendency to dark blue shows lower levels of vulnerability and risk, the tendency to red shows higher vulnerability or risk values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

risk. Drought risk varies substantially for rainfed and irrigated systems (Fig. 7). There is a high-risk pattern towards the North provinces for rainfed agricultural systems. Meanwhile, high-risk hotspots for irrigated agricultural systems can be found in some local municipalities of Limpopo (e.g. Modimolle, Polokwane local municipalities), North West (e.g. Merafong, Rustenburg) and Gauteng (e.g. Merafong city, Rand West city) provinces.

When analyzing the risk for rainfed systems, among the local municipalities in the Northern Cape, Emthanjeni has the lowest risk score than other provinces despite its high hazard and exposure levels; it is explained by a lower social susceptibility (e.g. overall quality of water services, less population have experienced crime and theft of livestock), and higher coping capacities (e.g. access to credits). In contrast, the local municipality of Khai-Ma in the same province has lower vulnerability than other local municipalities, but its high hazard and exposure scores result in a high risk.

In order to identify priority areas for disaster risk management, the risk assessment of each agricultural system was plotted against the crop dependent population in each local municipality (Fig. 8). The comparison shows that the local municipalities with higher irrigated and rainfed systems are not among the highest in terms of crop dependent population. The city of Johannesburg presents a higher crop dependency, but also has high risk for both systems. Its drought hazard and exposure are high, and the vulnerability analysis reveals that their lack of environmental awareness, fertilization rate and land degradation are key factors contributing to their overall very high risk; highlighting the relevance to take actions in this municipality. Johannesburg, the largest city in South Africa, is facing enormous challenges which reflect on the drought vulnerability level. Challenges like urbanisation's impact on the soil and water quality and availability, and facing non-sustainable growth paths (SACN, 2016) have significant impacts on the magnitude of Johannesburg's vulnerability towards drought.

In contrast, the city of Tshwane has a high number of crop dependent population, but it presents a medium rainfed risk and very low irrigated risk. Its medium risk is explained by its medium-low vulnerability as a result of better performance in nutrition level, good water quality and road density, among others.

The Northern-Cape province has the lowest population dependent on crops. However, it is one of the provinces with more local municipalities on high rainfed risk, as this province has arid climate which exposes rainfed crops to high drought hazard. In contrast, the Limpopo province has a higher amount of population dependent on crops, but more local municipalities are at high risk for irrigated systems.

4. Discussion

The dependency of agriculture on water resources (approx. 60% of the total water demand (Schreiner et al., 2018) is making water availability one of the key factors for the agricultural system, furthermore, the predominance of rain-fed agriculture in South Africa makes the country extremely susceptible to drought. Despite this, drought risk management remains ambiguous and mainly reactive (Hornby et al., 2016; Baudoin et al., 2017; Vogel and Olivier, 2019). Drought is a recurrent phenomenon in South Africa's climate and is one of the most relevant hazards (Gibberd et al., 1996; Jordaan et al., 2017a). In fact, all local municipalities were affected by drought during the last 30 years (Figs. 4 and 5). The dependency of South Africa's economy on agricultural products emphasises the importance of drought risk assessments and the identification of potential entry points for reducing its vulnerability. An integrated hazard, exposure and vulnerability assessment of the agricultural sector (irrigated, rainfed) specifically was lacking so far for South Africa at national level, and it is presented here for the first time. Furthermore, the methodology can be transferable in other regions, the hazard and exposure assessment can be reproduced in any country, however the vulnerability assessment is context specific and some indicators that might be relevant for South Africa will not be for another country, therefore, we suggest to identify key indicators following the methodology applied on this paper.

4.1. Limitations

Our innovative methodology to simulate hazard indicators captured the spatiotemporal pattern of the drought for a long-term period (back to 1980s); the time that remote sensing was not available (generally

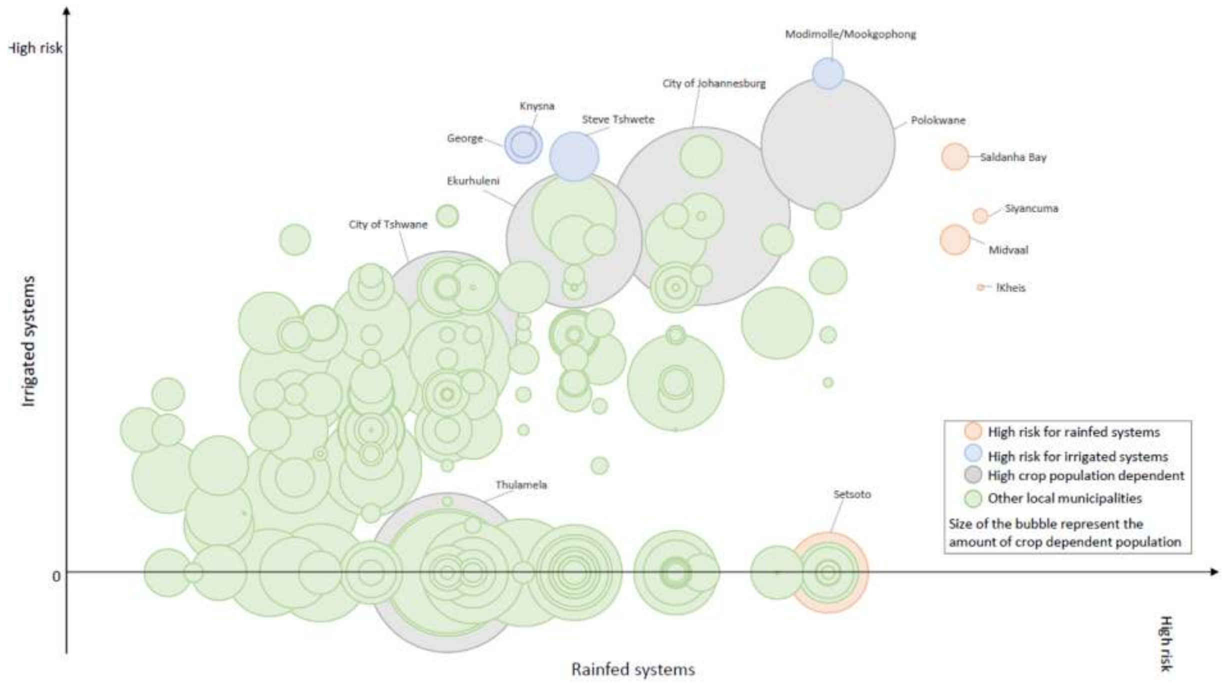

Fig. 8. Local municipalities contrasted with drought risk for rainfed (x axis) and irrigated (y axis) systems. The size of the bubbles represent the amount of crop dependent population by local municipality (Data from Statsa, 2016a, 2016b).

available from early 2000s). Our results show that exposure to drought in croplands varies for rainfed and irrigated systems, spatially and temporally. A time series of exposure for irrigated and rainfed agriculture shows different patterns; this proves the necessity for separate analysis for these two cropping systems. The hazard indicators for rainfed and irrigated systems were computed in different ways; for rainfed systems, we assume a strong impact of meteorological drought on the system while for irrigated systems, we assume a strong impact of hydrological drought on the system. Therefore, hazard indicators and, subsequently, risk indicators for irrigated and rainfed systems should not be directly compared.

To better manage and mitigate drought risk, it is necessary to improve the response to drought impacts, the preventive actions and actively address the root causes of vulnerability as well as build capacities as in the local communities and the government. The vulnerability assessment helps to identify potential entry points to reduce the level of drought risk for both irrigated and rainfed systems; which include better water quality, reduction of land degradation, and increasing the dam storage capacity. Specifically for rainfed systems with high risk could become irrigated if they are located in regions where irrigated risk is low as areas equipped for irrigation can help in supporting the livelihood of rural communities and food production. However, it is relevant to consider the water availability, the access to the water source, the soil and topography conditions, among others before installing any irrigation system.

The contribution of relevant experts on selecting and weighting vulnerability indicators is an added value of this assessment. However, the expert survey consultation could be enhanced by expert interviews, where more details and the rationality behind the ranking of the different indicators could be further explained. Another point of improvement is the number of experts who responded to the survey. With more time and resources, more experts could participate.

As this study is the first to separately assess the drought risk for rainfed and irrigated agricultural systems, there is no comparison of our findings with other national assessments. However, the drought risk analysis results and its components agree with other studies conducted at the local level for agricultural systems. For instance, Eastern Cape's vulnerability pattern follows an east-west descending gradient reported by Walz et al. (2018). Jordaan et al. (2013) showed that the coping capacities such as the land ratio and management, access to credit and markets are key in determining the level of risk in the Northern Cape. Similar to the results of this study, Schreiner et al. (2018) suggests that expanding the storage capacity of existing dams and water conservation practices would reduce drought risk, especially for irrigated agricultural systems. Furthermore, the low drought risk values identified for the Northern Cape for irrigated systems also agree with previous drought risk assessments performed by Jordaan (2011) and Jordaan et al. (2013).

It is necessary to analyse and interpret the drought risk through systems perspective (Vogel and Olivier, 2019), as extreme droughts and its impacts are not a result of a linear equation, rather they reflect the dynamic and complex realities of the socio-ecological system. To address the complex realities in this assessment, we considered the nature of farming in South Africa in terms of climate and social factors (e.g. dependency ratio, unemployment rate). An enhancement for future assessments could be the integration of temporal dynamic exposure and vulnerability with the hazard data. As Schreiner et al. (2018) stated, the South African government knows that drought is a recurrent hazard, and particularly with climate change, it is critical to implement the necessary structures to support the diverse makeup of the agricultural sector. Further, it is necessary to plan actions according to specific needs of the system, irrigated or rainfed. We also need to understand better how severe, prolonged and repetitive drought events might shift policies, local and rural economies, and actions (Schreiner et al., 2018).

Despite the wealth of climate change and drought policies and responses in South Africa, recent droughts are a stark reminder of the realities of climate variability and the difficulty of effectively responding. Notwithstanding the examples and legislation mentioned, recent responses to drought reveal a lack of awareness and a need for a broadly informed assessment of drought in a rapidly changing socio-environmental context (Vogel and Olivier, 2019). So far, while the changes on policy over time have had the goal to improve drought risk management, the focus is still largely on relief and emergency support instead of implementing proactive policies (Vogel and Van Zyl, 2016; Bruwer, 1989; Vogel et al., 2010;

South African Weather Service, 2017 in Baudoin et al., 2017). Interdisciplinary drought risk assessments like the one presented here can be used in decision-making processes. These assessments help to identify potential pathways and actions towards proactive drought risk reduction policies such as the increasing access to finance, increasing extension services and programs in order to improve the environmental awareness, reducing land degradation and increasing farmers' capacities towards a sustainable agroecosystems.

Limitations in data availability impact the accuracy of our research like many others. For instance, the hazard and exposure analysis is based on the land cover data from one timestep (static input data), which can impact the results (i.e., as cropping patterns are dynamic and often can change over time).

Furthermore, future analysis can be improved by accounting for risk differences of individual crop types, and exposed farmers.

4.2. Recommendations and next steps

There are various ways to measure drought hazard, and composite indices could make additional use of surface and ground water deficit, provided that time series for these variables can be reliably derived from hydrological modeling. In recent years the observation of surface water volume changes from remote sensing, and of groundwater variability from the GRACE and GRACE-FO satellite missions combined with data assimilation, has made tremendous progress and we expect that adding such indices would lend more robustness to our risk assessment framework.

Future assessments may benefit from new approaches to assess vulnerability beyond administrative boundaries (e.g., pixel-level vulnerability data), since much of the information and effort in analyzing hazard and exposure at the smallest possible resolution is lost when aggregated at administrative boundary levels reducing the capacity to accurately reflect reality. In addition to examining the environmental, social and political processes shaping drought risk, an enhancement for this assessment could be developing a reliable and standardized database of losses and damages regarding agricultural systems in South Africa. Such database can help better examine the medium- and long-term impacts of drought and allow the comparison of impacts of similar hazard events in different parts of the country (e.g. drought of 2015-2016) (JRC (Joint Research Centre. European Commission), 2014). It could also help identify indirect and cascading effects even after the drought hazard event is finished. Moreover, loss data collections can be useful to identify trends and patterns in data over time (JRC (Joint Research Centre. European Commission), 2014), and to achieve consistent and coordinated implementation of risk reduction strategies.

5. Conclusions

Drought impacts on South Africa's agricultural sector are recurrent; these drought events provide opportunities to learn and to improve drought risk reduction efforts. We present, for the first time, an integrated drought risk assessment that considers hazard, exposure and vulnerability to evaluate the impact of drought on irrigated and rainfed systems (separately) at national level. In addition, we pioneer an expert survey to weigh relevant indicators at national level. Our spatially explicit results assist to identify priority regions to take actions. Our findings highlight the relevance of assessing and discussing drought risk in relation to specific impacts and diagnosing entry points to reduce drought risk in a context-specific manner (i.e. irrigated and rainfed systems). This ensures that relevant proactive policies and planning can be effective even within the same sector (i.e. agricultural sector) before the worst impacts occur. While this assessment provides valuable information at local municipality level, the assessment can be enhanced with a temporal dynamic exposure and more spatially explicit vulnerability information.

CRediT authorship contribution statement

IM conducted the risk assessment with the support of EER, SS, and MH. SS, JK, HG, CH, EP, EER and HN developed the hazard indicators and EER conducted the hazard/exposure analysis. IM conducted the expert survey. IM and MH were responsible for the vulnerability assessment. All authors have contributed to drafting the manuscript, the interpretation of the results, and the process of approving the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.149505.

References

AFRA (Association for Rural Advancement), 1993. Drought Relief and Rural Communities. Special Rep. No. 9. Pietermaritzburg, South Africa.
Ahmadalipour, A., Moradkhani, H., Castelletti, A., Magliocca, N., 2019. Future drought risk in Africa: integrating vulnerability, climate change, and population growth. Sci. Total Environ. 662, 672–686. https://doi.org/10.1016/j.scitotenv.2019.01.278.
Asadieh, B., Krakauer, N.Y., 2017. Global change in streamflow extremes under climate change over the 21st century. Hydrol. Earth Syst. Sci. 21, 5863–5874. https://doi.org/10.5194/hess-21-5863-2017.
Batjes, N.H., 2016. Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. Geoderma 269, 61–68. https://doi.org/10.1016/j.geoderma.2016.01.034.
Baudoin, M.-A., Vogel, C., Nortje, K., Naik, M., 2017. Living with drought in South Africa: lessons learnt from the recent El Niño drought period. Int. J. Disaster Risk Reduct. 23, 128–137. https://doi.org/10.1016/j.ijdrr.2017.05.005.
Beccari, B., 2016. A comparative analysis of disaster risk, vulnerability and resilience composite indicators. PLoS Curr. 8.
Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci. Data 5, 180214. https://doi.org/10.1038/sdata.2018.214.
BFAP (Bureau for Food and Agricultural Policy), 2016. Policy brief on 2015/2016 drought. Available at. http://www.nstf.org.za/wp-content/uploads/2016/06/Agri-SA-Drought-Report_CS4.pdf. (Accessed 23 November 2020).
Bruwer, J.J., 1989. Drought policy in the Republic of South Africa. Proceedings of the SARCCUS Workshop on Drought, Alpha Training Center, South Africa P.23.
Bruwer, J.J., 1993. Drought policy in the Republic of South Africa. In: Wilhite, D.A. (Ed.) Drought Assessment, Management, and Planning: Theory and Case Studies. Natural Resource Management and Policy vol 2. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-3224-8_11.
Carrão, H., Naumann, G., Barbosa, P., 2016. Mapping global patterns of drought risk: an empirical framework based on sub-national estimates of hazard, exposure and vulnerability. Glob. Environ. Chang. 39, 108–124. https://doi.org/10.1016/j.gloenvcha.2016.04.012.
Chen, J., Deng, M., Xia, L., Wang, H., 2017. Risk assessment of drought, based on IDM-VFS in the Nanpan River Basin, Yunnan Province, China. Sustainability 9 (7), 1124. https://doi.org/10.3390/su9071124.
Chibba, M., Luiz, J.M., 2011. P. Econ. Pap. 30, 307–315. https://doi.org/10.1111/j.1759-3441.2011.00129.x.
DAFF, 2018. Abstract of agricultural statistics. South African Department of Agriculture, Forestry and Fisheries. http://www.daff.gov.za/Daffweb3/Portals/0/Statistics%20and%20Economic%20Analysis/Statistical%20Information/Abstract%202018.pdf. (Accessed 7 October 2020).

DAFF, 2019. Abstract of agricultural statistics. South African Department of Agriculture, Forestry and Fisheries. https://www.dalrrd.gov.za/Portals/0/Statistics%20and%20Economic%20Analysis/Statistical%20Information/Abstract%202019.pdf. (Accessed 1 May 2021).
Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Chang. 3 (1), 52.
DALRRD (Department of Agriculture, Land Reform and Rural Development, 2020. Agriculture, land reform and rural development | South African government. https://www.gov.za/about-sa/agriculture. (Accessed 20 May 2021).
DEA, 2019. Department of Environmental Affairs. https://www.environment.gov.za/projectsprogrammes/egis_landcover_datasets. (Accessed 15 February 2020).
de Sherbinin, A., Bukvic, A., Rohat, G., Gall, M., McCusker, B., Preston, B., Apotsos, A., Fish, C., Kienberger, S., Muhonda, P., Wilhelmi, O., Macharia, D., Shubert, W., Sliuzas, R., Tomaszewski, B., Zhang, S., 2019. Climate vulnerability mapping: a systematic review and future prospects. WIREs Clim Change https://doi.org/10.1002/wcc.600.
Deng, M., Chen, J., Huang, J., Niu, W., 2018. Agricultural drought risk evaluation based on an optimized comprehensive index system. Sustainability 10 (10), 3465. https://doi.org/10.3390/su10103465.
Department of Agriculture, Forestry and Fisheries (DAFF), 2016. LADA Degradation Index. https://doi.org/10.15493/DEA.CARBON.10000018.
Dilley, M., Chen, R.S., Deichmann, U., Lerner-Lam, A.L., Arnold, M., Agwe, J., Buys, P., Kjekstad, O., Lyon, B., Yetman, G., 2005. Natural Disaster Hotspots: A Global Risk Analysis (Disaster Risk Management Series; No. 5). The World Bank Group.
Downing, T.E., Bakker, K., 2000. Drought Discourse and Vulnerability. Chapter 45. In: Wilhite, D.A. (Ed.), Drought: A Global Assessment, Natural Hazards and Disasters Series. Routledge Publishers, Abingdon.
du Pisani, L.G., Fouché, H.J., Venter, J.C., 1998. Assessing rangeland drought in South Africa. Agric. Syst. 57, 367–380. https://doi.org/10.1016/S0308-521X(98)00024-9.
DWA, 2002. Governing Board Induction Manual. Department of Water Affairs.
European Commission, Joint Research Centre, 2017. Index for risk management - INFORM: concept and methodology, version 2017. Publications Office, LU. https://drmkc.jrc.ec.europa.eu/inform-index. (Accessed 18 February 2020).
European Commission, Joint Research Centre, 2019. Drought vulnerability indicators for global-scale drought risk assessments: global expert survey results report. Publications Office, LU. https://publications.jrc.ec.europa.eu/repository/handle/JRC117546. (Accessed 15 March 2020).
FAO, 1997. The political economy of food, agriculture and irrigation development in East and Southern Africa [WWW Document]. http://www.fao.org/3/w7314e/w7314e09.htm. (Accessed 26 January 2021).
Fao, 2016. AQUASTAT Country Profile –South Africa. Rome, Italy, Food and Agriculture Organization of the United Nations (FAO).
FAO, 2019. GIEWS Update. Southern AfricaDry weather conditions reduce agricultural production prospects in 2019. Available at. https://reliefweb.int/sites/reliefweb.int/files/resources/ca3071en_0.pdf. (Accessed 10 July 2020).
FAO, 2020a. FAOSTAT crops dataset. Available at. http://www.fao.org/faostat/en/#data/QC. (Accessed 2 May 2021).
FAO, 2020a. Country profile, South Africa. http://www.fao.org/3/x9751e/x9751e07.htm. (Accessed 8 January 2020).
FAO, 2020b. Digital Agriculture Profile South Africa. http://www.fao.org/3/cb2506en/CB2506EN.pdf. (Accessed 2 January 2021).
FAO, 2021. FAOSTAT crops dataset. Available at. http://www.fao.org/faostat/en/#data/QC. (Accessed 2 May 2021).
Frigerio, I., De Amicis, M., 2016. Mapping social vulnerability to natural hazards in Italy: a suitable tool for risk mitigation strategies. Environ. Sci. Pol. 63, 187–196. https://doi.org/10.1016/j.envsci.2016.06.001.
Frischen, J., Meza, I., Rupp, D., Wietler, K., Hagenlocher, M., 2020. Drought risk to agricultural Systems in Zimbabwe: a spatial analysis of Hazard, exposure, and vulnerability. Sustainability 12 (3), 752. https://doi.org/10.3390/su12030752.
Gibberd, V., Rook, J., Sear, C.B., Williams, J.B., 1996. Drought Risk Management in Southern Africa. The Potential of Long Lead Climate Forecasts for Improved Drought Management.
Global Dams Database, 2020. GraND Data Catalog [WWW Document]. https://datacatalog.worldbank.org/dataset/global-dams-database. (Accessed 12 March 2020).
Hagenlocher, M., Renaud, F.G., Haas, S., Sebesvari, Z., 2018. Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards. Sci. Total Environ. 631–632, 71–80. https://doi.org/10.1016/j.scitotenv.2018.03.013.
Hagenlocher, M., Renaud, F.G., Haas, S., Sebesvari, Z., 2018. Vulnerability and risk of deltaic social-ecological systems exposed to multiple hazards. Sci. Total Environ. 631–632, 71–80. https://doi.org/10.1016/j.scitotenv.2018.03.013.
Hagenlocher, M., Meza, I., Anderson, C.C., Min, A., Renaud, F.G., Walz, Y., Siebert, S., Sebesvari, Z., 2019. Drought vulnerability and risk assessments: state of the art, persistent gaps, and research agenda. Environ. Res. Lett. 14, 083002. https://doi.org/10.1088/1748-9326/ab225d.
Han, L., Zhang, Q., Ma, P., Jia, J., Wang, J., 2016. The spatial distribution characteristics of a comprehensive drought risk index in southwestern China and underlying causes. Theor. Appl. Climatol. 124 (3–4), 517–528. https://doi.org/10.1007/s00704-015-1432-z.
Hardy, M., Dziba, L., Kilian, W., Tolmay, J., 2011. Rainfed farming systems in South Africa. In: Tow, P., Cooper, I., Partridge, I., Birch, C. (Eds.), Rainfed Farming Systems. Springer, Netherlands, Dordrecht, pp. 395–432 https://doi.org/10.1007/978-1-4020-9132-2_16.
Hassan, R., 2013. Drought management strategies in South Africa and the potential for economic policy instruments. In: Schwabe, K., Albiac, J., Connor, J., Hassan, R., Meza González, L. (Eds.), Drought in Arid and Semi-Arid Regions. Springer, Dordrecht https://doi.org/10.1007/978-94-007-6636-5_21.
Heim Jr., R.R., 2002. A review of twentieth century drought indices used in the United States. Bull. Am. Meteorol. Soc. 83 (8), 1149–1165.
Hengl, T., Heuvelink, G.B.M., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Shepherd, K.D., Sila, A., MacMillan, R.A., Mendes de Jesus, J., Tamene, L., Tondoh, J.E., 2015. Mapping soil properties of Africa at 250 m resolution: random forests significantly improve current predictions. PLoS ONE 10, e0125814. https://doi.org/10.1371/journal.pone.0125814.
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146, 1999–2049. https://doi.org/10.1002/qj.3803.
Hornby, D., Vanderhaeghen, Y., Versveld, D., Ngubane, M., 2016. A harvest of dysfunction – rethinking the approach to drought, its causes and impacts in South Africa. Oxfam Report, Johannesburg. https://www.oxfam.org.za/wp-content/uploads/2017/03/Final-Final-OZA-Oxfam-Drought-Report.pdf. (Accessed 15 June 2020).
Huang, L., He, B., Han, L., Liu, J., Wang, H., Chen, Z., 2017. A global examination of the response of ecosystem water-use efficiency to drought based on MODIS data. Sci. Total Environ. 601–602, 1097–1107. https://doi.org/10.1016/j.scitotenv.2017.05.084.
IEC (International Electrotechnical Commission), 2019. Technical Committee 56, International Organization for Septuagint and Cognate Studies, Congress. Risk management: risk assessment techniques = Management du risque -Techniques d'appreciation du risque.
IPCC, 2014. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York - Cambridge.
Jordaan, A.J., 2011. Drought Risk Reduction in the Northern Cape. University of the Free State, Bloemfontein.
Jordaan, A., Sakulski, D., Jordaan, A., 2013. Interdisciplinary drought risk assessment for agriculture: the case of communal farmers in the northern Cape Province, South Africa. S. Afr. J. Agric. Ext. 41, 01–16.
Jordaan, A.J., South Africa, Water Research Commission, South Africa, Department of Agriculture, F., and Fisheries, Sakulski, D.M., Muyambo, F., 2017a. Vulnerability, adaptation to and coping with drought: the case of commercial and subsistence rain fed farming in the Eastern Cape. Volume I: report to the Water Research Commission and Department of Agriculture, Forestry and Fisheries Volume I: report to the Water Research Commission and Department of Agriculture, Forestry and Fisheries. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT%20716-17.pdf. (Accessed 9 May 2020).
Jordaan, A.J., Water Research Commission, Sakulski, D.M., Muyambo, F., Africa, South, 2017b. Vulnerability, adaptation to and coping with drought: the case of commercial and subsistence rain fed farming in the Eastern Cape. Vol. II. WRC. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT%20716-2-17.pdf. (Accessed 29 October 2020).
JRC (Joint Research Centre. European Commission), 2014. Current status and best practices for disaster loss data recording in EU Member States. Institute for the Protection and the Security of the Citizen. Publications Office, LU.
Kamali, B., Abbaspour, K.C., Wehrli, B., Yang, H., 2018. Drought vulnerability assessment of maize in Sub-Saharan Africa: insights from physical and social perspectives. Glob. Planet. Chang. 162, 266–274. https://doi.org/10.1016/j.gloplacha.2018.01.011.
Kamruzzaman, Md., Kabir, Md.E., Rahman, A.T.M.S., Jahan, C.S., Mazumder, Q.H., Rahman, M.S., 2018. Modeling of agricultural drought risk pattern using Markov chain and GIS in the western part of Bangladesh. Environ. Dev. Sustain. 20 (2), 569–588. https://doi.org/10.1007/s10668-016-9898-0.
Le Maitre, D.C., Seyler, H., Holland, M., Smith-Adao, L., Nel, J.L., Maherry, A., Witthüser, K., 2018. Identification, Delineation and Importance of the Strategic Water Source Areas of South Africa, Lesotho and Swaziland for Surface Water and Groundwater, Report No. TT 743/1/18. Water Research Commission, Pretoria.
Lehner, B., Liermann, C.R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rödel, R., Sindorf, N., Wisser, D., 2011. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Front. Ecol. Environ. 9, 494–502. https://doi.org/10.1890/100125.
Machethe, C.L., 2004. Agriculture and poverty in South Africa: can agriculture reduce poverty. Overcoming Underdevelopment Conference Held in Pretoria. Citeseer, p. 29.
Magombeyi, M.S., Taigbenu, A.E., 2008. Crop yield risk analysis and mitigation of smallholder farmers at quaternary catchment level: case study of B72A in Olifants river basin, South Africa. Phys. Chem. Earth 33, 744–756. https://doi.org/10.1016/j.pce.2008.06.050.
Mahlalela, P.T., Blamey, R.C., Hart, N.C.G., Reason, C.J.C., 2020. Drought in the eastern cape region of South Africa and trends in rainfall characteristics. Clim. Dyn. 55, 2743–2759. https://doi.org/10.1007/s00382-020-05413-0.
Masupha, T.E., Moeletsi, M.E., 2020. The use of water requirement satisfaction index for assessing agricultural drought on rain-fed maize, in the Luvuvhu River catchment, South Africa. Agric. Water Manag. 237, 106142. https://doi.org/10.1016/j.agwat.2020.106142.
Meza, I., Siebert, S., Döll, P., Kusche, J., Herbert, C., Eyshi Rezaei, E., Nouri, H., Gerdener, H., Popat, E., Frischen, J., Naumann, G., Vogt, J.V., Walz, Y., Sebesvari, Z., Hagenlocher, M., 2020. Global-scale drought risk assessment for agricultural systems. Nat. Hazards Earth Syst. Sci. 20, 695–712. https://doi.org/10.5194/nhess-20-695-2020.
Meza, I., Siebert, S., Döll, P., Kusche, J., Herbert, C., Eyshi Rezaei, E., Nouri, H., Gerdener, H., Popat, E., Frischen, J., Naumann, G., Vogt, J.V., Walz, Y., Sebesvari, Z., Hagenlocher, M.,

2020. Global-scale drought risk assessment for agricultural systems. Nat. Hazards Earth Syst. Sci. 20, 695–712. https://doi.org/10.5194/nhess-20-695-2020.
Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257. https://doi.org/10.1038/nature11420.
Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., Peiris, T.A., Popat, E., Portmann, F.T., Reinecke, R., Schumacher, M., Shadkam, S., Telteu, C.-E., Trautmann, T., Döll, P., 2020. The global water resources and use model WaterGAP v2.2d: Model description and evaluation. Geosci. Model Dev. Discuss. https://doi.org/10.5194/gmd-2020-225.
Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., Peiris, T.A., Popat, E., Portmann, F.T., Reinecke, R., Schumacher, M., Shadkam, S., Telteu, C.-E., Trautmann, T., Döll, P., 2020. The global water resources and use model WaterGAP v2.2d: Model description and evaluation. Geosci. Model Dev. Discuss. https://doi.org/10.5194/gmd-2020-225.
Muyambo, F., Jordaan, A.J., Bahta, Y.T., 2017. Assessing social vulnerability to drought in South Africa: policy implication for drought risk reduction. Jàmbá 9. https://doi.org/10.4102/jamba.v9i1.326.
National Treasury, 2003. Intergovernmental Fiscal Review, Republic of South Africa.
National Treasury, 2019. Balance Sheet Municipal Finance Data Tables Municipal Money Data [WWW Document]. https://municipaldata.treasury.gov.za/table/aged_creditor/?year=2019&amountType=AUDA. (Accessed 13 March 2021).
Naumann, G., Barbosa, P., Garrote, L., Iglesias, A., Vogt, J., 2014. Exploring drought vulnerability in Africa: an indicator based analysis to be used in early warning systems. Hydrol. Earth Syst. Sci. 18 (5), 1591–1604. https://doi.org/10.5194/hess-18-1591-2014.
Naumann, G., Barbosa, P., Garrote, L., Iglesias, A., Vogt, J., 2014. Exploring drought vulnerability in Africa: an indicator based analysis to be used in early warning systems. Hydrol. Earth Syst. Sci. 18 (5), 1591–1604. https://doi.org/10.5194/hess-18-1591-2014.
Ngaka, M., 2012. Drought preparedness, impact and response: a case of the eastern cape and Free State provinces of South Africa. Jàmbá J. Disaster Risk Stud. 4 (1), 1–10.
OECD, 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. https://doi.org/10.1787/9789264043466-en.
OECD, 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. https://doi.org/10.1787/9789264043466-en.
Ortega-Gaucin, D., Ceballos-Tavares, J.A., Ordoñez Sánchez, A., Castellano-Bahena, H.V., 2021. Agricultural drought risk assessment: a spatial analysis of Hazard, exposure, and vulnerability in Zacatecas, Mexico. Water 13 (10), 1431. https://doi.org/10.3390/w13101431.
Pei, W., Fu, Q., Liu, D., Li, T., Cheng, K., Cui, S., 2018. patiotemporal analysis of the agricultural drought risk in Heilongjiang Province, China. Theor. Appl. Climatol. 133 (1–2), 151–164. https://doi.org/10.1007/s00704-017-2182-x.
Peng, L., Zeng, Z., Wei, Z., Chen, A., Wood, E.F., Sheffield, J., 2019. Determinants of the ratio of actual to potential evapotranspiration. Glob. Chang. Biol. 25, 1326–1343. https://doi.org/10.1111/gcb.14577.
Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000-global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling: monthly irrigated and rainfed crop areas. Glob. Biogeochem. Cycles 24. https://doi.org/10.1029/2008GB003435 n/a-n/a.
Rother, H., Hall, R., London, L., 2008. Pesticide use among emerging farmers in South Africa: contributing factors and stakeholder perspectives. Dev. South. Afr. 25 (4), 399–424.
Running, Steve, Mu, Qiaozhen, Zhao, Maosheng, 2017. MOD16A2 MODIS/Terra Net Evapotranspiration 8-Day L4 Global 500m SIN Grid V006. https://doi.org/10.5067/MODIS/MOD16A2.006.
SACN, 2016. State of South African Cities Report 2016. Johannesburg: SACN. http://www.socr.co.za/wp-content/uploads/2016/06/SoCR16-Main-Report-online.pdf. (Accessed 2 January 2021).
Schreiner, B.G., Mungatana, E.D., Baleta, H., 2018. Impacts of Drought Induced Water Shortages in South Africa: Sector Policy Briefs.
Schulze, R.E., 2016. On observations, climate challenges, the South African agriculture sector and considerations for an adaptation handbook. In: Schulze, R.E. (Ed.), Handbook for Farmers, Officials and Other Stakeholders on Adaptation to Climate Change in the Agriculture Sector within South Africa. Section A: Agriculture and Climate Change in South Africa: Setting the Scene, Chapter A1.
Schwarz, M., Landmann, T., Cornish, N., Wetzel, K.-F., Siebert, S., Franke, J., 2020. A spatially transferable drought hazard and drought risk modeling approach based on remote sensing data. Remote Sens. 12 (2), 237. https://doi.org/10.3390/rs12020237.
Siebert, S., Döll, P., 2010. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. J. Hydrol. 384, 198–217. https://doi.org/10.1016/j.jhydrol.2009.07.031.
Siebert, S., Döll, P., 2010. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. J. Hydrol. 384, 198–217. https://doi.org/10.1016/j.jhydrol.2009.07.031.
Sivakumar, M.V.K., Stefanski, R., Bazza, M., Zelaya, S., Wilhite, D., Magalhaes, A.R., 2014. High level meeting on National Drought Policy: summary and major outcomes. Weather Climate Extremes 3, 126–132. https://doi.org/10.1016/j.wace.2014.03.007.
StatSA, 2011. Statistics South Africa Data. http://superweb.statssa.gov.za/webapi/jsf/dataCatalogueExplorer.xhtml. (Accessed 8 May 2019).
StatSA, 2016. Statistics South Africa Data. http://superweb.statssa.gov.za/webapi/jsf/dataCatalogueExplorer.xhtml. (Accessed 8 June 2019).
StatSA, 2016. Statistics South Africa Data. http://superweb.statssa.gov.za/webapi/jsf/dataCatalogueExplorer.xhtml. (Accessed 8 June 2019).
Thamaga-Chitja, J.M., Morojele, P., 2014. The context of smallholder farming in South Africa: towards a livelihood asset building framework. J. Hum. Ecol. 45, 147–155. https://doi.org/10.1080/09709274.2014.11906688.
Thompson, 2019. South African National Land-Cover (SANLC) 2018. Department of Environmental Affairs of the Republic of South Africa, 2019. https://www.environment.gov.za/projectsprogrammes/egis_landcover_datasets. (Accessed 8 July 2020).
Thompson, 2019. South African National Land-Cover (SANLC) 2018. Department of Environmental Affairs of the Republic of South Africa, 2019. https://www.environment.gov.za/projectsprogrammes/egis_landcover_datasets. (Accessed 8 July 2020).
Trenberth, K.E., Dai, A., Van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat. Clim. Chang. 4, 17–22. https://doi.org/10.1038/nclimate2067.
Tung, C.-P., Tsao, J.-H., Tien, Y.-C., Lin, C.-Y., Jhong, B.-C., 2019. Development of a novel climate adaptation algorithm for climate risk assessment. Water 11, 497. https://doi.org/10.3390/w11030497.
UNDRR, 2015. Sendai Framework for Disaster Risk Reduction 2015-2030. Geneva, Switzerland. http://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf. (Accessed 18 October 2020).
Undrr, 2019. Global Assessment Report on Disaster Risk Reduction 2019, Chapter 6: Special Section on Drought. UN, New York.
Unganai, L.S., Kogan, F.N., 1998. Drought monitoring and corn yield estimation in southern Africa from AVHRR data. Remote Sens. Environ. 63, 219–232. https://doi.org/10.1016/S0034-4257(97)00132-6.
VERBI Software, 2019. MAXQDA 2020, Somputer Program. VERBI Software, Berlin.
Vogel, C., Olivier, D., 2019. Re-imagining the potential of effective drought responses in South Africa. Reg. Environ. Chang. 19, 1561–1570. https://doi.org/10.1007/s10113-018-1389-4.
Vogel, C., Van Zyl, K., 2016. Drought - in search of sustainable solutions to a persistent 'wicked' problem in South Africa. In: Salzmann, N., Huggel, C., Nussbaumer, S.U., Ziervogel, G. (Eds.), Climate Change Adaptation Strategies: an Upstream-Downstream Perspective. Springer, Cham, pp. 197–211 https://doi.org/10.1007/978-3-319-40773-9_11.
Vogel, C., Koch, I., Van Zyl, K., 2010. “A Persistent Truth”—Reflections on Drought Risk Management in Southern Africa. 2. Weather, Climate, and Society, pp. 9–22. https://doi.org/10.1175/2009WCAS1017.1.
Waldner, F., Hansen, M.C., Potapov, P.V., Löw, F., Newby, T., Ferreira, S., Defourny, P., 2017. National-scale cropland mapping based on spectral-temporal features and outdated land cover information. PLoS ONE 12, e0181911. https://doi.org/10.1371/journal.pone.0181911.
Walz, Y., Dall, K., Graw, V., León, J., Haas, S., Kussul, N., Jordaan, A., 2018. Understanding and reducing agricultural drought risk. Examples From South Africa and Ukraine.
Walz, Y., Min, A., Dall, K., Duguru, M., Villagran de Leon, J.-C., Graw, V., Dubovyk, O., Sebesvari, Z., Jordaan, A., Post, J., 2020. Monitoring progress of the Sendai framework using a geospatial model: the example of people affected by agricultural droughts in Eastern Cape, South Africa. Progress in Disaster Science. 5, p. 100062. https://doi.org/10.1016/j.pdisas.2019.100062.
Weiss, D.J., Nelson, A., Gibson, H.S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., Mappin, B., Dalrymple, U., Rozier, J., Lucas, T.C.D., Howes, R.E., Tusting, L.S., Kang, S.Y., Cameron, E., Bisanzio, D., Battle, K.E., Bhatt, S., Gething, P.W., 2018. A global map of travel time to cities to assess inequalities in accessibility in 2015. Nature 553, 333–336. https://doi.org/10.1038/nature25181.
West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. https://doi.org/10.1126/science.1246067.
WMO World Meteorological Organization, 2020. World Meteorological Organization Commission for Climatology. State of the Climate in Africa 2019. World Meteorological Organisation, Geneva.
World Bank, 2019. Assessing Drought Hazard and Risk: Principles and Implementation Guidance. World Bank, Washington, DC.
World bank, 2020. Global - Dams Database | Data Catalog [WWW Document]. https://datacatalog.worldbank.org/dataset/global-dams-database. (Accessed 1 December 2021).
WWFW (World Wide Fund for Nature), 2018. Agriculture: Facts and Trends, South Africa [online]. World Wide Fund. http://awsassets.wwf.org.za/downloads/facts_brochure_mockup_04_b.pdf. (Accessed 6 July 2020).
Zeng, Z., Wu, W., Li, Z., Zhou, Y., Guo, Y., Huang, H., 2019. Agricultural drought risk assessment in Southwest China. Water 11 (5), 1064. https://doi.org/10.3390/w11051064.
Zhang, D., Wang, G., Zhou, H., 2011. Assessment on agricultural drought risk based on variable fuzzy sets model. Chin. Geogr. Sci. 21 (2), 167–175. https://doi.org/10.1007/s11769-011-0456-2.