Nature-Based Solutions 6 (2024) 100149

Contents lists available at ScienceDirect

Nature-Based Solutions

journal homepage: www.elsevier.com/locate/nbsj

A geographic information system and analytic hierarchy process drought risk analysis approach in arid south-western Zimbabwe: Prospects for informed resilience building

Oshneck Mupepi *, Mark Makomborero Matsa, John Hove

Department of Geography, Environmental Sustainability and Resilience Building, Midlands State University, P. Bag. 9055, Zimbabwe

ARTICLE INFO

Keywords:
Drought risk
Geographic information system
Analytic hierarchy process
Drought vulnerability
Drought resilience

ABSTRACT

Climate change is increasing the vulnerability of communities to drought, with rural communities in developing countries being affected the most. The study assessed drought vulnerability in south western Zimbabwe based on the Analytic Hierarchy Process (AHP) supported by Geographic Information System (GIS) and remote sensing techniques. An empirical research design based on verifiable evidence of drought vulnerability was adopted. GIS and remote sensing data were used to execute the multi-criteria AHP for the determination of drought vulnerability. ArcMap 10.8 software was used for the analysis of drought influencing factors and carrying out the weighted overlay. Results indicate that almost the whole of south western Zimbabwe is prone to droughts with only 0.6 % of the area being comparatively better. It was also noted that the majority of the population are exposed to high and extreme risk of droughts as they are settled in extreme and high drought risk zones. The study recommends implementation of resilience building interventions from an informed dimension where specific resilience building initiatives are implemented in appropriate environments for high returns. This can sustain the communities in the face of increasing drought risk due to climate change in line with the aspirations of the universal sustainable development goals and the country's vision of attaining an upper middle-income society by 2030. A framework for creating drought resilience was developed to ensure that development stakeholders cooperate to build drought resilient communities in tropical regions with drought challenges like Zimbabwe and the rest of Southern Africa.

Introduction

Drought was defined by Pachauri and Reisinger [1] as the prolongation of dry weather leading to unstable hydrological balance. The prime cause of drought in Zimbabwe is precipitation deficit, which is influenced by various natural causes [2] like precipitation, soil type, temperatures among others [3]. Therefore, the definition of drought as an extreme meteorological event that originates from shortage of precipitation which results in water shortage for specific uses is appropriate to define drought in the context of Zimbabwe [2,4]. Drought pose a serious threat to the food security of rural communities of developing countries as it affects agriculture which is the backbone of life for the majority [5,6]. Monitoring drought is a difficult task since it is a complex phenomenon dependent on myriad of factors [7]. Drought in a region can result from lack of precipitation [3], high temperature induced evapotranspiration [8] (meteorological drought) or from the changes in the availability of surface or groundwater (hydrological drought). These can be affected by changes in land use/ cover, distribution of soil texture and moisture [9], and slope [10].

Several studies have been conducted on drought spatial and temporal variability and associated impacts on crop production in different parts of the world using meteorological and remote sensing data [11–17] but these were based on drought impact or evidence of drought occurrence. However, drought vulnerability can be determined based on existing parameters that influence moisture availability from a multi-criteria decision making perspective [18] which when merged with drought severity mapping can give a better understanding of spatial vulnerability of communities to drought. When data on factors affecting drought is available, a collective method of summarizing and quickening the understanding of drought vulnerability is possible with the help of Multi-Criteria Decision Making/Analysis (MCDM/MCDA) [19,20]. Some studies that included MCDM focused on aspects like vulnerability

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* Corresponding author.
E-mail address: omupepi@gmail.com (O. Mupepi).

https://doi.org/10.1016/j.nbsj.2024.100149
Received 7 February 2024; Received in revised form 30 June 2024; Accepted 30 June 2024

to desertification [21]. However, a number of studies capitalized on the utility of AHP to overlay a number of factors for drought vulnerability. Sivakumar et al. [22] assessed drought vulnerability based on precipitation, slope, water areas, population density, land use/cover and soil using Multi-Criteria Decision Making (MCDM) and application of Analytic Hierarchy Process (AHP) for Namakkal District in India. In their study they managed to determine spatial vulnerability of Namakkal District to drought. A similar study was carried out by Saini et al. [23] who used a spatial multi-criteria integrated technique for an all-out drought vulnerability assessment and mapping based on geographic information systems (GIS) and Analytic Hierarchy Process (AHP) techniques. They acquired data from various secondary sources which include rainfall, temperature, evapotranspiration, elevation, groundwater level, groundwater development, surface water bodies, agricultural, water holding capacity of soils, land use and slope as well as density of population. Several studies have been conducted in the same research domain using various GIS and remote sensing techniques including fuzzy logic and weighted overlay of remote sensing and GIS data that determined moisture supply, for instance, rainfall and those that determine water storage like slope and soil types as well as those that determine moisture loss like land cover and temperature among others. Such studies include Palchaudhuri and Biswas [24] in Puruliya district, West Bengal, India, where fourteen parameters, such as annual rainfall, monthly rainfall, maximum temperature, monthly temperature, maximum evapotranspiration, monthly evapotranspiration, relative humidity, soil texture, land use/land cover, slope, groundwater, cultivators, and population were used. Wijitkosum and Sriburi [25] used Fuzzy AHP in Upper Phetchaburi River Basin, Thailand emphasizing on use of four main factors influencing drought: Climate, physical factors, soil and land utilization factors. Some studies majored more on the socio-economic dimension of vulnerability where population density, marginalized population agricultural labourers, literacy among others and physical variables like precipitation, temperature, land cover and others were employed [26]. Based on such criteria, most of the districts under hot semi-arid agro-climatic zone located in the Uttar Pradesh (UP) part of Bundelkhand were found to be highly vulnerable mainly due to high density of population and extensive agricultural activities. Out of the total area under highly vulnerable zone (27.8 %), about 20 % fall under semi-arid agro-ecological zone covering a large part of UP. This literature indicates that drought vulnerability can be mapped using multitudes of factors but the type of hazard under consideration may differ from socio-economic, meteorological and agricultural drought. These studies managed to map drought vulnerability but the population exposed could not be established, especially those exposed to various severity categories. This research intends to cover this gap by taping on global datasets to unleash the population exposed to various agro-meteorological drought conditions and advance the way forward for exposed populations, something that lacked in these previous studies.

Literature indicates that the majority of drought vulnerability mapping studies that used multi-criteria decision making or the analytic hierarchy process are in Asia [22,23,27–30] whilst most of those conducted in Europe [31,32], America [33–35] and Africa [15,36,37,] were based on remote sensing indices and other meteorological drought indices. This indicates paucity of research on drought vulnerability from a multi-criteria perspective which suggests that most studies in other regions of the world except Asia are aligned more towards mapping drought impacts and severity than mapping risks and exposure prior to drought occurrence.

Given this background with a clear bias towards remote sensing, it becomes essential to show the importance and feasibility of using multi-criteria decision analysis to map existing vulnerability in developing regions of the world, including Southern Africa and Zimbabwe, that rely on rain-fed agriculture, for informed drought resilience building. Therefore, this study aims to 1) map drought vulnerability over the drought-prone geographical area of south-western Zimbabwe, 2) estimate the population vulnerable to each drought severity category and 3) advance a nature-based drought resilience framework for communities in drought prone regions of the country. This covers the gap exposed by the reviewed literature where only drought vulnerability and impact were mapped with limited information on exposed populations and how available opportunities from nature can be harnessed to sustain socio-economic development of vulnerable societies. Based on this, Sustainable development can be achieved through enhanced climate action (SDG 13), improving response and mitigation mechanisms to climate change, poverty eradication (SDG 1) and hunger reduction (SDG 2) through informed establishment of climate/drought resilient livelihood sources in the study area.

Study area

The study was conducted on a 7,455,103.2-hectare area which covers 11 districts in South-Western Zimbabwe. These include Beitbridge, Bubi, Tsholotsho, Mangwe, Gwanda, Insiza, Umzingwane, Matobo, Umguza, Bulilima and Bulawayo. This is a semi-arid area falling under agro-ecological regions 4, and 5 in Zimbabwe where annual precipitation is very low, averaging 500 mm whilst mean annual temperature is very high, ranging around 28 °C. This region constitutes the greater part of the driest areas in Zimbabwe which makes it worth considering to assess drought vulnerability in this region. The soils are generally infertile, sandy soils, derived from Archaean granites and gneisses of the Zimbabwe Craton and Limpopo Belt [38]. These soils are well to very well drained, moderately shallow, greyish brown to yellowish red, gravely coarse-grained sands to sandy loams, with an acidic soil moisture [39]. These soils have low moisture retention capacity which makes them susceptible to agricultural drought [14]. Given very low precipitation averaging 500 mm, the whole of this region is vulnerable to drought Figs. 1–7.

Most of the households in this area live in communal smallholder-farming lands, held under semi-traditional tenure. Matebeleland South Province which constitutes over ¾ of the total study area has 760,345 people who are mainly rural peasant farmers whilst Tsholotsho, Umguza and Bubi of Matebeleland North Province which forms part of the study area have 115 782, 113 265 and 74,084 people respectively with over 75 % of people in rural areas (ZIMTAT,2022). Communal areas, especially around Gwanda and Beitbridge are mostly grazing areas with over 70 % of land being heavily grazed [40,41]. Crops grown under rain fed agriculture frequently fail, which makes households rely on livestock along with external sources like remittances from their family members in South Africa and Botswana [42]

Materials and methods

Geographic Information System (GIS), Remote Sensing (RS) and the Analytic Hierarchy Process (AHP) were adopted to come up with drought sensitivity based on factors that affect meteorological and agricultural drought in Zimbabwe. Factor analysis and identification was done to determine the 7 factors (precipitation, temperature, slope, soil type, land cover, wind speed, water vapour) of drought vulnerability in South-Western Zimbabwe. These are factors which literature confirm to be major determinants of droughts ([18,22]; Saini et al., 2021). In this case, the Analytic Hierarchy Process (AHP) allowed for multi-criteria decision making based on 7 factors of agro-meteorological drought vulnerability (precipitation, temperature, slope, soil type, land cover, wind speed, water vapour) [3,7]. The AHP was employed due to its utility when integrating various factors with different weighted contributions to drought as was the case with the selected 7 factors. A pairwise comparison technique [43] was used to derive the priorities for the criteria in terms of their importance in achieving the intended research outcomes using a scale developed by Estoque, [44]. The very first step was stating the problem and broadening the objectives of the problem by considering all factors that determine drought vulnerability. The

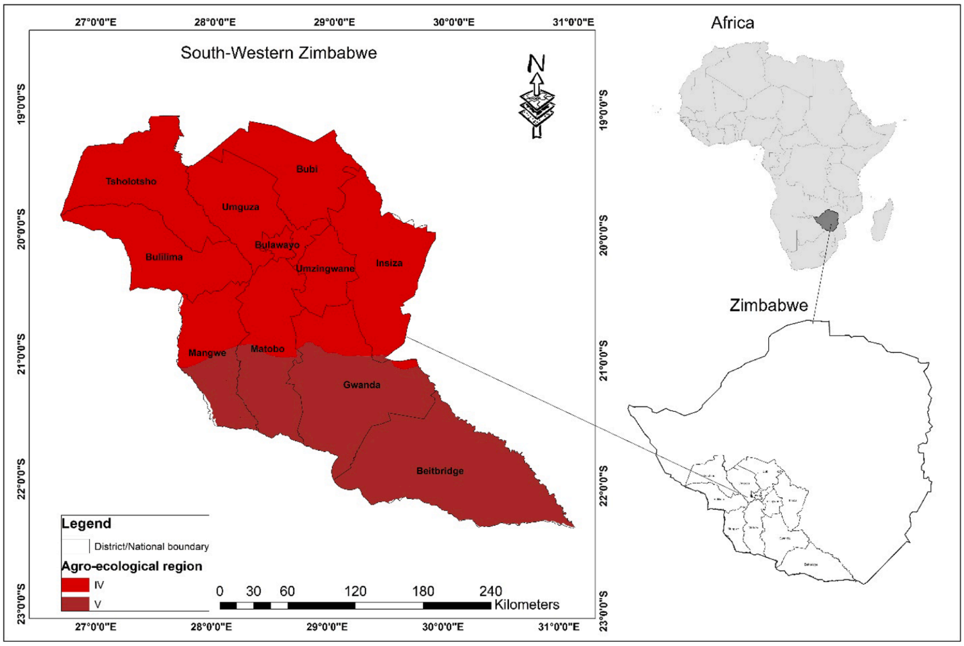


Fig. 1. South-western Zimbabwe.

decision elements were set up into a hierarchy of interrelated decision aspects constituting the goal, criteria, sub-criteria, and alternatives [45]. At the topmost position of the hierarchy is the overall goal followed by criteria that contribute to attainment of the overall goal. The lowest level contained the alternative decisions from which the researchers would select (Fig. 2).

The next step involved ranking for each of the criteria and alternatives using a pairwise comparison technique. This also included the rating scale of relative importance of factors under consideration. Each comparison (for example, Criteria 1 *versus* Criteria 2 or Alternative 1 *versus* Alternative 2) was rated using the 9-point scale developed by Saaty, [46] for a pairwise comparison technique (Table 1).

The intensity of importance was allocated to criteria i against criteria j, where reciprocal value was assigned to criteria j as intensity of importance. In this case, for example, basing on the above matrix, i (Precipitation) = 2 while j (Temperature) = 1/2. After comparison between all possible criteria pairs is complete (Table 2), the weight (w) of criteria i is calculated based on equation 1 [43].

$$Wi = \left(\Sigma Pij \middle/ \sum_{i=1}^{n} \sum_{j=1}^{n} Pij \right)$$

Where Pij = relative importance in pairwise comparison of criterion i compared to criterion j

n = number of factors i & j = criterion

W = priority weight

The relative importance of the criteria and the relative importance of the alternatives with respect to the criteria were determined after a pairwise comparison matrix for the criteria and alternatives has been prepared based on the formulae by Dai [43]. This was done by calculating the normalized values (Table 3) for each criterion and alternative and determining the normalized principal eigenvectors or priority vectors (relative weights). In calculating the normalized values for each criterion and alternative in their respective matrices, the value for each cell was divided by its column total [47]. This process produced a column total of 1 for each matrix. The resulting values gave the relative weights of the criteria with respect to the goal, and the relative weights of the alternatives with respect to the criteria. This whole process was done by the three authors in consultation with other similar studies which ranked the contribution of each of these factors to droughts in the semi-arid tropics ([18,21,22]; Saini et al., 2021). More so, the authors have done extensive research in parts of the study area during their previous studies on drought ([14,15]a; [15]b) and rainfall and soil moisture retention capacity [14,42] as well as impacts of climate change [48,49]. During these studies, authors interacted with experts from the Zimbabwe Meteorological Services Department, AGRITEX among other key informants who have been included in developing agro-ecological zones of Zimbabwe (Mugandani et al., 2012). This made authors well equipped to rank factors of drought in south western Zimbabwe as their influence and contribution to drought are well known. In addition, a review of literature by Darko et al. [50] on application of AHP confirms no strict requirement on minimum sample size with most scholars using between 3 and 9 experts whilst some using only judgement from one expert depending on context [51]. This study is based on complex factors on climate change and drought, which makes the authors some of the most important experts based on previously acquired knowledge from their prior work. However, the authors also used ideas from other key informants as indicated.

Verification was done to determine the consistency of the evaluation by calculating the consistency ratio before the decision was made. The researchers performed calculations to find the maximum eigenvalue, consistency index, consistency ratio, and normalized values for each criteria/alternative. Saaty, [46] suggested that if the ratio exceeds 0.1, the set of judgments may be too inconsistent to be reliable. Thus, a consistent ratio (CR) below 0.1 % or 10 % is acceptable. When the evaluation is inconsistent, the procedure is repeated until the CR is within the desired range. Table 2

To determine consistency, the Lambda maximum value (ʎmax) was determined by dividing the weighted sum value by the criteria weights for each row followed by averaging all resulting values (Table 3). The next procedure was to calculate the Consistency Index (CI). This was done by subtracting the number of criteria (which in this case is 7) from (ʎmax) followed by dividing the result by the value obtained after subtracting 1 from the criteria value (CI = (ʎmax-n) / n-1). The final procedure was calculating the Consistency Ratio (CR) which was done by dividing the Consistent Index by the Random Index obtained using the random index table by Saaty [46] (Table 4)

As proposed by Saaty [46], the RI used depends on the number of criteria. This study had 7 (7) criteria hence RI used was 1.32 (Table 4.)

This translated the consistency ratio to 0.06 which is below standard

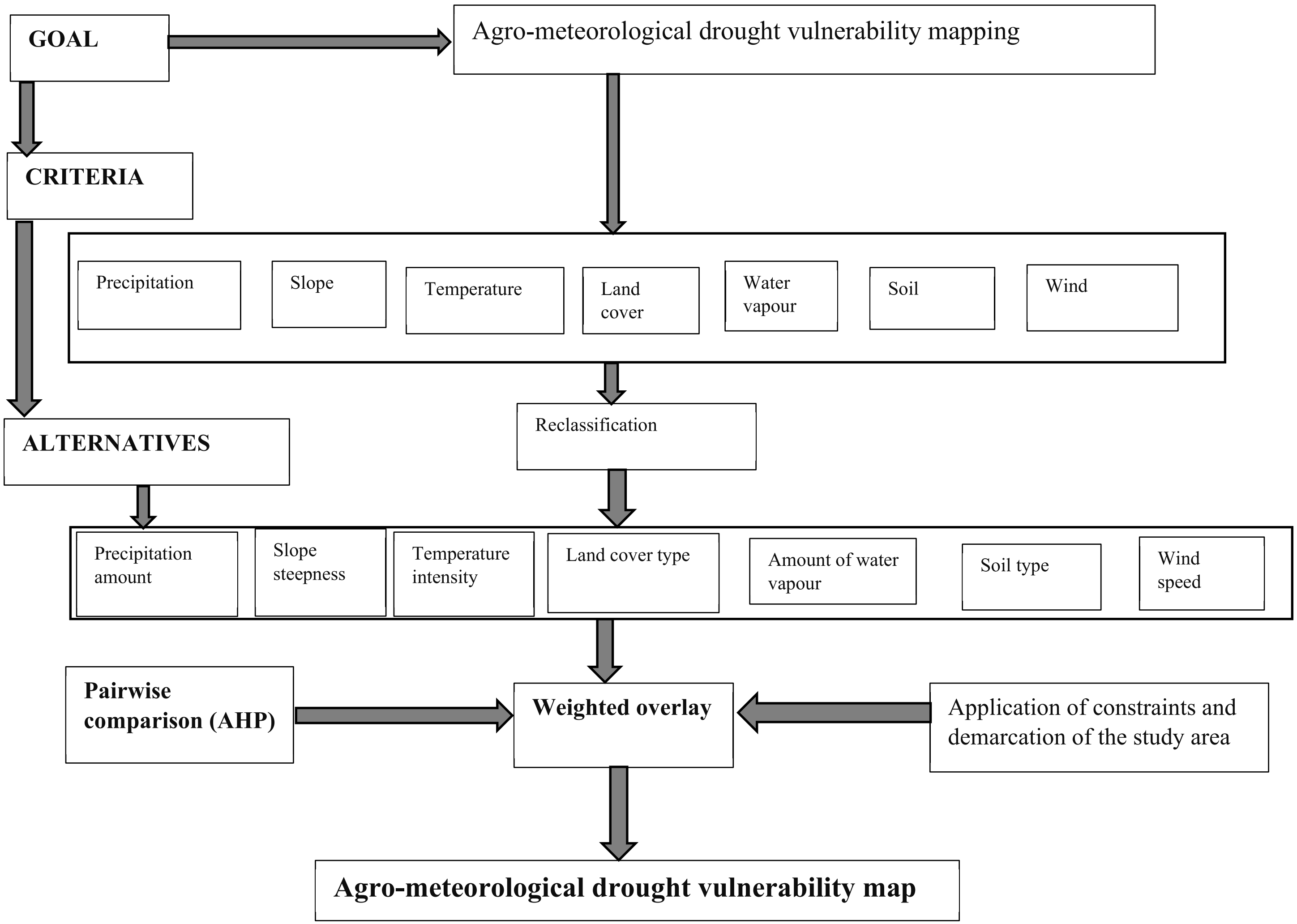


Fig. 2. The AHP methodology components and structure.

Table 1
Nine-point intensity of importance scale.

Intensity of importance	Definition	Description
1	Equally important	Two factors contribute equally to the objective
3	Moderately more important	Experience and judgement slightly favour one over the other
5	Strongly more important	Experience and judgement strongly favour one over the other
7	Very strong more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Extremely more important	The evidence favouring one over the other is of the highest possible validity
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals of above	If an element i has one of the above numbers assigned to it when compared with element j, then j has the reciprocal value when compared with i.	–
Ratios (1.1–1.9)	If the activities(elements) are very close	May be difficult to assign the best value, but when compared with other contrasting activities(elements), the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities (elements)

Source: [44].

0.1 as expected. Table 5

Temperature, precipitation, water vapour and wind speed datasets were downloaded from the World Climate website as long term averaged and gridded raster data with spatial resolution of 30 s(Table 5). This was appropriate for mapping a large area of 7,455,103.2 hectares which constitute the 11 district study area in South-western Zimbabwe. Slope data was derived from the ASTER Digital Elevation Model (DEM) with a spatial resolution of 15 m thus allowing for detailed visualization of slope in the study area. Soil data was downloaded from the Food and

Table 5
Data sources.

Dataset	Source	Spatial resolution	Format	Dates
Precipitation	World Climate website	30 arc-second	Geo-tiff (raster)	1971–2018
Temperature	World Climate website	30 arc-second	Geo-tiff (raster)	1971–2018
Wind speed	World Climate website	30 arc-second	Geo-tiff (raster)	1971–2000
Water vapour	World Climate website	30 arc-second	Geo-tiff (raster)	1971–2000
Global population	Socio-economic Data and Application Center (SEDAC) website	30 arc-second	Geo-tiff (raster)	2020
MODIS NDVI (Land cover)	United States Geological Survey (USGS)	250 m	Geo-tiff (raster)	September 15 (2022)
ASTER DEM	NASA (USGS)	30 m	Geo-tiff (raster)	
Soil	FAO (World Reference Base for Soil Resources)	N/A	Vector (. shp)	

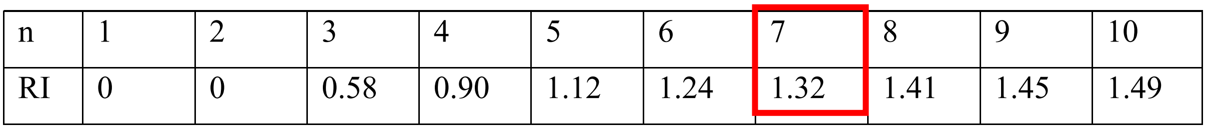
Table 2
Ranking of drought vulnerability criteria to obtain the pairwise comparison matrix.

	Precipitation	Temperature	Soil	Wind	Land cover	Water vapour	Slope
Precipitation	1	2	5	5	6	3	5
Temperature	1/2	1	4	4	5	2	4
Soil	1/5	¼	1	3	4	2	3
Wind	1/5	¼	1/3	1	3	1/3	1/2
Land cover	1/6	1/5	1/4	1/3	1	1/4	1/2
Water vapour	1/3	½	1/2	3	4	1	3
Slope	1/5	¼	1/3	2	2	1/3	1

Table 3
Normalization and Weight Determination of criteria contributing to drought vulnerability.

	Precipitation	Temperature	Soil	Wind	Land cover	Water vapour	Slope	Criteria weight	Weighted sum	% weight
Precipitation	0.35	0.47	0.68	0.29	0.21	0.38	0.32	0.35	2.69	34.51
Temperature	0.17	0.24	0.54	0.23	0.18	0.26	0.26	0.24	1.87	23.51
Soil	0.07	0.06	0.14	0.17	0.14	0.26	0.19	0.14	1.02	13.50
Wind	0.07	0.06	0.04	0.06	0.11	0.04	0.03	0.06	0.41	5.76
Land cover	0.06	0.05	0.03	0.02	0.04	0.03	0.03	0.04	0.26	3.54
Water vapour	0.11	0.12	0.07	0.17	0.14	0.13	0.19	0.13	0.93	12.79
Slope	0.07	0.06	0.04	0.12	0.07	0.04	0.06	0.06	0.46	6.39
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**7**	**100.00**

Table 4
Random index (RI) used to compute consistency ratios (CR).



n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Agriculture Organization's website as world soil data set which was in vector format. Land cover data was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor with 250 m' spatial resolution. This data was downloaded from the United States Geological Survey (USGS) website as eMODIS NDVI V6. Therefore, Normalized Difference Vegetation Index (NDVI) values were used to extract different land covers from this data set.

After determining the weight for each factor dataset, there was the need to combine all the weighted criteria to obtain a drought vulnerability map by performing a weighted overlay analysis in ArcMap 10.8. In this study, the weighted overlay of raster images for all the weighted datasets was done whereby the weighted contribution for each factor was considered on a pixel to pixel basis. The overlay results were calibrated to produce 4 categories of vulnerability magnitude which were low, moderate, high and extreme vulnerability. These categories were developed by setting break values for the least drought inducing to the most drought inducing or sensitivity category. For instance, areas with very low precipitation values of less than 250 mm were considered extreme drought areas whilst those with precipitation values above 600 were considered the least drought areas. The same was done for temperature, slope and other factors before overlaying all these layers. This resulted in a vulnerability map indicating spatial vulnerability in South-western Zimbabwe. The Gridded Population of the World (GPW), v4 dataset from the Socioeconomic Data and Applications Center (SEDAC) (https://sedac.ciesin.columbia.edu/.) which indicates the gridded population estimates for the whole globe was used to extract population density information of the study area. This data provides a spatially disaggregated population layer that is compatible with data sets from Earth science disciplines and remote sensing [52]. This made it an ideal data source with a format (georeferenced-geotif) that is compatible with other GIS data layers used in this study. This dataset is fed with up to date information from censuses conducted across the globe which makes it reliable and representative of local population estimates. Since this data shows population density per square kilometer, it was overlaid on the produced drought vulnerability map to estimate population exposed to each drought vulnerability category. To do this, the drought vulnerability map was vectorized and used to create boundaries that we used to mask out population densities for the areas from the global population dataset. This allowed for the determination of average population densities per each drought vulnerability category based on average pixel values. The framework for drought resilience was developed based on data provided from vulnerability map and population exposed as well as the spatial distribution of factors of drought sensitivity. This framework was advanced as the way forward for drought resilience building.

Results

Drought vulnerability in south-western Zimbabwe

Multi-criteria decision making was done to determine vulnerability of areas in South-western Zimbabwe to drought. Temperature, precipitation, water vapour, soil type, slope, land cover and wind speed were weighted based on their contribution to drought with precipitation being given largest weight as a moisture supply aspect whilst temperature, water vapour, and wind speed constituted moisture loss enhancing factors. Soil type, land cover and slope were considered propellers of water loss and supply through enhancing or impeding infiltration (Fig. 3).

In terms of soils, high moisture retention capability soils like vertisols, solonetz and fluvisols were found in western Tsholotsho and central Umguza which makes these areas manage to retain little available moisture despite low precipitation and high temperatures compared to other areas (Fig. 3). Dominant soils which are almost evenly distributed across the whole of south western Zimbabwe are sandy luvisols with low moisture retention capacity covering greater parts of Bubi, Matobo, Gwanda, eastern Beitbridge and Insiza followed by arenosols characterized by low clay content covering northern parts of Tsholotsho, central Bulilima and western Umguza. Leptosols are dominant in western Beitbridge, and northern Matobo and they have low moisture retention capacities though better than arenosols and luvisols. Lixisols which have moderate moisture holding capacity are found in patches within Umguza, Bubi, Bililima, Southern Insiza and some parts of northern Gwanda.

The spatial distribution of these factors brought about heterogeneity

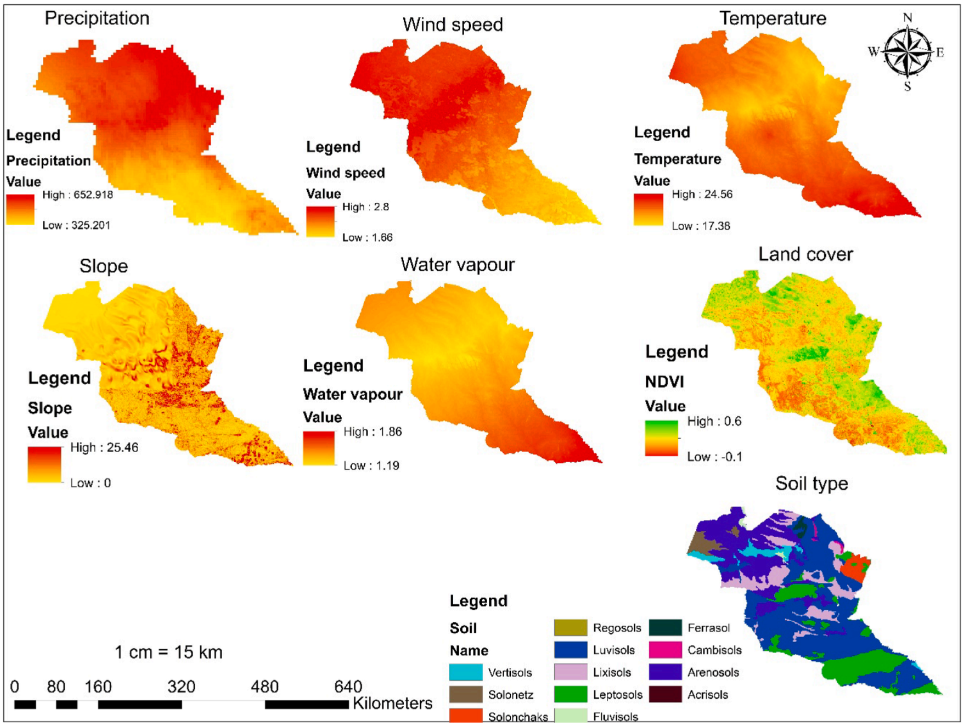


Fig. 3. The general distribution of drought vulnerability factors in South-western Zimbabwe.

in the spatial distribution of drought vulnerability which was critical to determine areas which can be severely affected by droughts based on behaviours of these parameters in these respective areas which constitute soil moisture balance. In terms of average precipitation distribution for 1971–2018, it was noted that Beitbridge, Gwanda, and southern parts of Matobo and Mangwe received very low precipitation averaging 325–350 mm per year whilst most areas that include Bubi, Umguza, Umzingwane and Bulawayo received comparatively high precipitation averaging between 600 and 652 mm. Tsholotsho District proved to be drier with some of the western and southern parts receiving as low as 400–500 mm (Fig. 3). This distribution of precipitation as the key determinant of drought speaks volumes when it comes to drought vulnerability in South-western Zimbabwe. In terms of wind speed Tsholotsho, Bulawayo, Mangwe, Bililima, Bubi, Insiza, Umzingwane, and Matobo were confirmed experiencing high wind speeds ranging between 2 and 2.8 km/h which makes them lose moisture faster than Beitbridge and Gwanda which experience low wind speeds averaging between 1.19 and 1.5 km/h.

Vegetated areas in Tsholotsho, Umguza, Bubi, Insiza, Gwanda and eastern parts of Beitbridge were found supportive to moisture accumulation through infiltration as well as reducing direct soil moisture loss whilst southern parts of Mangwe, Matobo and Beitbridge as well as some parts of Bulilima were found less vegetated which results in elevated direct soil moisture loss and lower infiltration rates.

In terms of mean annual temperature, Beitbridge, Gwanda and Tsholotsho were confirmed very high temperature zones averaging between 20 and 24.56 °C whilst eastern parts of Bulilima, greater parts of Umguza and Bubi were confirmed lowest temperature zones in this region, experiencing average temperatures between 17.38 and 19 °C thus low likelihood of losing large quantities of moisture due to temperature-induced evapotranspiration unlike Beitbridge, Tsholotsho and southern parts of Mangwe and Bulilima Districts.

In terms of slope, Tsholotsho, Bulilima and parts of Umguza were found to be gentle, which makes moisture accumulation higher whilst steep slopes around Matobo, Insiza, northern Mangwe and Matobo as well as eastern parts of Beitbridge were found disadvantaging to moisture accumulation through infiltration. On water vapour, Beitbridge and Gwanda were confirmed to be very high evapotranspiration zones as confirmed by water vapour between 1.7–1.86 g/m^3. Tsholotsho experiences comparatively low evapotranspiration as indicated by water vapour ranging between 1.5 and 1.6 g/m^3 whilst eastern parts of Bulilima, greater parts of Umguza and Bubi were confirmed to experience lowest water vapour in this region, experiencing average water vapour between 1.19 and 1.4 g/m^3 an indication of losing smaller quantities of moisture through evapotranspiration (Fig. 4).

After reclassification into classes of various vulnerability levels with respect to each factor, a final vulnerability index map based on weighted contribution of each factor to vulnerability magnitude was developed. Results showed that almost the whole of South-western Zimbabwe is prone to drought, the level of vulnerability is not homogeneous across districts in this region. Extreme drought vulnerability was confirmed in 0.6 % of South-western Zimbabwe which is mainly Beitbridge District, especially in rural wards 16, 2 and 6 where all drought vulnerability factors are extreme. Most parts of the urban area were also confirmed to be extremely vulnerable which reduces the potential for urban agriculture. Based on this situation, Beitbridge needs more attention with regards to drought resilience building as it suffers from low precipitation, high temperature as well as high evapotranspiration which leaves it dry during most rainy seasons. Previous drought studies [53,14] confirmed high drought frequency in Beitbridge (7 severe droughts in 30 years) which indicates that the developed drought risk map agrees with mapped drought incidences (Fig. 5).

Despite the areas under extreme vulnerability being less than 1 % of south western Zimbabwe, 42 % of the total area was confirmed highly vulnerable and these areas include the greater part of Beitbridge, the whole of Gwanda District except a small part of ward 23 and small parts of wards 21, 10 and 22. The southern half of Matobo and the greater part of southern (wards 9, 10, 17, 16, 8, 7 15 and parts of 6 and 5) and western Mangwe District (wards 3, 14 and 4) were also under the high vulnerability category. The same is true for western Tsholotsho (wards 7, parts of ward 1 and 8) and Bulilima (wards 9, 10, parts of 11, 12, 13 and 14. Greater parts of wards 22, 23 and 14 of Insiza District and parts of ward 19, 21, 12 and 15 of Bubi District were confirmed to be lowly vulnerable to drought which also applies to wards 2, 18, 17 and some

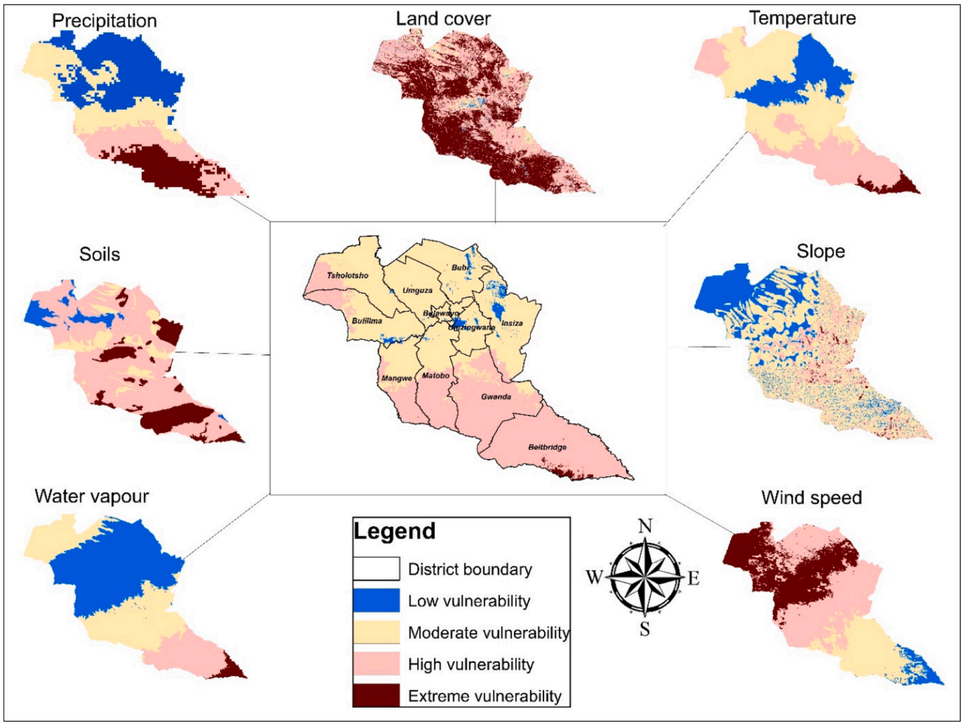


Fig. 4. Weighted contribution of drought vulnerability factors to drought in South-western Zimbabwe.

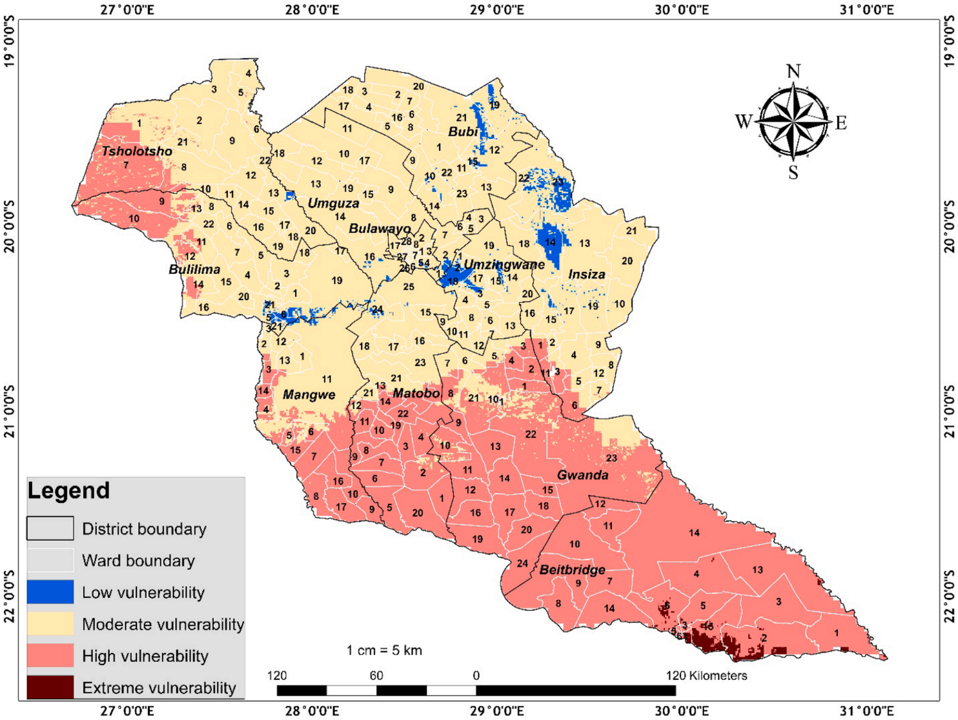


Fig. 5. Drought vulnerability map of South-western Zimbabwe.

parts of ward 15 to the east as well as wards 21, 5 and 6 of Bulilima District.

Wards 1 and 2 of Umguza District and ward 24 of Matobo and south-eastern parts of ward 13 of Tsholotsho have their parts at low risk of drought. The total area under this drought risk category constitutes 1.8 % of the total area under study (Fig. 5). The remaining section of South-western Zimbabwe including central, eastern and northern parts of Tsholotsho, northern, eastern and southern Bulilima, the whole of Umguza and Bulawayo, northern Mangwe and Matobo, western, central and southern Bubi, eastern and southern Insiza and northern and southern Umzingwane were confirmed to be under moderate drought risk. In total this category of drought risk covered 55 % of South-western Zimbabwe, mainly northern and central parts of the whole region.

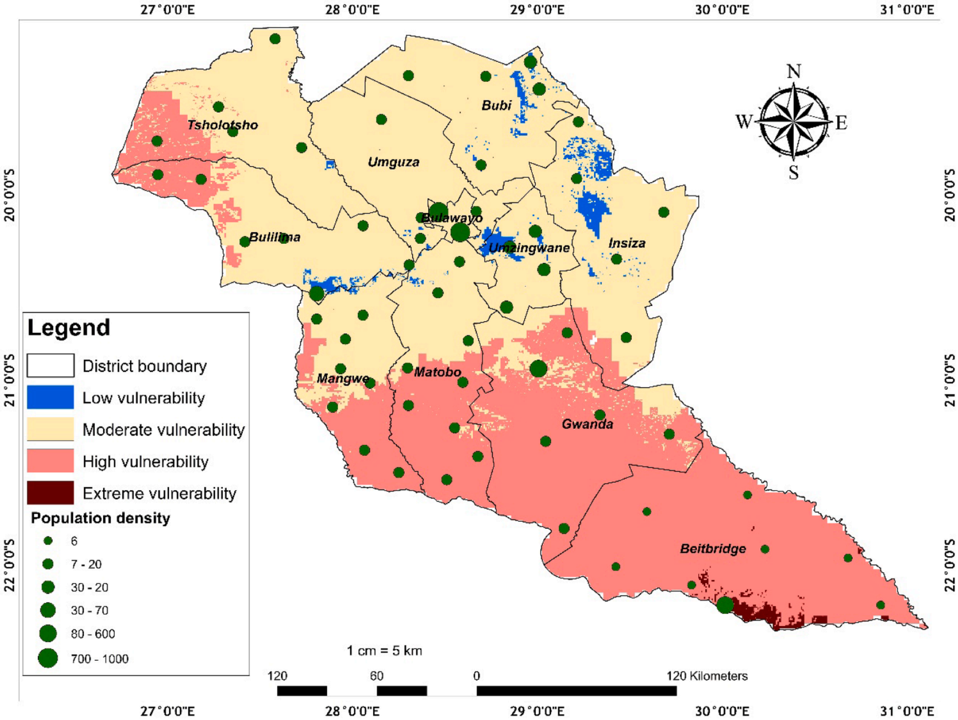


Fig. 6. Drought exposed population in South-western Zimbabwe.

Estimates of population exposed to each drought vulnerability magnitude in south-western Zimbabwe

Results based on an overlay of population density on drought vulnerability map indicated that significant proportions of the population are exposed to extreme and high drought risk (Fig. 6).

Findings indicated that almost all people in South-western Zimbabwe are vulnerable to drought although the levels of vulnerability are different depending on locations. It was noted that to the far south of Beitbridge, areas under extreme drought risk have population densities averaging 9 per km^2. With coverage of 433.5 km^2, findings indicated that approximately 3897 people are extremely vulnerable to drought (Fig. 6). This is a significant figure which requires the government of Zimbabwe, through the Zimbabwe Resilience Building Fund to prioritize funding resilience building projects to build resilience of households to drought in these drought-stricken areas in southern Zimbabwe. Findings also showed that the area under high vulnerability (southern parts of Gwanda, Matobo, Mangwe and western parts of Tsholotsho) to drought accommodates approximately 6.5 people per km^2 on average (Fig. 6). Roughly19898.5 people were found highly vulnerable to drought. For moderately vulnerable areas which cover 39,556.28 km^2, the population distribution is 15.75 on average per km^2. Findings indicates that approximately between 62,307 people are moderately vulnerable to drought. An area of 1280.2 km^2 is lowly vulnerable and it accommodates an average of 11 people per km^2. Average vulnerability was found to be approximately 14,082. Overall, the majority are exposed to drought and there is need to address drought vulnerability as informed by findings from this study as to where and

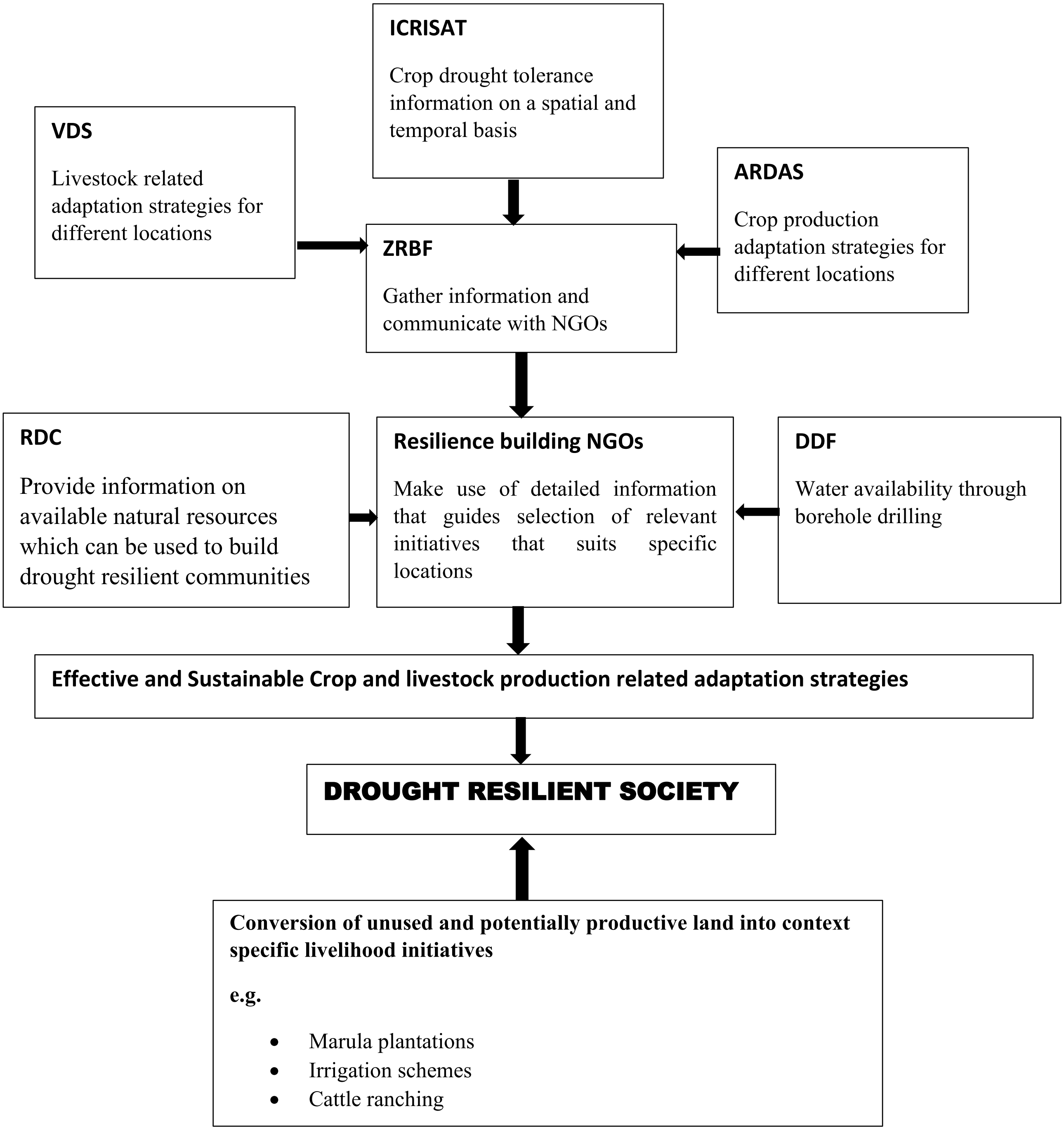


Fig. 7. Framework for creating drought resilient societies in arid-semi-arid communities of Zimbabwe and Southern Africa.

how many people are exposed to drought and drought-related risks.

Framework for drought risk reduction in south-western Zimbabwe and other similar contexts

The study indicated that some areas in South-western Zimbabwe are extremely vulnerable to droughts whilst others are lowly vulnerable based on the spatial distribution of drought determining factors. Despite that areas like western Tsholotsho and parts of Bubi Districts are highly vulnerable to droughts due to high temperatures and low precipitation, it was noted that they have vertisol type of soils which have good soil moisture retention capacity owing to the high clay percentage. Therefore, physical conditions of the area and their potential to support specific types of crops and agricultural activities must be understood and taken into considerations when implementing resilience building initiatives (Fig. 7). This was confirmed by Mupepi and Matsa [14] in their study on the influence of precipitation and soil type distribution on crop production in Mberengwa and Zvishavane districts in Southern Zimbabwe where soils of low moisture retention capacity determined the types of crops grown. These soils are good for agriculture but they are lacking moisture supply and suffering from excessive evapotranspiration. However, if ground water can be harnessed to power irrigation schemes, high crop productivity can be achieved. This calls for stakeholders like Agriculture, Rural Development and Advisory Services (ARDAS) and the International Crop Research Institute for Southern African Tropics (ICRISAT) to work on crop and irrigation scheme suitability analysis based on soils and climate so as to inform resilience building stakeholders to fund or support relevant initiatives like irrigations and solar powered community gardens as main drought resilience initiatives in such areas (Fig. 7). The District Development Fund (DDF) need to be equipped and empowered to do borehole drilling for the availability of water resources which can be used for irrigation in dry areas with soils which can support good crop production.

Areas like Beitbridge, Matobo, Gwanda and Mangwe Districts, with luvisols type of soils which promote good cattle pastures (given precipitation amounts averaging around 400 mm) should be developed to support pasture productivity. These areas need to be prioritized for livestock production projects and Marula plantations which thrive in these environments. This makes the Veterinary Services Department (VSD) and District Development Fund (DDF) key stakeholders who need to be empowered to support livestock production and ground water resources abstraction initiatives respectively in these areas.

The local authorities are encouraged to be supportive of drought resilience- building initiatives which best help communities to be drought resilient. All NGOs that come to focus on drought resilience must be informed by the RDC, ARDAS, VSD, ICRISAT and the local communities themselves on specific initiatives which the communities need to be drought resilient (Fig. 7). The mapping results from this study can be used as the starting point to inform stakeholders what needs to be done in specific areas with distinct physical characteristics which can be taken advantage of when capacitating communities in South-western Zimbabwe to respond to climate change induced droughts.

Discussion

Assessing vulnerability to agro-meteorological drought based on physical parameters is important prior to conducting household level vulnerability assessment. This is mainly because drought severity is determined by physical characteristics of any area, for instance, soil moisture retention capacity, slope, evapotranspiration and temperatures [54]. This implies that even if all areas receive uniform precipitation, still some can experience soil moisture deficit as a result of moisture loss and supply factor differences. Therefore, determining vulnerability to drought from this perspective is proactive and informs subsequent drought resilience measures that can be put in place. This was supported by Alharbi et al. [55] as they realized that drought risk maps informed implementation of water supply initiatives in the Kangsabati River Basin. Factors like precipitation, temperature, water vapour, wind speed, slope, land use/cover and soil are important parameters that can tell the vulnerability of an area to drought as they all influence moisture/water supply and availability for agricultural activities. This explains why drought vulnerability studies are conducted from a multi-criteria perspective using data about these factors [22,55,56]. The current study brought about an improved vulnerability assessment by adding water vapour and wind speed which were not considered by some studies in the same research domain [22,54,55]. Several studies conducted to determine drought vulnerability using physical and climatological factors agreed that high soil moisture retention capacity of soils like vertisols, solonetz and fluvisols helps some areas to be less affected by agricultural drought as they can store moisture for long [57, 58]. Therefore, the existence of soil dominated by sand, as is the case with most of the areas in south western Zimbabwe, contributes to agricultural drought vulnerability of these areas as the soil quickly loses little moisture received during the rainy season [59,60], which averages 500 mm per year [15]. However, some soils like lixisols have moderate soil moisture retention which makes areas with such soils better in terms of drought vulnerability [61]. This shows that soil has a great contribution to drought conditions in any area in the context of agriculture within the semi-arid tropics. Soil is therefore, widely used as an important factor together with obvious factors like precipitation and temperature. This study respected the influence of wind speed and evapotranspiration which are rarely used factors in droughts vulnerability studies ([18]; Saini et al., 2021). This is despite that literature acknowledges their contribution to moisture loss in any area as was the case in Bangladesh [28]. However, the study by Hoque et al. [28] was broad scoped as it looked at socio-economic drought which limited its detail with regard to agricultural and meteorological drought. This makes this study of value as it tried to show vulnerability to agricultural and meteorological factors which are primary drivers of socio-economic hardships in agro-based communities of the tropics. In this respect, this study regarded socio-economic drought as a secondary drought that can be informed by physical and meteorological factors which were used in this study. However, assessment of socio-economic drought is important to determine social and economic factors that exacerbate the impacts of any of agricultural and meteorological droughts [26]. Combining such studies is important to have comprehensive understanding of vulnerabilities before making resilience building efforts. These findings imply that mapping drought vulnerability using physical factors should be primary before assessing socio-economic factors which are also important, to have a complete understanding of climate change induced drought vulnerability.

Most of the studies conducted in the drought vulnerability assessment domain used population data as one of the factors of drought vulnerability [22,55] whilst in this study it was taken as a factor of confirming the existence of population in areas under various drought vulnerability conditions to determine areas with people who need assistance. Based on this, it can be argued that drought can impact both populated and unpopulated areas of the landscape hence it cannot significantly constitute the criteria for predicting drought occurrence but can constitute the criteria to confirm the observed vulnerability of existing population. Therefore, there is a need to understand vulnerability based on meteorological and physical factors followed by an overlay of population information to confirm the existence of humanity in drought risk areas. In light of this, Weber et al. [62] predicted an increase in climate change induced extreme weather events in the future which indicates that the current level of vulnerability to drought will keep worsening due to declining moisture supply and increasing moisture loss due to decreased precipitation and increased temperatures which are major determinants of drought. This validates prioritizing temperature and rainfall and the most important factors in drought vulnerability prediction. Other studies conducted in the drought vulnerability mapping domain based on AHP and Geographic

Information System confirmed vulnerability of over 50 % of geographic areas under consideration to drought. In the Kangsabati basin, it was noted that 28.5 % of the area falls under the medium drought category, followed by the high (21.1%), no drought (20%), low (19.5%), and very high (10.6%) categories [55]. These findings indicate that the greater part of this area is vulnerable to drought. Another study in Bhima River Basin of western India showed that 55 % of the area is vulnerable to drought [56]. However, in some areas like Madawa Watershed in northern Iraq, it was noted that only 16 % of the area is vulnerable to droughts whilst the rest is hardly affected and less vulnerable [63]. Overall, this literature indicates that drought vulnerability is high in most of the mapped-out areas though some few are less vulnerable which calls for the need to leverage nature-based solutions in building resilience to the increasing impact of climate change. This is in line with the findings from this study as the greater part of the study area was found highly vulnerable and therefore need assistance to build resilience.

Despite indicating areas vulnerable to various drought severity, the present study brought light to some of the possible nature-based solutions to the prevailing drought conditions in South-western Zimbabwe. Based on spatial distribution of factors used to determine drought vulnerability, including soil types and land cover, it was noted that resilience building initiatives can be tailor-made for specific areas with different physical and climatological solutions. That became the basis for developing a framework which recommends use of locally available resources which can efficiently and effectively address the impacts of droughts. Given the potential for cattle production in vast grasslands that exist in South-western Zimbabwe and fruit trees like amarula, as well as soils with great crop production potential, the need for initiatives that enhance wise exploitation of nature, for instance, amarula plantations, solar powered borehole supported horticulture and cattle production projects among others is advisable. This was supported by Jinga et al. [64] who indicated that Amarula trees do well in very dry and hot condition which becomes an opportunity for amarula plantations in these areas. This can change livelihoods for communities in southern Zimbabwe as they can industrialize Marula wine which is currently being produced at small scale. Various stakeholders with expertise in these initiatives as well as local authorities were found to be key in making this dream come true. Therefore, drought vulnerable areas can capitalize on these existing opportunities to be climate change resilient. Matsa and Dzawanda [65] also stressed that there is need to make use of natural resources in drought stricken South-western Zimbabwe to better livelihoods of communities in these areas. This indicates that resilience building must take advantage of available natural resources to efficiently achieve their main targets of reducing hunger and poverty. Given that some of the areas are rugged and mountainous in these districts, they need to be intensively used for ranching to ensure that the communities are supported on initiatives which benefit the most given the physical conditions of this region.

Conclusion and recommendations

The study assessed drought vulnerability of south western Zimbabwe based on multi-criteria decision making AHP supported by GIS and remote sensing techniques. Results indicate that almost the whole of south western Zimbabwe is prone to droughts though some few areas are comparatively better. It was also noted that the majority of the population are at high and extreme risk of agricultural and meteorological droughts. However, the study showed that resilience building interventions need to be implemented from an informed dimension, where specific resilience building initiatives are implemented in conducive environments and all neglected areas are converted to appropriate land uses which at least sustain the communities in the face of increasing drought risk due to climate change. Community development stakeholders with expertise in different aspects of development can cooperate to build a drought resilient society in south-western Zimbabwe and also in regions with similar challenges in Zimbabwe and Southern Africa as a whole. Though objectives of this study were achieved, more factors of drought vulnerability need to be factored in when future studies are conducted. This study underscores the importance of using physical parameters to predict drought risk before venturing into assessment of social factors in communities. However, emphasis is given on considering socio-economic and hydrological factors for holistic understanding of vulnerability to all possible drought types. Drought vulnerability assessment needs to be scaled up to national and regional levels so that variabilities in drought vulnerability can be observed whilst at the same time most vulnerable areas are identified for assistance. Drought risk assessment could be improved through considering both drought risk and drought occurrence frequency to ensure ground truthed information generation. Future studies are encouraged to factor in remote sensing of drought to aide predicted drought vulnerability based on drought factor analysis. Contributions of vulnerable communities are important when assessing drought vulnerability hence need to be prioritized in future studies for improved ground truthing of drought risk mapping.

CRediT authorship contribution statement

Oshneck Mupepi: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Mark Makomborero Matsa:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **John Hove:** Writing – review & editing, Validation, Conceptualization.

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.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2024.100149.

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