Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area (KAZA-GROW)

2021-2022

Water Scarcity Vulnerability Map of the Kwando River Basin and Kwando River Wildlife Dispersal Area

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Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area KAZA-GROW

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Authors:

Manuel Magombeyi, International Water Management Institute (IWMI)
Karen G. Villholth, International Water Management Institute (IWMI)

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Cover photo: Zambezi River at junction of Namibia, Zambia, Zimbabwe and Botswana before the construction of the bridge connecting Zambia with Botswana. Credit: Brian McMorrow (2006)

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ACRONYMS AND ABBREVIATIONS

AHP	Analytical Hierarchy Process
CI	Consistency Index
CR	Consistency Ratio
CBNRM	Community Based Natural Resource Management
CGIAR	Consultative Group on International Agricultural Research
CRIDF	Climate Resilient Infrastructure Development Facility
GIP	Groundwater Information Portal
GESI	Gender Equality and Social Inclusion
HWC	Human-wildlife conflict
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
KAZA-GROW	The project: Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area
KAZA TFCA MIDP	Kavango Zambezi Transfrontier Conservation Area Master Integrated Development Plan
KAZA	Kavango Zambezi
KRB	Kwando River Basin
KRWDA	Kwando River Wildlife Dispersal Area
MCDM	Multi-criteria decision making
GIS-MCDA	Multi-Criteria Decision Analysis in Geographic Information System software programs
Peace Parks	Peace Parks Foundation
RI	Random index
RESILIM	Resilience in the Limpopo Program
SADC	Southern African Development Community
SADC-GMI	Southern African Development Community Groundwater Management Institute
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
TBA	Transboundary Aquifer

TDA	Transboundary Diagnostic Analysis
TFCA	Transfrontier Conservation Area
USAID	United States Agency for International Development
WASH	Water Sanitation and Hygiene
WDA	Wildlife Dispersal Area
WLE	Water, Land and Ecosystems

SUMMARY

This report serves as the Kwando River Basin (KRB) and Kwando River Wildlife Dispersal Area (KRWDA) water scarcity vulnerability mapping for the ***Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area*** Project – shortly denoted **KAZA-GROW.** The KAZA-GROW flagship project (**Grant Agreement No. RWP-G13-IWMI**) is a project implemented by the International Water Management Institute (IWMI) in partnership with the KAZA TFCA Secretariat and Peace Parks Foundation (Peace Parks) and funded by the United States Agency for International Development (USAID) - under the Resilient Waters Program - and the CGIAR (Consultative Group on International Agricultural Research) Research Program on Water, Land and Ecosystems (WLE), led by IWMI. The project runs over two years from **January 18, 2021 to February 15, 2023**.

The objective of this report is to identify and map water scarcity vulnerable areas in the Kwando River Basin (KRB) and Kwando River Wildlife Dispersal Area (KRWDA). Careful water scarcity vulnerability mapping requires delineation of areas based on scientific and expert judgement. The Multi Criteria Decision Making (MCDM) method in conjunction with Geographic Information Systems (GIS) was applied in this study to identify areas with different levels of human vulnerability to water scarcity. A set of ten parameters (rainfall, population density, poverty level, wetlands, protected areas, and distance to rivers, roads, wildlife corridors, boreholes and fire outbreaks) were used in the final overlay analysis in GIS. The Analytical Hierarchy Process (AHP) method was then applied to calculate the influence or the weights of individual parameters on the water scarcity vulnerability. The normalized individual weighted layers were then overlaid using map algebra in ArcMap to assess the water scarcity vulnerable areas for the KRB and KRWDA. The results revealed that more than half (65.1%) of the study area was classified as having high to very high water scarcity vulnerability. Most significant parameters for the assessment of human vulnerability to water scarcity are rainfall, rivers, wetlands and wildlife corridors, while the most sensitive factors include rainfall, population density, poverty level, wetland location, and distance to roads, boreholes, and fire outbreaks. Human vulnerability is influenced by natural as well as anthropogenic factors. These factors, in turn, influence the environment, which exacerbates human vulnerability. Water availability and infrastructure are key, and with climate change, infrastructure becomes more important.

1. INTRODUCTION

This report serves as the Kwando River Basin (KRB) and Kwando River Wildlife Dispersal Area (KRWDA) water scarcity vulnerability mapping for the ***Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area*** Project – shortly denoted **KAZA-GROW.** The KAZA-GROW flagship project (**Grant Agreement No. RWP-G13-IWMI**) is a project implemented by the International Water Management Institute (IWMI) in partnership with the KAZA TFCA Secretariat and Peace Parks Foundation (Peace Parks) and funded by the United States Agency for International Development (USAID) - under the Resilient Waters Program - and the CGIAR (Consultative Group on International Agricultural Research) Research Program on Water, Land and Ecosystems (WLE), led by IWMI. The project runs over two years from **January 18, 2021 to February 15, 2023**.

1.1 Background

Water plays a critical role in sustaining livelihoods, wildlife and ecosystem services. However, water availability at catchment scale is not always abundant throughout the year. It varies according to the seasons and over years, exacerbated by climate change and increasing demand from growing populations and economic growth. During the wet season, there is usually more water to satisfy the needs, while during the dry season and dry years, water availability dwindles, unless there is managed natural or built infrastructure to even the supply throughout the year and over years. This reduction in water availability in some areas results in water scarcity putting livelihoods, wildlife and ecosystem services under pressure, increasing overall vulnerability. In this study, we focus on the vulnerability of poor communities in the KRB and KRWDA in terms of basic and productive water uses.

UNDP (2020) defined vulnerability as the inability of people, organizations, and societies to withstand adverse impacts from multiple stressors to which they are exposed. In this study linked to the KAZA TFCA, water scarcity vulnerable areas are defined as areas far away from a surface water source (e.g., river). However, areas very close to the river in rural communities have greater likelihood of experiencing conflict between humans and wildlife, enhancing vulnerability. Areas where there is no water supply infrastructure, such as boreholes in the villages are also considered as vulnerable, as communities have to go to rivers to fetch water. There is a high degree of malfunctioning of groundwater infrastructure, with an estimated 40% of SADC population (SADC, 2012) not having proper access to drinking water and relying on "unimproved" water sources from either groundwater or surface water (WHO, 2013). In the proposed definitions, water scarcity vulnerability is a function of potential impact and the available adaptive capacity of the communities.

Water scarcity is prevalent in semi-arid regions, driving human vulnerability, often exacerbated by high human population density, lack of resources, land degradation, pollution, and climate-induced floods and droughts (Petrie et al., 2014). Falkenmark et al. (1989) developed a water scarcity indicator to measure the total water resources that are available to the population of a country or region and is expressed as the renewable freshwater that is available per person per year, with below 1,700 m^3/a, classified as water stress; below 1,000 m^3/a as water scarcity; and below 500 m^3/a, as absolute water scarcity. UN Water (2006) defined water scarcity as the lack of freshwater resources to meet the standard water demand for both human and ecosystem water needs. Two types of water scarcity have been defined: physical and economic water scarcity (UNDP, 2006). Physical water scarcity is when the demand of the population exceeds the available water resources of a region, while under economic water scarcity, the water resources are available, but there is lack of suitable infrastructure to exploit the resource for the benefit for the communities.

Water scarcity is rapidly growing around the world due to increased overexploitation of freshwater resources due to population increase, changes in water consumption patterns, and possible impacts of climate variability and change (Bond et al., 2019). OKACOM (2011) identified the same drivers to water scarcity in both the KRB and KRWDA, including urbanization, land use change, and human-wildlife conflict (HWC). Water scarcity creates ongoing restrictions and barriers to agricultural productivity and to non-farming economic development, such as industrial and tourism activities in the KRB (CRIDF, 2019a).

A water scarcity vulnerability map gives the locations where people, communities, the environment or infrastructure are at risk of experiencing water shortage (Bond et al., 2019). In this study, focus is on human vulnerability, as influenced by a host of biotic and abiotic factors, including human factors. Water is key to livelihoods and there is a need to balance the needs of people, livestock, wildlife, and environment. In the KRB and KRWDA, water is both a key part of livelihoods and a key cause of conflicts (CRIDF, 2019a). Livelihood aspects are a critical component of vulnerability, both as part of resultant poverty and as part of impact of water scarcity. In the KAZA TFCA, the livelihood strategies of most inhabitants (more than 70%, mostly rural) depend on natural resources, subsistence farming, livestock, fisheries and tourism-related activities (CRIDF, 2019a). Residents in towns function on a cash economy, with the majority engaged in informal trade and services (CRIDF, 2019b; USAID, 2016).

Communities in the KRB and KRWDA are dependent on water from:

- Unprotected river and shallow groundwater sources for domestic and small-scale livelihood strategies,
- Formal reticulation systems, mostly in major settlements,
- Wells and boreholes tapping shallow and deep groundwater and transboundary aquifers (TBAs).

There is growing human-wildlife and land use conflicts, which adds to vulnerability of both humans and wildlife. Human-wildlife conflicts (HWC) are due to growing human population and large mammal species, e.g. re-colonising formerly abandoned areas as reported by Stoldt et al. (2020) in the Namibian component of the KAZA TFCA. Seasonal animal movements often bring wildlife into conflict with human settlements as they compete for the same water and land resources (CRIDF, 2019b). CRIDF (2019b) reported that during the dry season, when wildlife move closer to water sources, farmers see significant losses of crops as large wildlife raid crops, break down fences and water tanks, or when predators kill livestock, while in the wet season there is a decrease in conflict as wildlife tend to disperse over a much wider area. Stoldt et al. (2020) argue that HWC has the potential to significantly contribute to the failure of the TFCA concept, if not monitored.

1.2 Objective

The objective of this report is to map areas of water scarcity vulnerability in the Kwando River Basin (KRB) and Kwando River Wildlife Dispersal Area (KRWDA). The mapping of water scarcity vulnerable areas is important for identification of livelihood vulnerability and investments needed to enhance adaptation and resilience building of communities under climate change, considering both current and potential future impacts in the KRB and KRWDA.

Target audiences of the report include those concerned with TFCA transboundary management, cooperation and local governance, those who make decisions on natural (land and water) resource management, and those who invest in building climate adaptation and resilience. To a lesser extent the outputs also address local community water planning and management.

2 REVIEW OF VULNERABILITY MAPPING METHODS

2.1 Standard quantitative mapping overlay and validation by basin experts

The method of standard quantitative mapping overlay was applied for the transboundary Limpopo River Basin, done by Petrie et al. (2014). Geographical Information Systems (GIS) were used to map vulnerability, capturing the spatial variability of different climatic (including extreme weather events such as floods and droughts), biophysical, biological, and socioeconomic indicators into spatial models of risk and vulnerability. This study provided insights into systems that are highly sensitive to modest changes in climate, and whose ability to adapt is severely constrained (IPCC, 2000). Petrie et al. (2014) used the 1st to 4th Order Impact Framework, a method that requires the examination of the propagation from climate effects to ecosystem and livelihood impacts (Figure 1). This method of evaluation makes explicit linkages and feedbacks between basic climate parameters (1st order), the resulting physical and chemical processes in the physical and biotic environment (2nd order), the resulting ecosystem services and production potential (3rd order), and finally the resultant social and economic conditions (4th order).

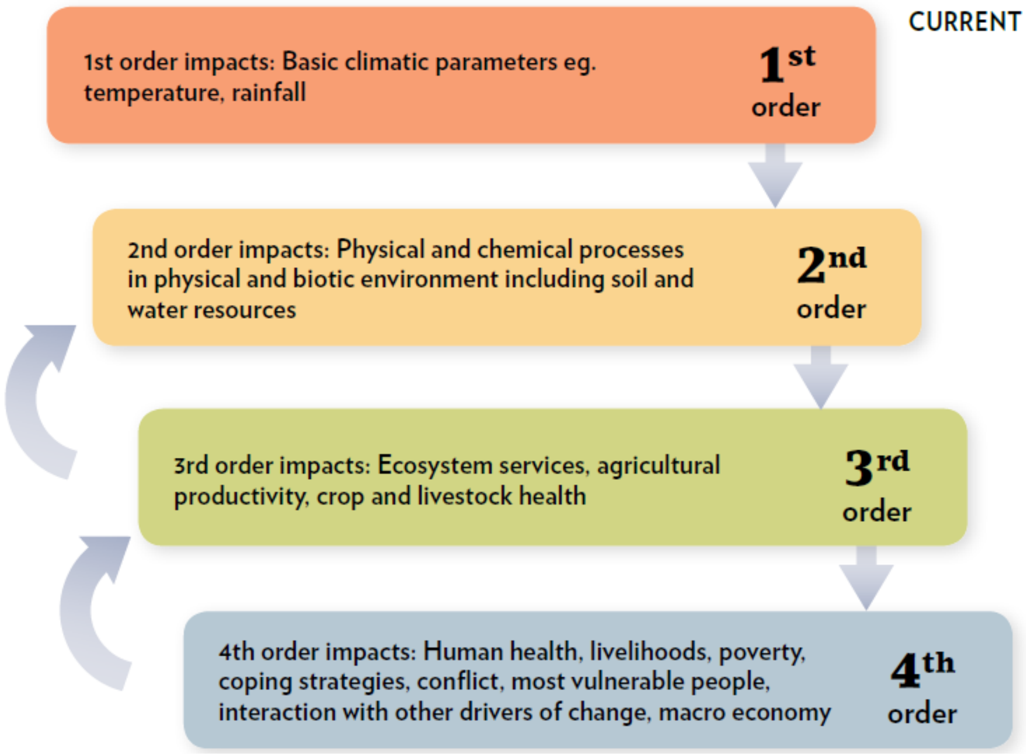

Figure 1 Applying the 1st to 4th Order Impact Framework (Petrie et al., 2014).

This analysis revealed an initial set of ten highly vulnerable areas in the Limpopo River Basin. Three areas that were transboundary in nature were selected and validated by Limpopo River Basin experts. This combined study methodology provided an integrated platform for understanding the basin's current and future levels of adaptive capacity and ability to build resilience, although it was performed at a relatively large scale with limited details.

Other mapping studies used similar overlay mapping methodologies, e.g. for mapping human-wildlife conflict incidents in the Namibian component of the KAZA TFCA (Stoldt et al., 2020), and for mapping of groundwater drought risk in the Southern African Development Community (SADC) region using an integrated management support tool, GRiMMS (Villholth et al., 2013).

2.2. Qualitative mapping and validation with basin stakeholders

A standard quantitative overlay process, as described in the previous section, was not suitable for the Cubango-Okavango River Basin (CORB) due to spatial data availability limitations (CRIDF, 2019b). This complicated the process of identifying vulnerability hotspots across the basin in a single overview, using the same variables mapped in a distributed manner. To overcome this challenge, the basin was sub-divided into five more or less homogenous vulnerability zones that reflected similarities in environmental and socioeconomic characteristics. Within these homogenous zones, land cover and related elements of natural and socioeconomic (e.g., proximity to markets) variables were similar. A hotspot or several hotspot areas were identified within each zone with the help of experts. The list of parameters considered included surface water (wetlands, streams, rivers and dams), vegetation, soils, agricultural potential, erosion risk, roads, railway, distance to schools/clinics, WASH access, health data, electricity access, conflict zones, drought information, protected zones/nature reserves, and future climate. Although total standardisation with regard to parameters was not possible, and despite observing significant differences between local community features, the homogenous zones reflected similarities in terms of the type of interventions that may be suitable to reduce livelihood vulnerabilities. The validity of these zone delineations was then interrogated with basin stakeholders, to ensure that the distinct and differing nature of specific areas was captured. The zonal delineation of homogenous areas enabled more effective hotspot identification at zonal scale, with land cover satellite image data providing a backdrop to the zonal map.

2.2.1 Weighting

Parameters that were deemed key to water resource-related livelihood interventions were given more weight, given the inherent relationship between livelihoods and water resources in the basin. These key parameters included rainfall, population density, poverty level, wetlands, protected areas, and distance to rivers, roads, wildlife corridors, boreholes and fire outbreaks. The weighting was based on the Analytical Hierarchy Process (AHP) method and presented in the methods section.

2.2.2 Mapping

Areas of compounding vulnerability were considered potential areas where the implementation of sustainable livelihood support measures would have a disproportionate positive socioeconomic impact and increase the resilience of affected communities, while taking clear remedial actions to ensure ecological integrity. Qualitative and narrative-based assessment processes were applied to verify and enhance the hotspot mapping outcomes. These narratives to unpack each of the livelihood capital categories as well as climate futures and transboundary implications, by drawing on literature, maps and quantitative statistics that are not spatially represented, were derived per homogenous zone.

3 STUDY AREA

The KRB and KRWDA, with a combined total area of 190,000 km^2 are shared among the four countries Angola, Botswana, Namibia and Zambia. The districts covered in the KRB and KRWDA include Angola (Bundas (Lumbala-Nguimbo), Cuito Cuanavale, Dirico, Luchazes, Luena, Mavinga, Nancova, and Rivungo), Botswana (Chobe and Ngamiland East & West - North West), Namibia (Mukwe, Kongola, Judea Lyaboloma, Linyanti, Sibbinda, Katima Mulilo Rural, Katima Mulilo Urban, Kabbe North, and Kabbe South), and Zambia (Itezhi-tezhi, Luampa, Mongu, Mulobezi, Nalolo, Senanga, Sesheke, Shang'ombo, Sikongo, and Sioma). The proportion of the KRB and KRWDA in Angola is 55.9%, Botswana 9.6%, Namibia 7.2%, and Zambia 27.3%. Zambia has the highest population in the KRB and KRWDA, with an estimated 573,700 people, followed by Angola (102,800), Namibia (49,100) and Botswana (28,800).

4 METHODS

Several studies have assessed the nature of specific areas for various purposes using Multi-Criteria Decision Analysis in Geographic Information System software programs (GIS-MCDA). In this process, a decision maker evaluates alternative solutions combining different decision criteria to find the best solution to a specific problem. A similar approach was applied in this study to identify areas with different vulnerability levels of water scarcity. The essential parameters considered for water scarcity vulnerability mapping included bio-physical and socioeconomic conditions (Murray, 2008).

A set of ten parameters (rainfall, population density, poverty level, wetlands, protected areas, and distance to rivers, roads, wildlife corridors, boreholes, and fire outbreaks) were used for analysis in GIS. The Analytical Hierarchy Process (AHP) method and software (http://bpmsg.com) was then applied to calculate the influence, or sensitivity, of the weights of individual parameters on the water scarcity vulnerability. The weighting was calculated by comparing the importance on a scale of 1-9 (1-equal importance, 3- moderate importance, 5- strong importance, 7- very strong importance, and 9-most important) of one parameter with the other parameters in a matrix. Two parameters are compared at a time, with the objective of identifying which parameter of each pair is more important, and how much more important on a scale 1-9. For example, comparison of rainfall with rainfall gives 1, while when comparing rainfall with river, rainfall has stronger importance (with scale of 5). The judgement on the scale used was based on the knowledge of the study area. This pairwise comparison was done until all the parameters were covered and a full pairwise comparison matrix based on Saaty (1980) was developed, with the number of row and columns equal to the number of parameters considered for vulnerability analysis (in this study it was 10 parameters, that yielded a (10 × 10) matrix. The matrix was checked for consistence, using the Consistency Ratio (*CR*), which should be less than or equal to 10% (Goepel, 2018). The *CR* given in Equation 1 was used to identify and correct the logical inconsistency of the pairwise comparison matrix developed based on experience or expert judgement.

Each matrix was checked for consistency throughout the process by calculating the following consistency ratio from the Consistency Index (*CI*) and dividing it by the Random Index (*RI*) (Saaty, 1980). The *CI* given in Equation 2 forms an input for determining the *CR*.

$$CR = \frac{CI}{RI} \qquad \text{Equation 1}$$

where *CR* is the consistency ratio, *CI is the con*sistency index, and *RI is the* random index.

$$CI = \frac{\lambda_{max} - n}{(n-1)} \qquad \text{Equation 2}$$

where λ_{max} is the maximum Eigenvalue, and *n* is the number of criteria or parameters.

The *RI* was presented in a table by the Oak Ridge National Laboratory for matrices with up to 15 rows (Saaty, 1980). In cases where the *CR* value is greater than 10%, the assigned weight of the parameter/ criterion from judgement is classified as inconsistent or unreliable due to its randomness and thus require modification before solving the matrix, while values less than 10% are acceptable (Saaty, 1980). This matrix was solved by the AHP software to give the normalized principal Eigenvector, which contains the optimal weights of each parameter (Goepel, 2018).

Before the AHP assessment, each parameter was reclassified into five classes in GIS environment, mostly using Jenks Natural Breaks or natural groupings inherent in the data. The classes were then standardized using a common scale of 1–5 (where 1 = very low vulnerability, 2 = low vulnerability, 3 = medium vulnerability, 4 = high vulnerability and 5 = very high vulnerability). Standardization by reclassification helped to convert each criterion/parameter map to a uniform measurement scale for easy comparison and overlay analysis (Yalew et al., 2016). Using raster calculator in map algebra in ArcMap, the reclassified raster maps and their weighting on water scarcity vulnerability were combined into a single or composite vulnerability map, with a common scale of 1–5 mentioned above. The weighting from the AHP method of all the reclassified raster maps should add up to 1 or 100%.

4.1 Data used in water scarcity vulnerability mapping

The metadata for the data used in the vulnerability mapping are given in Table 1. The data and metadata were sourced from different online databases. Roads and boreholes were treated as two separate maps and the same for protected areas and wetlands under land use. The spatial resolution of the water scarcity vulnerability assessment was 30 m.

Table 1 Metadata for parameters used and their relation to water scarcity vulnerability.

No	Parameter	Data source	Relation between parameter and vulnerability
1	**Rainfall**	SASSCAL- CHIRPS	Areas with higher rainfall are less vulnerable than those with less rainfall. Annual rainfall data (mm/a) were used.
2	**Population density**	Worldometer (2021)	Areas with high population density are more vulnerable than areas with low population density, as there is likely to be more competition for water resources. People/km^2 were used.
3	**Poverty level**	World Bank (2020)	Areas with high poverty are more vulnerable than areas with low poverty. Communities with high poverty are not able to invest in water supply infrastructure to enhance their water access. The poverty rate was based on the percentage of the population living on less than US$ 1.9 per person per day at 2011 international prices (World Bank, 2020).
4	**Wetlands**	Peace Parks Foundation	Wetland areas are less vulnerable than non-wetland areas. Water scarcity vulnerability increases as one moves away from the wetland.
5	**Protected areas**	Peace Parks Foundation	Protected areas are less vulnerable to human water scarcity than other areas although they have concentrated wildlife populations.
6	**Rivers**	Peace Parks Foundation	Areas close to rivers and other surface sources (lakes, dams and other impoundments) are less vulnerable, due to access to water. The nature of the river is important (perennial, flow volume, and water quality), The risk of HWC is not considered here, but it likely higher near water sources or water points.
7	**Roads**	https://rcmrd.africageoportal.com/datasets	Borehole locations are typically along main roads e.g., in Namibia and Zambia. We assume the same pattern to hold for other areas in the study area. Hence, areas near roads are less vulnerable than areas far from roads. There is also access to external resources via roads, and HWC associated activities (such as roads follow boundaries, boundaries have fences which impact on animal migration, urbanization movements and access etc.).
8	**Wildlife corridors**	Stoldt et al. (2020)	Wildlife corridors are more vulnerable due to concentrated wildlife and possible conflict with humans. Water scarcity decreases as one moves away from the corridors.
9	**Boreholes**	Peace Parks Foundation	Areas with boreholes are less vulnerable as these boreholes supply water to the communities and wildlife. The vulnerability increases as one moves away from the boreholes.
10	**Fire outbreaks**	Peace Parks Foundation	Areas with high frequency of veld fire outbreaks are more vulnerable than other areas with less frequency of fire outbreaks. Fire also damages water infrastructure. Vulnerability decreases with distance from the fire outbreak areas.

4.2 Weighted overlay analysis

The weighted overlay spatial analysis tool in ArcMap was used to assess the vulnerability index for a pixel by multiplying the vulnerability value and the weight per parameter. Doing this for all parameters for the pixel and summation, the results yielded a vulnerability index (*V*), based on Equation 3 (Yalew et al., 2016).

$$V = \sum W_i x_i \qquad \text{Equation 3}$$

where *V* is the vulnerability index, W_i is the weight of the parameter *i, and* x_i is the vulnerability value for parameter *i*. In this case, x_i=1, 2, 3, 4, or 5, and i=1,…, 10. In addition, $\sum W_i$ = 1.0. This is repeated for all pixels to produce the composite vulnerability map.

4.3 Sensitivity analysis of input data

Many studies on vulnerability mapping perform an automated sensitivity analysis by changing inputs on weights and observing the response in terms of outputs. Sensitivity analysis accounts for data uncertainty and the subjectivity in decision-making on which parameter is more important than the next. A manual sensitivity analysis was applied to estimate the robustness of the AHP weighting technique and to estimate the parameter that mostly affects the vulnerability outcome (Gibson and Campana, 2018). In this study, weighting of one parameter was reduced by 50% from the final (the AHP generated) vulnerability map parameter weights, while the difference was evenly distributed over the other parameters. Multiple simulations were conducted (until all parameters were reduced by 50%) and the resultant areas under very low, low, moderate, high and very high vulnerability levels noted.

4.4 Validation of vulnerability map by stakeholders (at higher level and local level meetings)

Comparison of the water scarcity vulnerability map with past studies in the study area, such as CRIDF (2019a) and SADC (2021) was done. Further consultation with stakeholders in the study area is planned and will be done in conjunction with the Regional Transboundary Diagnostic Analysis (TDA) Consultation Workshop (October-November 2021). During this workshop, a few questions drafted together with the Resilient Waters Program Gender Equality and Social Inclusion (GESI) team will be shared with the participants. Further validation will be done during the November 2021 field visit to the KRB and KRWDA.

5 RESULTS

5.1 Reclassified data

The reclassified parameters are presented in Table 2 and individual maps shown in Figures 2 to 11. Wetlands were reclassified as low vulnerability (vulnerability value 2), while non-wetland areas were reclassified as highly vulnerable (vulnerability value 4). Protected areas were reclassified as moderate vulnerability (vulnerability value 3), while areas outside protected areas were reclassified as highly vulnerable (vulnerability value 4). The reclassification enabled uniform comparison among the different parameters. Lack of data on water infrastructure such as borehole locations were noted in Angola, Botswana, Namibia and Zambia (Figure 10). Availability of this data can improve the vulnerability analysis. Areas with missing data were represented as no data in the reclassification and presented in white colour.

Table 2 Reclassified parameters[a]

No	Parameter	Vulnerability class/value				
		Very low	Low	Moderate	High	Very high
		1	2	3	4	5
1	**Rainfall (mm/a)**	> 950	850-950	650-850	500-650	350-500
2	**Population density (people/km²)**	0-2	2-5	5-10	10-30	> 30
3	**Poverty level (%)**	0-14	14-20	20-30	30-40	> 40
4	**Wetlands**	na	Wetland exists	na	Wetland doesn't exist	na
5	**Protected areas**	na	na	Protected area exists	Protected area doesn't exist	na
6	**Rivers (m)**	0-1,000	1,000-3,000	3,000-5,000	5,000-8,000	> 8,000
7	**Roads (m)**	0-1,000	1,000-3,000	3,000-5,000	5,000-8,000	> 8,000
8	**Wildlife corridors (m)**	> 11,000	8,000-11,000	5,000-8,000	2,000-5,000	< 2,000
9	**Boreholes (m)**	0-1,000	1,000-3,000	3,000-5,000	5,000-8,000	> 8,000
10	**Fire outbreaks (m)**	> 15,000	10,000-15,000	6,000-10,000	2,000-6,000	< 2,000

[a] The distance from rivers, roads, wildlife corridors, boreholes, and fire outbreaks is given.

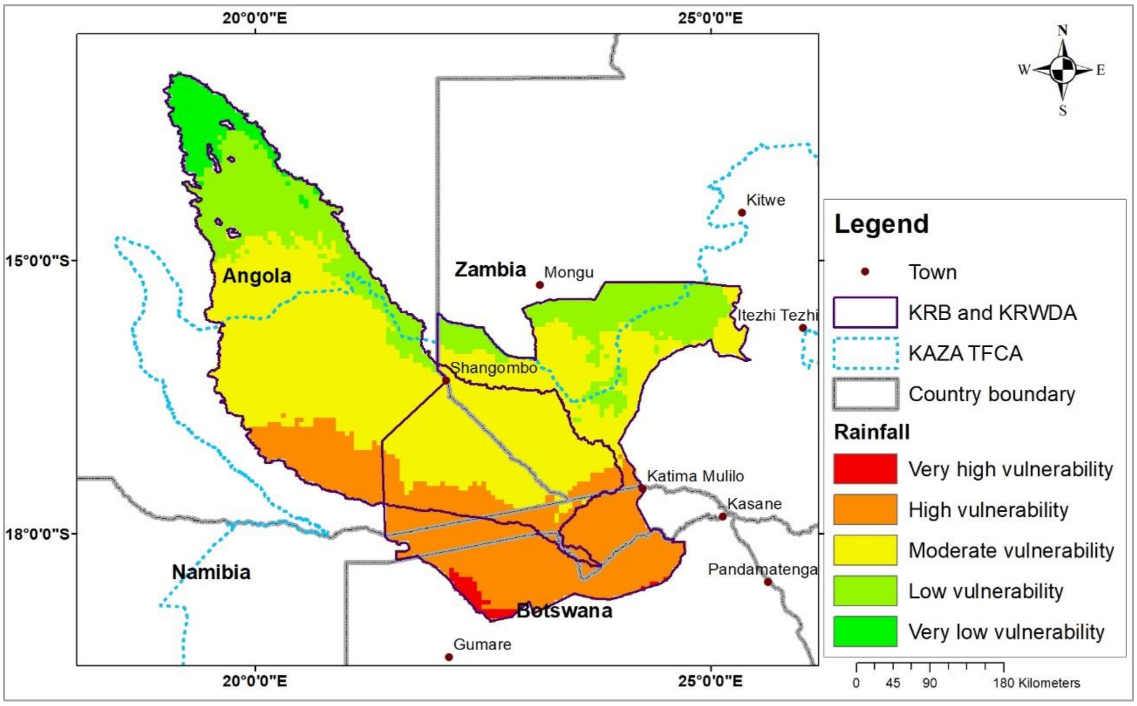

Figure 2 Vulnerability as a function of reclassified rainfall in the KRB and KRWDA.

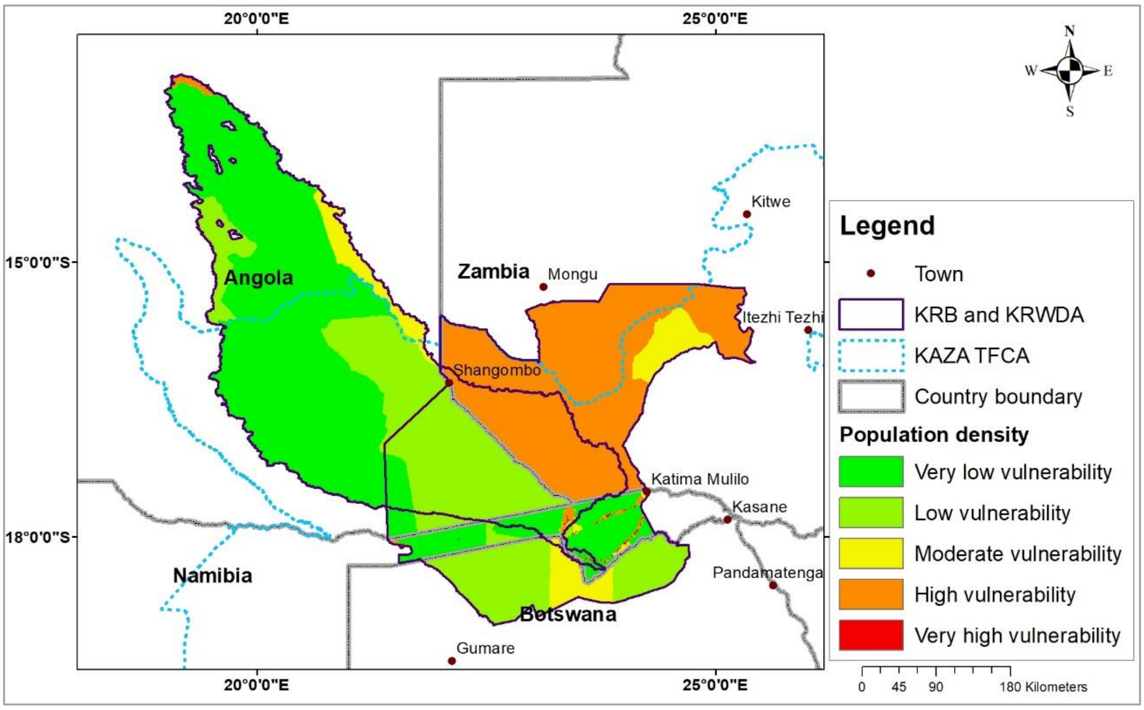

Figure 3 Vulnerability as a function of reclassified population density in the KRB and KRWDA.

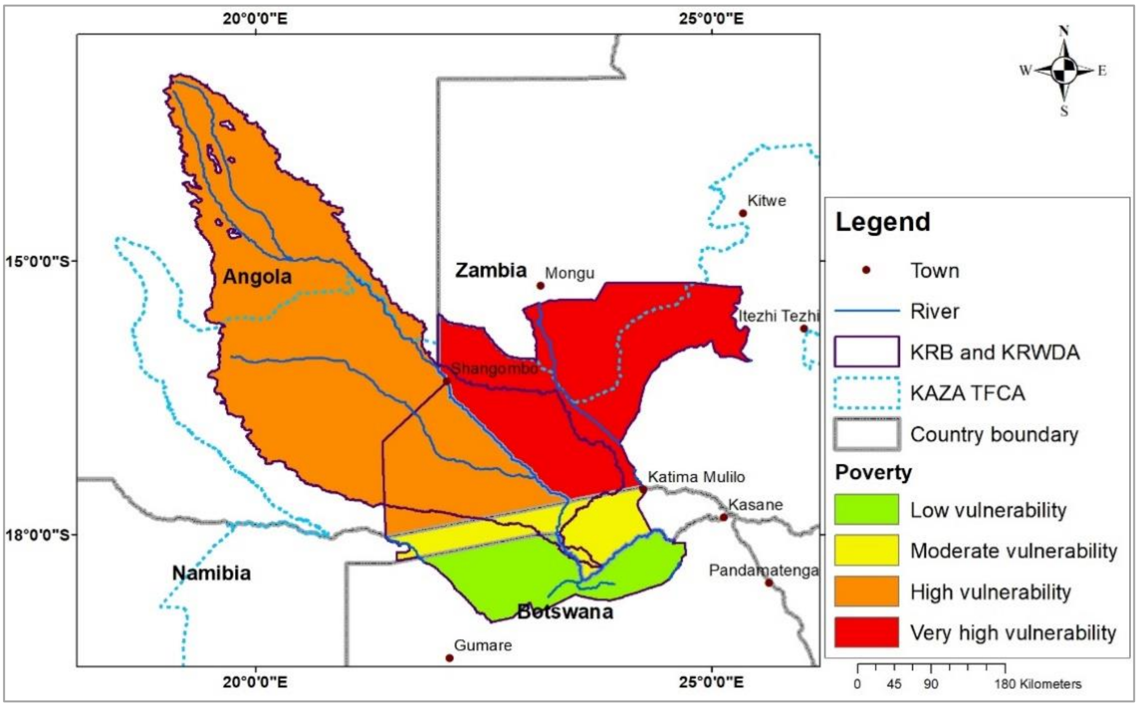

Figure 4 Vulnerability as a function of reclassified poverty level in the KRB and KRWDA.

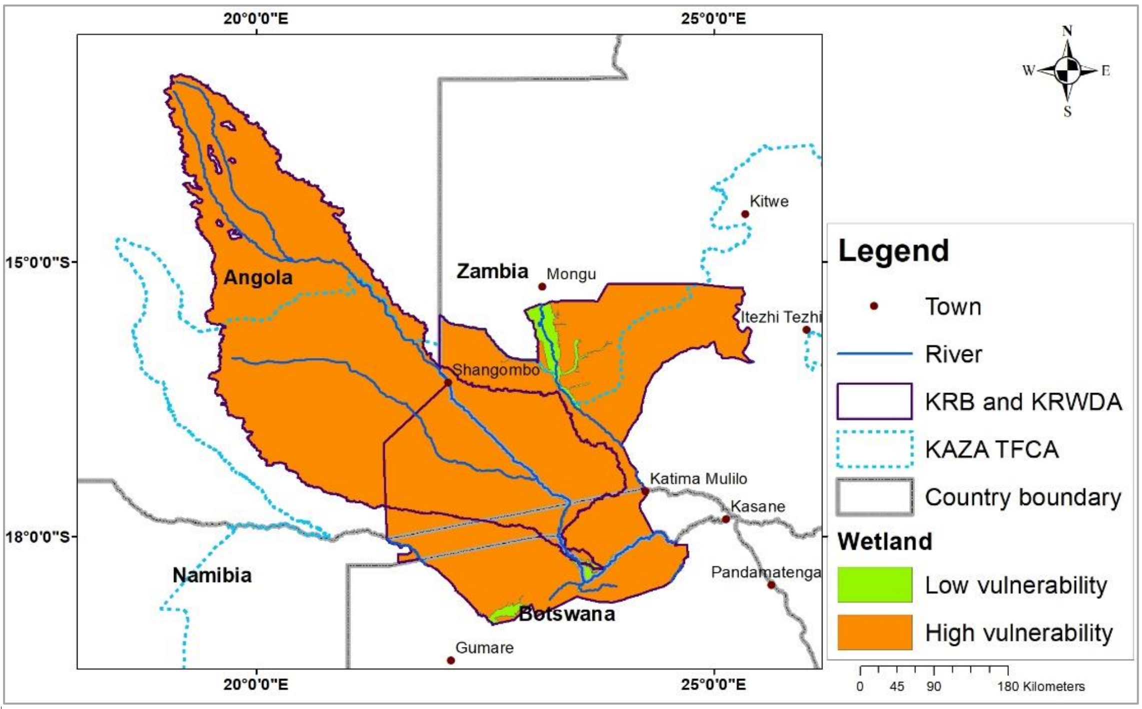

Figure 5 Vulnerability as a function of reclassified wetland areas in the KRB and KRWDA.

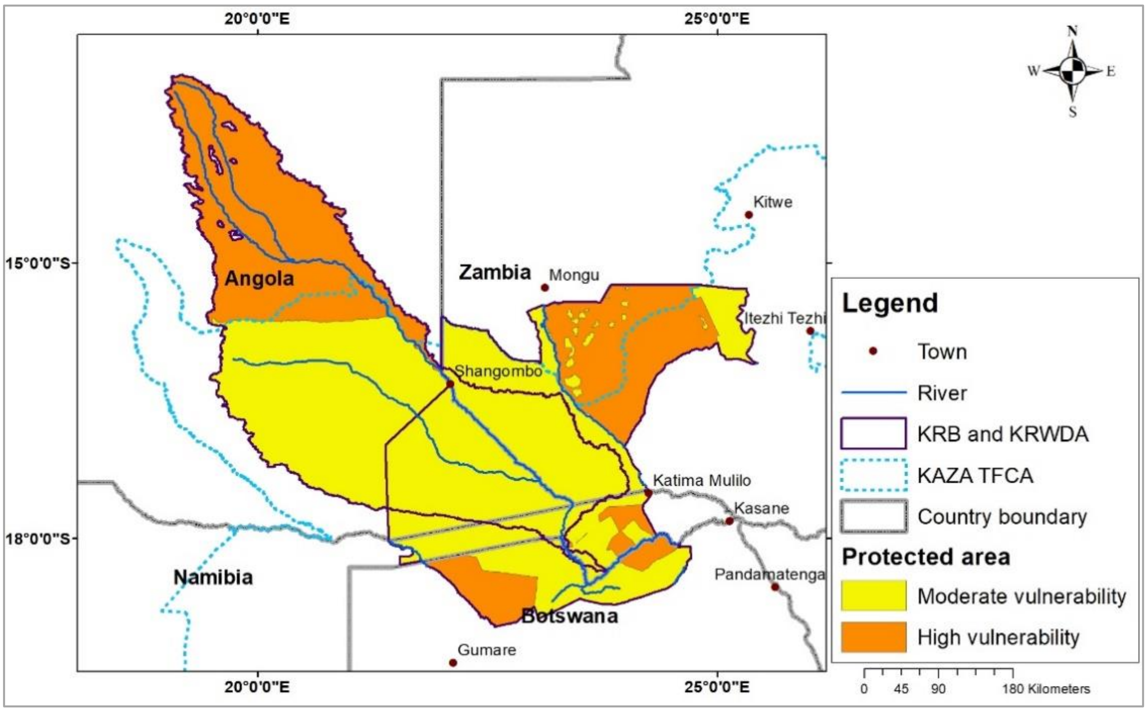

Figure 6 Vulnerability as a function of reclassified protected areas in the KRB and KRWDA.

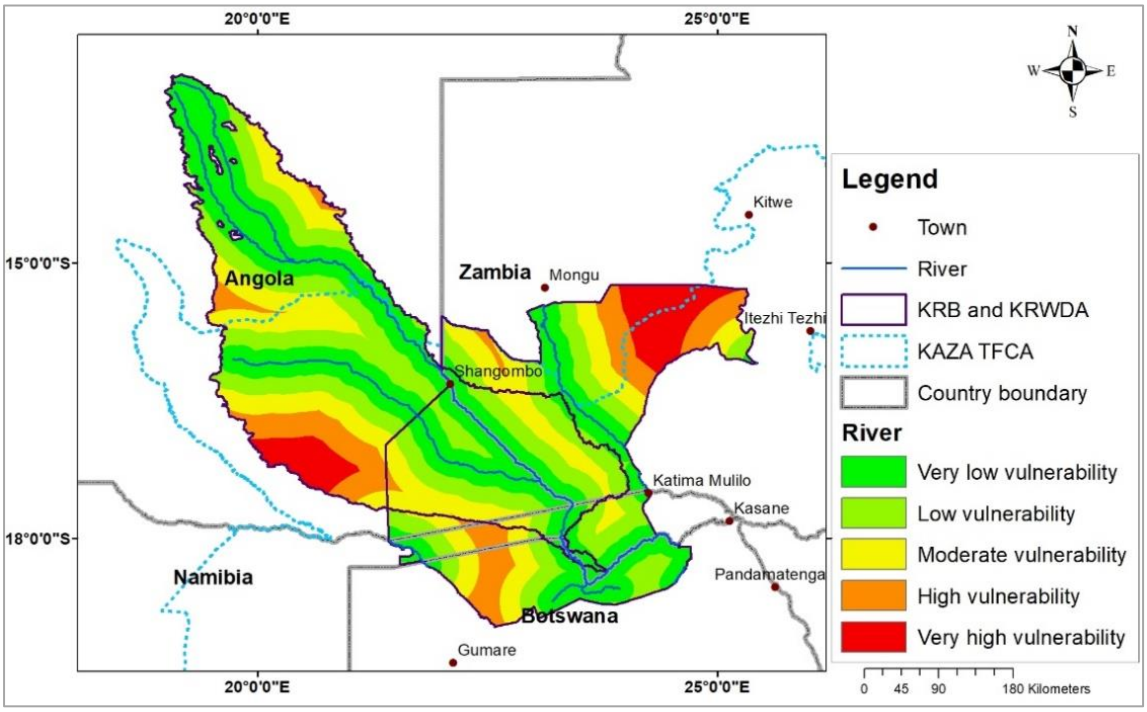

Figure 7 Vulnerability as a function of reclassified distance from rivers in the KRB and KRWDA.

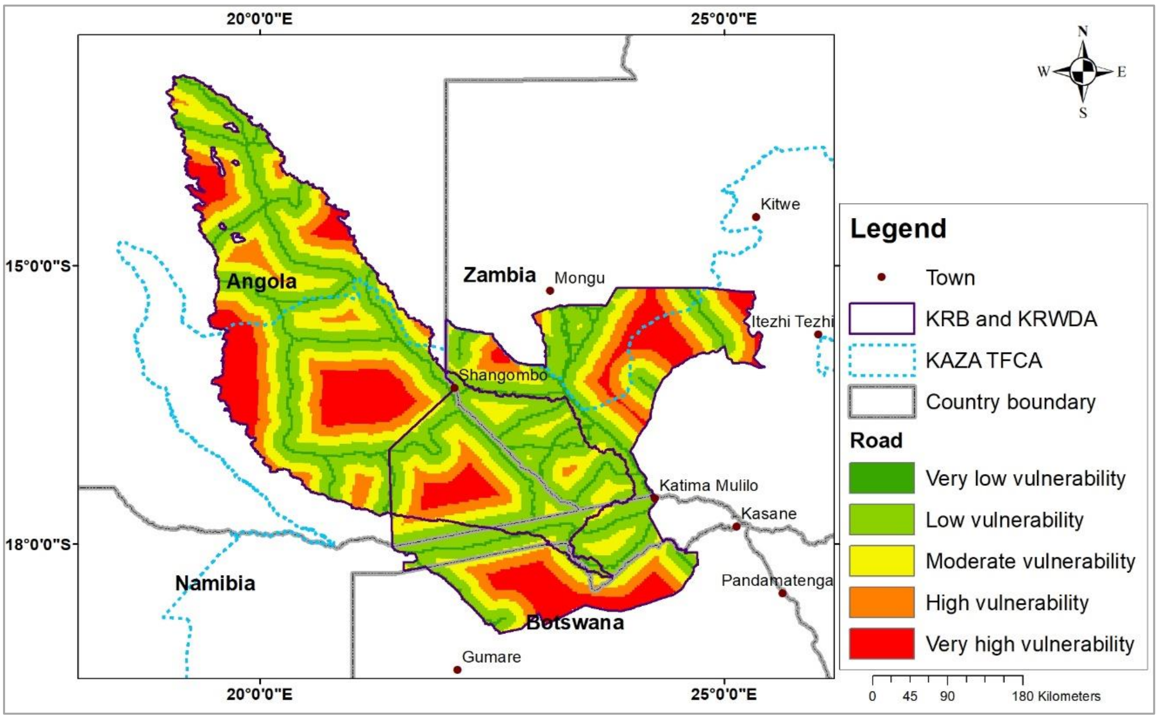

Figure 8 Vulnerability as a function of reclassified distance from roads in the KRB and KRWDA.

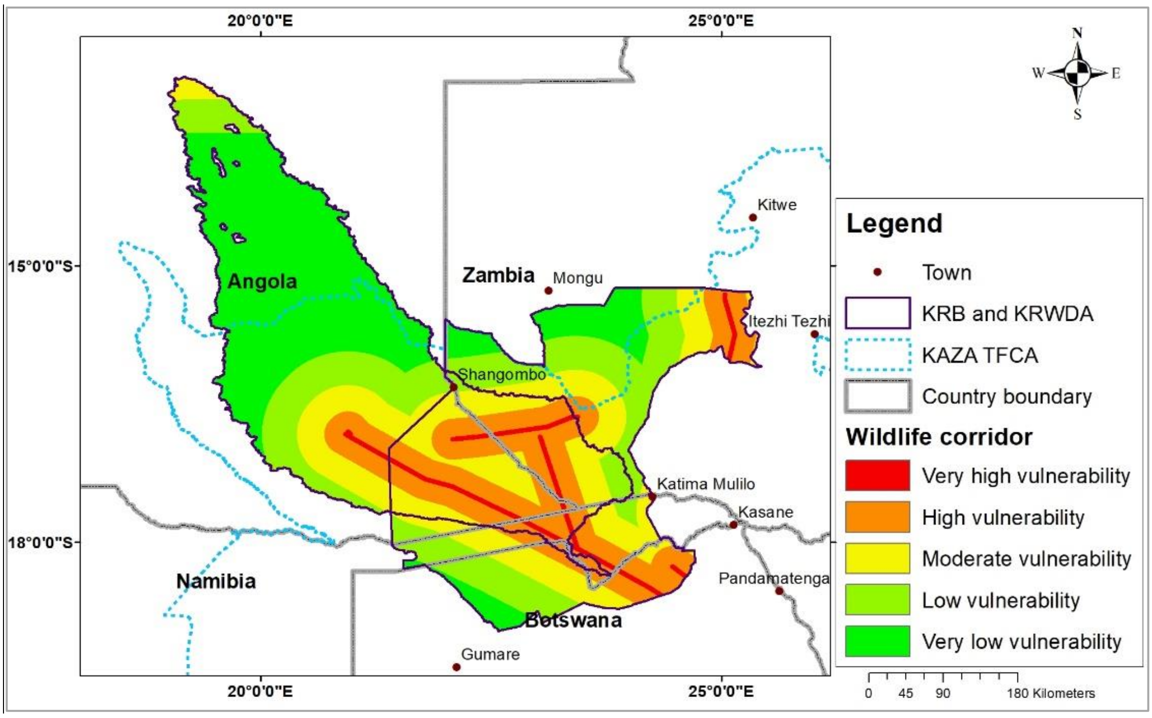

Figure 9 Vulnerability as a function of reclassified distance from wildlife corridors in the KRB and KRWDA.

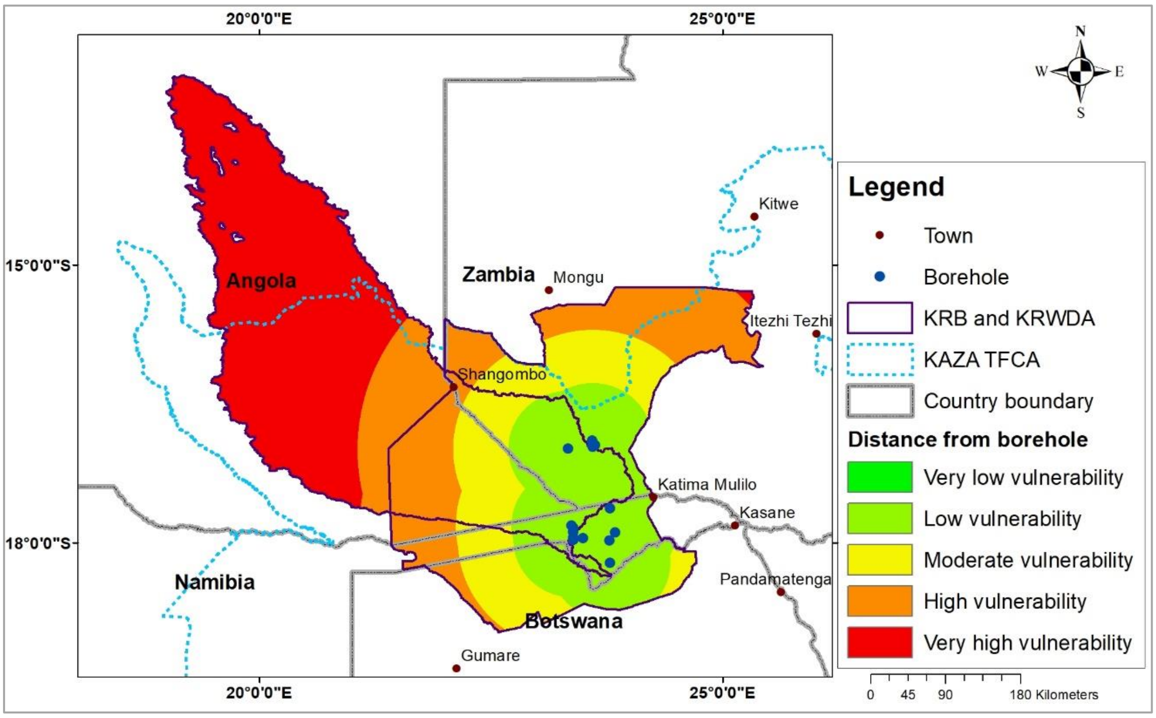

Figure 10 Vulnerability as a function of reclassified distance from boreholes in the KRB and KRWDA.

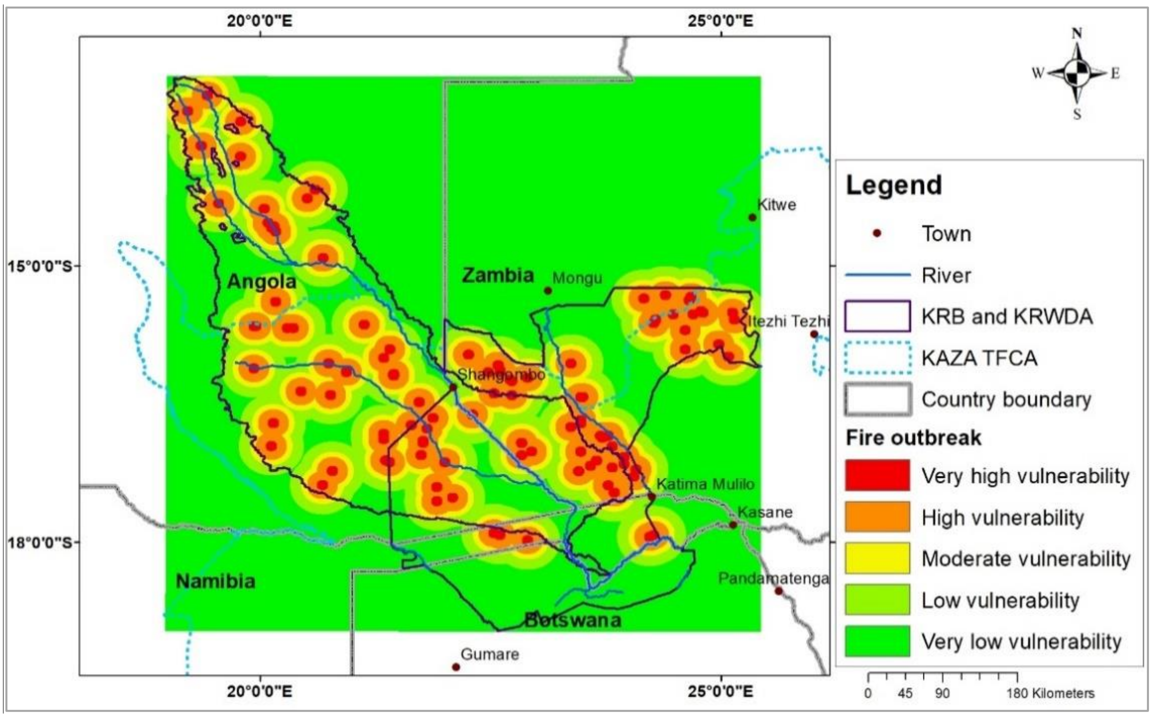

Figure 11 Vulnerability as a function of reclassified distance from fire outbreaks in the KRB and KRWDA.

5.2 Analytical Hierarchy Process and weighted overlay analysis

The parameter weighting (shown as the normalized principal Eigenvector) in Table 3 was used for the Analytical Hierarchy Process (AHP) to construct the final composite vulnerability map (Figure 12), using Equation 3. The consistency ratio (CR) from the constructed matrix (10 × 10) of weights was 9%. This CR of 9% is acceptable as it is less than 10% required for a matrix larger than 4 × 4. Hence, the assigned weights and pairwise comparison matrix were consistent and acceptable (Saaty, 1980). The most significant parameters from the developed matrix of weights (Table 3) are rainfall, rivers, wetlands and wildlife corridors. Rainfall is the water source that feeds rivers, groundwater, wetlands and other landuse/land cover areas, including the wildlife corridors. The wildlife corridors are important as they are associated with wildlife movement and potential human-wildlife conflict that may include destruction of water supply infrastructure.

Table 3 Parameter weighting, totalling 100% (last column) used in overlay analysis (based on Saaty (1980)).

Weighting		Rainfall 1	Rivers 2	Wetlands 3	Wildlife corridors 4	Roads 5	Fire outbreaks 6	Protected areas 7	Population density 8	Poverty 9	Boreholes 10	normalized principal Eigenvector
Rainfall	1	1	5	4	3	3	3	3	5	3	3	27.15%
Rivers	2	1/5	1	3	3	3	3	3	3	3	3	17.21%
Wetlands	3	1/4	1/3	1	1	1	3	3	3	5	3	11.55%
Wildlife corridors	4	1/3	1/3	1	1	3	1	3	5	3	3	11.66%
Roads	5	1/3	1/3	1	1/3	1	1	1	3	3	3	7.95%
Fire outbreaks	6	1/3	1/3	1/3	1	1	1	1	3	1	3	7.04%
Protected areas	7	1/3	1/3	1/3	1/3	1	1	1	1	1	1	4.99%
Population density	8	1/5	1/3	1/3	1/5	1/3	1/3	1	1	1	1	3.61%
Poverty	9	1/3	1/3	1/5	1/3	1/3	1	1	1	1	3	5.05%
Boreholes	10	1/3	1/3	1/3	1/3	1/3	1/3	1	1	1/3	1	3.78%

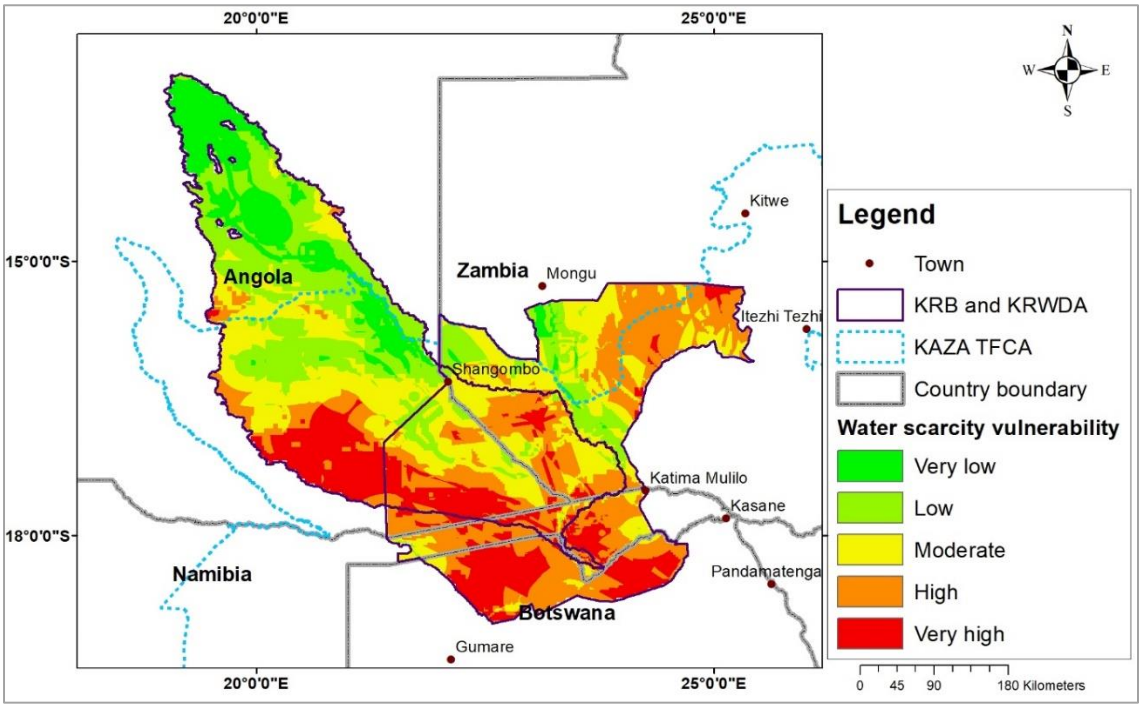

Figure 12 Final composite water scarcity vulnerability map for the KRB and KRWDA.

5.3 Sensitivity analysis of input data

The final mapping resulted in 11% of very low and low vulnerability areas, 24% moderate vulnerability areas and 65% of high and very high vulnerability areas (Table 4). Results of the sensitivity analysis with sequential 50% reduction of each parameter weight from the final weighting in Table 3, with equal distribution of the other 50% weight to the other parameters resulted in high to very high vulnerability areas ranging from 46% to 68% of study area, with areas changing by +3 to -19% compared to the baseline (final mapping). Areas with moderate vulnerability changed by +12% to +2%, while areas with very low to low vulnerability changed by +16% to -4% (Table 4). Human water scarcity vulnerability is most sensitive (highest % difference from baseline) to rainfall, population density, poverty level, wetland location, and distance to roads, boreholes, and fire outbreaks (Table 5).

Table 4 Summary of area under different water scarcity vulnerability classes in the KRB and KRWDA.

Water scarcity vulnerability	Area (km^2)	Area (%)
Very low	900	0.5
Low	18,611	10.0
Moderate	45,702	24.4
High	57,805	30.9
Very high	63,911	34.2
Total	186,930	100.0

5.4 Comparison of water scarcity vulnerability map with Surface Water Risk Map for SADC

The final water scarcity vulnerability map (resolution of 30 m) for the KRB and KRWDA developed by raster calculation of 10 reclassified and weighted layers (AHP) in map algebra is shown in Figure 12 and the area under each class is shown in Table 4. The water scarcity vulnerability map from this study (Figure 12) had some overall similarities to a coarser spatial resolution SADC surface water risk map (Figure 13) (SADC, 2021), as both maps show vulnerability to water scarcity in the southern part (in Botswana and Namibia) and less vulnerability due to high rainfall in the upper part of the study area in Angola. More importantly, the nuances that make water scarcity vulnerability map provide an added value is showing an integrated human vulnerability, influenced by a host of biotic and abiotic, including human and wildlife factors. The SADC surface water risk map is a product of SADC-GMI's Assessment of Groundwater Resources Development Priority Intervention Areas in the Southern African Development Community Region (SADC GMI-GDRI Project) and illustrates surface water risk for the SADC mainland. The map was produced using global hydrological model data from WaterGAP v2.2 and WorldClim v2.1, which were successfully validated against point discharge, runoff data from GRDA, and rainfall data from NOAA. The surface water risk map was also validated against drought areas identified by the SADC Climate Services Centre (2018/2019) and soil moisture anomalies in 2019 from the Famine Early Warning System Network (SADC, 2021).

Table 5 Results of the sensitivity analysis. For each parameter having its weight reduced by 50%, the resultant areas in various vulnerability classes are compared with the final (baseline) map**.**

No	Parameter	Baseline weight reduced by half compared to final map (%)	Area under very low vulnerability (km^2)	Area under low vulnerability (km^2)	Area under moderate vulnerability (km^2)	Area under high vulnerability (km^2)	Area under very high vulnerability (km^2)	Total area (km^2)	Relative area under very low/low vulnerability (%)	Relative area under moderate vulnerability (%)	Relative area under high/very high vulnerability (%)
1	**Rainfall**	13.5	1,183	31,915	55,270	70,444	28,118	186,930	18 (+7)	30 (+6)	53 (-12)
2	**Population density**	1.8	2,384	27,508	58,906	73,049	25,083	186,930	16 (+5)	32 (+8)	52 (-13)
3	**Poverty level**	2.5	7,495	42,489	51,217	58,036	27,694	186,930	27 (+16)	27 (+3)	46 (-19)
4	**Wetlands**	5.5	2,085	18,986	66,638	74,603	24,618	186,930	11 (0)	36 (+12)	53 (-12)
5	**Protected areas**	2.5	533	31,572	52,746	69,895	27,434	182,180	18 (+7)	29 (+5)	53 (-12)
6	**Rivers**	8.5	595	11,612	47,816	66,782	59,934	186,740	7 (-4)	26 (+2)	68 (+3)
7	**Roads**	4.0	2,881	26,242	60,114	66,281	31,412	186,930	16 (+5)	32 (+8)	52 (-13)
8	**Wildlife corridors**	6.3	1,092	12,651	49,576	82,459	41,153	186,930	7 (-4)	27 (+3)	66 (+1)
9	**Boreholes**	1.9	1,618	30,810	58,364	61,520	34,619	186,930	17 (+6)	31 (+7)	51 (-14)
10	**Fire outbreaks**	3.5	3,317	28,975	57,530	77,602	19,507	186,930	17 (+6)	31(+7)	52 (-13)
		Result from final (baseline) map							11	24	65

Note: ( ) in last three columns gives the percentage change in vulnerable areas as a result of halving the parameter weight for a particular parameter from the weight of the final (baseline) map (baseline – Table 3 and Table). For instance, for 'Rivers', this difference is -4% (7-11) for the very low/low vulnerability class, 2% (26-24) for the moderate vulnerability class, and 3% (68-65) for the high/very high vulnerability class.

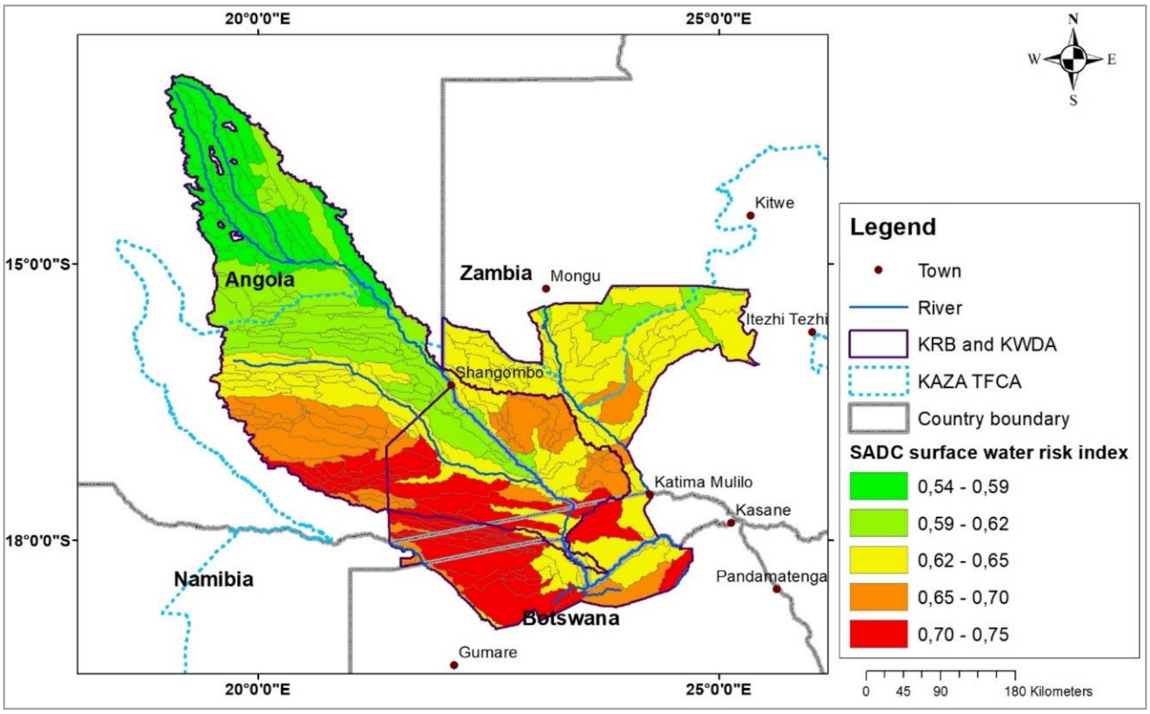

Figure 13 SADC surface water risk index map for the KRB and KRWDA (after SADC (2021)).

6 KEY MESSAGES

The results revealed that more than half (65.1%) of the KRB and KRWDA was classified as having high to very high water scarcity vulnerability, while 10.5% was classified as low to very low water scarcity vulnerability. Only 24.4% of the KRB and KRWDA was classified as moderately vulnerable to water scarcity.

Most significant parameters in identifying human vulnerability are rainfall, rivers, wetlands and wildlife corridors, while the most sensitive factors include rainfall, population density, poverty level, wetland location, and distance to roads, boreholes, and fire outbreaks.

Water scarcity vulnerability is dynamic because physical and economic conditions are in constant flux, which requires constant adaptation. This requires adaptation of several solutions (for present and future challenges) to reduce human water scarcity vulnerability at local scales of each country in the KRB and KRWDA.

The main limitation to the vulnerability mapping was the lack of information on borehole location throughout the area, inter-basin or catchment water transfers, other water supply infrastructure, water quality, and environmental water requirements. Data on water infrastructure such as boreholes was lacking in parts of the study area in Angola, Botswana, Namibia and Zambia. Water quality data from the different types of water infrastructure are needed in the future considering threat of salinity and pollution in the study area. Data on frequency of fire outbreak would also improve the analysis rather than using one fire event at the sites. Rainfall can be collected at a finer temporal and spatial resolution to capture variability in more detail.

This study contributes to identifying strategies, policies, and investments for solutions for managing vulnerable communities' risks, conflicts and disasters, thereby reducing both human suffering and economic loss.

Water scarcity poses a growing threat to maintaining the structure and functioning of river environments. This report presented some of the major interacting stressors that give rise to water scarcity vulnerability in arid and semiarid landscapes, especially the effects of habitat loss (e.g., through bush fires), land use change, and human-wildlife conflicts.

Water scarcity can exacerbate the frequency and severity of low flows, amplifying a range of potentially interacting stressors, including riverine or aquatic habitat loss, water quality declines, and increased human vulnerability that is influenced by natural as well as anthropogenic factors.

Water availability and adequate infrastructure constructed by institutions to ensure a regular supply (e.g., boreholes), especially under climate change, are key for supporting water supply and sanitation, livelihoods (through agriculture), wildlife and tourism. With climate change, appropriate infrastructure becomes important.

Combined establishment of climate-resilient groundwater infrastructure, climate and water-smart livelihood strategies (e.g., conservation agriculture), and local value chains for agri-products and other demanded by the tourism sector should reduce water scarcity vulnerability. Diversifying livelihood strategies to less water-intensive and climate-resilient ones, to minimize HWC and reduce water and environmental footprints are key.

Human vulnerability is reduced by diverse and less water-intensive livelihoods strategies that include (KAZA MIDP, 2014) conservation agriculture, introduction of new crop varieties, including chillies, cassava, maize, sorghum, millet, cowpeas, soya beans, groundnuts and new rice for Africa, market linkages, to boost community income, and small-scale producers supplying the tourism industry, especially lodges. Community Based Natural Resource Management (CBNRM), private sector support to value addition for non- timber forest products, fish, livestock, game, timber and agricultural products, trade across the borders supported by policies that promote open borders for trade of agreed products, and development of cultural tourism such as festivals and music, also play a key role in reduction of vulnerability.

The methodology applied in this report may serve as an example of how to assess human vulnerability to water scarcity, using mainly free and officially published information.

6.1 Next steps of the project

The next step of this exercise is validation of the water scarcity vulnerability map with stakeholders of the KRB and KRWDA. This is planned for January 2022 during the TDA consultation workshop with member states and the KAZA TFCA. With areas most vulnerable to human water scarcity identified in this report "**Water scarcity vulnerability map of the Kwando River Basin and Kwando River Wildlife Dispersal Area**", the next step in the project is the mapping for potential groundwater development. This study will look at prospects for addressing water scarcity vulnerability through sustainable groundwater development. The results from the potential mapping study will be combined with the water scarcity vulnerability mapping to generate a hotspot map for most feasible and impactful areas to develop groundwater. This map and information will be useful for guiding the effective identification of appropriate locations for groundwater extraction or exploitation to meet water needs of the most vulnerable communities in the KRB and KRWDA in order to increase resilience, water security and livelihoods. The approach developed in this study would be of benefit to the decision-makers, stakeholders, and the community at large in the study area to build resilience in face of climate change challenges.

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