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GEOGRAPHICAL INFORMATION SYSTEMS BASED DROUGHT VULNERABILITY ASSESSMENT OF THE NORTHWESTERN PHALOMBE PLAIN OF SOUTHERN MALAWI

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ABSTRACT

In Malawi, particularly the southern region, recurrent droughts have undermined food security and socioeconomic development. This study assessed drought vulnerability in Phalombe District using a GIS based approach integrating climatic, environmental, and hydrological factors. Remote sensing, spatial interpolation, and drought indices (SPI, SPEI, and SPDI) were used to analyse drought trends from 1980–2025. Results show that drought vulnerability is driven by climatic stress, land degradation, and hydrological constraints, with northwestern Phalombe identified as a drought hotspot due to higher temperatures and evapotranspiration linked to the rain-shadow effect of the Mulanje Massif. Hydrological analysis revealed sediment transport ranging from 0.01–1.5 STI across most areas and 1.5–3.5 STI in riverine systems. Recurrent droughts occurred during 2002–2004, 2007–2008, 2012–2016, and 2018–2023, increasing in severity alongside El Niño events. Validation using borehole yields showed strong agreement with SPDI projections, where drought-prone northern areas recorded low yields (0.0–0.42 l/s) while wetter southern zones showed higher yields (0.80–2.40 l/s). The study concludes that drought vulnerability in Phalombe is increasing and spatially uneven, recommending strengthened GIS-based monitoring, improved water management, and climate-smart land practices to enhance resilience.

Keywords: Geographical Information System, Drought Indices, Hydrological Factors, Temporal analysis, Drought event, Phalombe District

1 INTRODUCTION

Sub-Saharan Africa is considered one of the region's most vulnerable to drought due to its high dependence on rain-fed agriculture, limited adaptive capacity, and recurrent exposure to climate extremes (Kalisa et al., 2019). Malawi has experienced repeated drought events over the past three decades, significantly affecting food security, agricultural productivity, and economic stability (Mulungu et al., 2022). Phalombe District, located in southern Malawi, has been identified as one of the country's most drought-prone areas due to its

climatic variability and reliance on subsistence agriculture (Phiri et al., 2021). Since subsistence farming forms the backbone of livelihoods in the district, recurrent droughts have reduced agricultural productivity and intensified household food insecurity. Furthermore, Land Use and Land Cover (LULC) changes in Phalombe, characterized by cropland expansion, fragmented forest patches, and increasing bare land, reflect long-term environmental degradation associated with deforestation, agricultural expansion, and soil erosion.

Although previous drought vulnerability studies in Malawi and Sub-Saharan Africa have employed climatic indicators, remote sensing, or GIS-based approaches, many have focused on national or regional scales, emphasized isolated indicators, or inadequately integrated hydrological and groundwater dynamics into localized assessments (Mekonnen et al., 2020). Consequently, there remains limited district-level evidence that simultaneously integrates climate variability, land use change, hydrological dynamics, drought indices, and groundwater datasets to comprehensively assess drought vulnerability in Phalombe District. To address these limitations, this study applies Geographic Information Systems (GIS) and remote sensing as analytical tools within an integrated drought vulnerability framework. GIS enables spatial integration and analysis of diverse datasets, including land use, temperature, evapotranspiration, hydrological variables, and groundwater conditions, thereby facilitating a spatially explicit and evidence-based assessment of drought vulnerability at the local scale (Kabo-Bah et al., 2021).

Variations in temperature and evapotranspiration patterns also increase vulnerability in Phalombe. The northwestern zone of the district presents hotter and drier conditions because of rain shadow effect from the Mulanje Massif. Rising evapotranspiration rates increase agricultural water demand and soil moisture depletion (Kogo et al., 2021). While national studies acknowledge the role of rising temperatures in shaping drought risk, they do not capture such district specific microclimatic variations. Consequently, localized analyses are essential to identify drought hotspots and guide targeted interventions.

Soil erosion and siltation also contribute to drought vulnerability in Phalombe as riverine systems within the district show traits of localized siltation, which negatively affect water storage capacity, alters river flow, and worsens water quality (Gupta et al., 2019). Such hydrological degradation, though widely recognized at the national level, remains poorly documented in district-scale drought studies. The integration of hydrological stress factors into vulnerability assessments is therefore critical to understanding the full scope of drought risk in Phalombe.

To address the limitations of localized drought assessment, this study applied Geographic Information Systems (GIS) and remote sensing as analytical tools within an integrated drought vulnerability framework. GIS provided an effective platform for the spatial integration and analysis of diverse datasets, including land use, temperature, evapotranspiration, and hydrological variables, to generate spatially explicit drought vulnerability maps (Kabo-Bah et al., 2021). Spatial interpolation of temperature and evapotranspiration variables was performed using the Inverse Distance Weighting (IDW) method to estimate values in areas with limited meteorological observations. The interpolation process applied a power coefficient of 2 to assign

greater influence to nearby stations, while the search radius was determined based on the spatial distribution and density of available climate stations within and around the study area. Interpolation accuracy was assessed through cross-validation procedures using statistical error metrics to evaluate the reliability of predicted values.

Furthermore, drought variability was analysed using the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Precipitation Deficit Index (SPDI) to characterize temporal drought dynamics between 1980 and 2025. The indices were computed in R Studio using the packages *SPEI*, *SCI*, and supporting climatological libraries for time-series processing. SPI was calculated based on monthly precipitation data by fitting a Gamma probability distribution, followed by transformation into a standardized normal distribution, as implemented in the *SPEI* package, following the methodology proposed by McKellar (2022). SPEI was derived using the climatic water balance (precipitation minus potential evapotranspiration, $P - PET$), where PET was estimated using the Hargreaves-Samani method, and standardized using a log-logistic distribution to capture the influence of temperature-driven atmospheric water demand (Vicente-Serrano et al., 2010).

SPDI was computed to quantify cumulative precipitation deficits and persistent drought severity by analysing deviations from long-term precipitation normal and moisture deficits. Drought indices were calculated at 3-, 6-, and 12-month temporal scales to represent short-, medium-, and long-term drought conditions. A 1980–2025 climatic baseline period was used for index standardization and calibration (Ukkola et al., 2026. Future changes in seasonal drought in Australia. *Hydrology and Earth System Sciences*, 30(6), 1463-1485.

Statistical assumptions included stationarity of long-term climate records and adequacy of fitted distributions to represent precipitation variability. To enhance contextual reliability, consistency checks were conducted against historical climatic trends and groundwater indicators, including borehole yield data, within the local environmental setting of Phalombe District.

2 MATERIALS AND METHODS

2.1 Description of the study area

Phalombe district lies in the southern Malawi, bordered by Mulanje Massif to the southeast and Lake Chilwa to the northeast, as illustrated in Figure 1. The district's terrain is characterized by extensive cropland, fragmented forest patches and widespread bare land, reflecting decades of deforestation and soil degradation. The Mulanje Massif creates a shadow effect, resulting in hotter and drier conditions in the northeast zones. Lake Chilwa, a shallow and highly climate sensitive water body, experiences significant fluctuations in water levels during drought episodes, further accentuating hydrological vulnerability.

Figure 1

2.2 Scope of study

The study adopted a multi-method GIS-based approach to assess drought vulnerability by integrating climatic, environmental, and hydrological datasets to develop a localized, evidence-based understanding of drought risk within the study area (Figure 2). Climatic variables, including rainfall, temperature, and evapotranspiration, were analysed alongside environmental factors such as land use and land cover, vegetation condition, soil characteristics, and topography to evaluate the susceptibility of ecosystems and communities to drought impacts. Hydrological datasets, including surface water availability, drainage networks, and groundwater conditions, were incorporated to assess water resource vulnerability during prolonged dry periods. To capture both the spatial and temporal variability of drought, remote sensing techniques were employed to monitor vegetation health, land surface conditions, and moisture anomalies, while spatial interpolation methods were used to improve the representation of climatic patterns in areas with limited observational data (Ukkola et al.,2026). In addition, drought index analysis was applied to quantify the severity, frequency, and duration of drought events, enabling the identification of vulnerable areas and supporting evidence-based decision-making for drought risk management and adaptation planning.

Figure 2

The methodology adopted in this study followed an integrated Geographic Information Systems (GIS) and remote sensing approach to assess drought vulnerability in Phalombe District through three interconnected objectives. Under Objective 1, environmental, climatic, and hydrological factors influencing drought were analysed to establish baseline drought vulnerability conditions. Land Use and Land Cover (LULC) data were generated through supervised classification of Landsat 8 imagery, enabling the identification of

cropland, forest cover, and bare land distribution across the district. Climatic variables, including temperature and evapotranspiration, were spatially interpolated using the Inverse Distance Weighting (IDW) technique to produce continuous climatic surfaces. Additionally, bathymetric remote sensing surveys were conducted to assess siltation patterns, which served as indicators of hydrological stress affecting water availability. These datasets were integrated to provide a localized understanding of drought vulnerability drivers.

The study assessed temporal drought variability using multiple drought indices to capture different dimensions of drought occurrence and severity. The Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Precipitation Drought Index (SPDI) were computed using R statistical scripts to analyse drought patterns from 1980 to 2025. SPI was used to evaluate precipitation deficits, while SPEI incorporated evapotranspiration to account for climatic water balance. SPDI further strengthened the assessment by integrating broader drought dynamics. The outputs of these indices were spatially interpolated using IDW to map drought conditions and trends, helping identify drought-prone areas and periods of increasing drought severity.

Thirdly, drought projections were developed to assess future vulnerability scenarios for 2030, 2050, and 2080 based on the SPI, SPEI, and SPDI outputs. IDW interpolation was applied to generate future drought risk maps, highlighting projected spatial variations in drought intensity across Phalombe District. To validate the reliability of these projections, a borehole yield map was incorporated as an independent groundwater indicator. Areas projected to experience severe drought, particularly northern and northeastern Phalombe, were compared with observed borehole yields and showed low groundwater productivity (0.0–0.42 l/s), whereas relatively wetter southern areas corresponded with higher yields (0.80–2.40 l/s). This validation process strengthened confidence in the projected drought vulnerability patterns and ensured the robustness of the GIS-based assessment framework.

2.3 Validation of the Results

The validation of the projected drought vulnerability results was conducted by comparing the Standardized Precipitation Drought Index (SPDI) projections with observed borehole yield conditions across Phalombe District. Borehole yield data were used as an indicator of groundwater availability and hydrological response to drought conditions, allowing assessment of whether areas projected to be vulnerable to drought corresponded with actual groundwater stress conditions observed in the field. The comparison was intended to determine the reliability of the SPDI projections in identifying areas experiencing varying levels of drought-induced water scarcity.

To evaluate model performance and agreement between projected and observed conditions, two statistical performance metrics were employed: the Index of Agreement (d) and the Kling–Gupta Efficiency (KGE).

These validation metrics were calculated using the online Index of Agreement and Kling Gupta Efficiency calculator developed by Agrime tsoft (Gupta et al., 2019). The observed borehole yield data and projected SPDI values were entered into the calculator to assess the degree of correspondence between predicted drought severity and actual groundwater availability patterns.

2.4 Index of Agreement

The Index of Agreement was used as a standardized metric for quantifying the degree of prediction error in models, offering hydrologists a valuable tool for assessing model performance. This index, denoted by 'd', ranges between 0 and 1, where a value of 1 signifies a perfect match between model predictions and yield data, while a value of 0 indicates no agreement. In essence, it provides a comprehensive assessment by accounting for various sources of error, thereby offering insights into the overall accuracy and reliability of the model.

$$d = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (P_i - \bar{O}) + (O_i - \bar{O})^2} \quad 0 \leq d \leq 1 \quad 1$$

Equation 1 shows index agreement where O_i is the observation value and P_i is the forecast value and $\bar{O}$ is the average observation values and n represents number of observations.

2.5 Kling-Gupta Efficiency

Kling et al. (2012) proposed a refined version of this index to address potential issues of cross-correlation between bias and variability ratios. This revision ensures a more robust and accurate assessment of model performance, thereby enhancing the utility of Kling Gupta's efficiency in hydrological modelling studies.

$$KGE = 1 - \sqrt{(CC - 1)^2 + \left(\frac{cd}{rd} - 1\right)^2 + \left(\frac{cm}{rm} - 1\right)^2} \quad 2$$

Equation 2 shows KGE Where CC is the Pearson coefficient value and rm is the average of observed values and cm is average of forecast values and rd is standard deviation of observation values and cd is standard deviation of forecast values.

2.6 Research design and methods

The study adopted a quantitative and analytical research design, with a strong focus on spatial and temporal analysis to assess drought vulnerability and environmental change. Several key methods were employed to achieve the study objectives. Supervised Land Use and Land Cover (LULC) classification was used to

assess landscape dynamics and detect changes in land cover over time. Inverse Distance Weighting (IDW) interpolation was applied to map the spatial distribution of temperature and evapotranspiration, thereby identifying patterns of climatic variability across the study area. Siltation mapping, based on sediment transport indicators, was conducted to evaluate hydrological stress and its implications for water systems. In addition, drought index analysis, including the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Precipitation Deficit Index (SPDI), was utilized to examine temporal drought variability from 1980 to 2025. Finally, groundwater validation was performed using borehole yield data to establish the relationship between drought projections and water resource availability, thereby enhancing the reliability of the study findings.

2.7 Inclusion and Exclusion criteria

2.7.1 Inclusion criteria

The study included datasets and variables that were relevant to assessing drought vulnerability within the local context of Phalombe District. Climatic data, including temperature, rainfall, and evapotranspiration records spanning from 1980 to 2025, were incorporated to examine long-term climatic variability and drought trends. Land Use and Land Cover (LULC) datasets derived from satellite imagery were included to assess landscape dynamics and environmental changes over time. Hydrological datasets, including siltation mapping and borehole yield data, were considered to evaluate water resource availability and hydrological stress associated with drought conditions. In addition, drought indices, such as the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Precipitation Deficit Index (SPDI), were included to quantify the severity, frequency, and temporal variability of drought events.

2.7.2 Exclusion criteria

The study excluded datasets and information that did not align with the objectives or spatial scope of the research. National-level datasets lacking district-specific resolution were omitted due to their inability to adequately represent localized drought conditions in Phalombe District. Hydrological data that had not been validated at the local scale were also excluded to ensure the reliability and accuracy of the analysis. Furthermore, studies, indicators, or drought indices lacking relevance to the climatic, environmental, and hydrological context of Phalombe District were not considered, as they could limit the applicability and validity of the study findings.

2.8 Data collection instruments and analytical techniques

The study utilized a combination of remote sensing tools, GIS software, climate databases, and field-based validation techniques to assess drought vulnerability and associated environmental dynamics. Satellite imagery from the Landsat 8 platform was used for supervised Land Use and Land Cover (LULC) classification to evaluate landscape changes over time. GIS software was employed to conduct spatial interpolation using the Inverse Distance Weighting (IDW) method and to support siltation mapping for assessing hydrological stress patterns. Climate datasets obtained from climate engine were utilized to generate drought indices, including the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Precipitation Deficit Index (SPDI), enabling the analysis of drought variability across time.

Bathymetric surveys and sediment transport indicators were incorporated to map hydrological stress and sedimentation trends within water systems. Furthermore, ground-truthing points were collected to assess the accuracy of land cover classification outputs, while borehole metrics, including yield and performance indicators, were used to validate groundwater availability and strengthen the reliability of drought-related projections. To evaluate the performance and agreement between drought index projections and borehole yield data, the Index of Agreement (IoA) and the Kling–Gupta Efficiency (KGE) were applied as statistical accuracy measures, enabling the assessment of the predictive reliability and consistency of drought indices in representing groundwater availability.

2.9 Ethics

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and approved by the Malawi University of Business and Applied Sciences Ethics Committee (Details in the Ethics Declaration section). The study did not involve animals, but all data collection and analyses were performed in accordance with relevant institutional and international guidelines and regulations. The study did not conduct any clinical and/or human experiments. Data collection involved minimal interaction with people in the study area. Both written and confirmatory verbal informed consent was obtained from all participants. Participants were informed about the study objectives prior to data collection and analysis.

3 RESULTS AND DISCUSSION

3.1 Supervised Classification Land Use Land Cover Map Analysis (2025)

Figure 3

The supervised classification of satellite images for Phalombe District presented in Figure 3, showed clear patterns of land use and land cover, with farming being the most common activity. Phalombe is dominated with cropland, with limited forest cover and increasing in bare land, revealing land degradation.

The supervised classification highlights a landscape heavily shaped by agriculture but increasingly vulnerable to environmental stressors such as deforestation, land degradation, and drought, all of which threaten the sustainability of land resources and local livelihoods in Phalombe District.

Table 1

The accuracy assessment results indicate that the supervised classification of Phalombe District achieved a high overall accuracy of 94.2%, demonstrating strong agreement between the classified data and the reference points.

The user's accuracy values were between 0.9 and 1.0, which means that most classes were correctly identified and there were very few commission errors. The same was true for the producer's accuracy, which was high across all classes. Water, buildings, and cropland were all perfectly classified, but bare land had the lowest producer's accuracy at because it was confused with forest (

Table 1). The Kappa coefficient 0.9 further confirms that the classification is reliable, showing that the results are very likely to be correct. These results indicate that the supervised classification successfully differentiated the principal land cover categories within the district, with only negligible misclassifications noted between bare land and forest.

3.2 Temperature using An Inverse Distance Weighting (IDW) interpolation

Figure 4:

The spatial distribution of heat reveals a critical pattern linked to drought vulnerability (Figure 4). The map clearly shows a gradient. The hottest temperatures (28.8°C to 29.9°C) are in the northwestern interior, while the coolest temperatures (24.6°C to 25.7°C) are in the southeast. This pattern is a classic sign of a rain shadow effect. A mountain range to the southeast makes moist air from the ocean rise, cool, and drop its rain on the windward slopes.

The air mass has become dry and warm by the time it reaches the northwestern lowlands. This is what causes the intense heat shown on the map. Because of the dominant weather patterns that keep it dry and

hot, this area is very likely to experience drought. This causes soil moisture to drop, evaporation rates to rise, and water stress to rise for both crops and natural plants. Because of this, the highest isotherms clearly mark the northwestern region that would be the centre of historical and recurring droughts.

3.3 Evapotranspiration using An Inverse Distance Weighting (IDW) interpolation

Figure 5

The map in Figure 5 illustrates the spatial distribution of evapotranspiration (ET_o) rates in a Phalombe district, measured in millimeters per day (mm/day). The ET_o values are categorised into five colour-coded ranges, from low (blue: 3.501–3.763 mm/day) to high (red: 4.141–4.75 mm/day). The highest evapotranspiration occurs in the western part of the region, indicated by red, suggesting higher water demand or more arid conditions.

In contrast, the eastern and southeastern parts experience lower evapotranspiration, shown in blue and green, likely reflecting cooler or more humid conditions. The map also marks several meteorological stations with blue water droplet symbols, which are used to monitor and model these spatial patterns. Overall, the data show a clear west to east gradient in ET_o, useful for agricultural planning and water resource management.

3.4 Bathymetric Survey Method Siltation Mapping

Figure 6

In Phalombe District, the Sediment Transport Index (STI) map highlights how siltation is distributed across the landscape (Figure 6). The results show that most of the area falls within the lowest sediment transport class (0.01–1.5), represented in dark purple, meaning that most of the district experiences minimal soil erosion and sediment movement. However, areas along the main river channels, shown in blue, display slightly higher sediment transport potential (1.5–3.5), though higher-risk zones (3.5–7.5) are very limited or absent in this analysis. This suggests that while the district has generally stable soils, riverine zones remain vulnerable to siltation, which could affect water quality and riverbank stability. For Phalombe, this implies that soil conservation practices should be prioritized along rivers and drainage networks to reduce sediment loads and maintain ecological balance.

3.5 Standardized Precipitation Index (SPI)

The Standardised Precipitation Index (SPI) results for Phalombe from 1980 to 2025 show how rainfall and drought conditions change over time in the district (Figure 7). The graph shows that there are wet and dry periods that switch back and forth, and that precipitation trends change a lot. In the early 1980s and 1990s, SPI values were mostly positive, which means that the years were generally wetter. However, there were a few extreme peaks that suggested heavy rainfall events. But starting in the early 2000s, negative SPI values happen more often and are worse, which shows that droughts are happening again and again. The years 2002–2004, 2007–2008, 2012–2016, and 2018–2023 stand out as years of drought because the SPI values stayed negative for long periods of time.

These drought episodes coincide with well-documented El Niño events that historically reduce rainfall in southern Malawi, intensifying water scarcity and agricultural stress in Phalombe. Conversely, positive SPI values in years such as 1989, 1997, 2005, and 2010 suggest short-lived wet conditions, often associated with La Niña or cyclonic activity, which can lead to localized flooding in the district. Overall, the SPI results reveal a trend of increasing drought frequency and severity in recent decades compared to earlier periods, signifying heightened vulnerability of Phalombe to climate variability. This poses a serious challenge to groundwater recharge, crop production, and food security, as the district heavily relies on rain-fed agriculture.

Figure 7

3.6 Standardized Precipitation Evapotranspiration Index (SPEI)

The Standardized Precipitation Evapotranspiration Index (SPEI) results for Phalombe from 1980 to 2025 (Figure 8) highlight the combined influence of rainfall variability and evapotranspiration on drought severity. Compared to SPI, which is based solely on precipitation, SPEI provides a more integrated perspective by including temperature-driven water demand (Stagge et al., 2017). The graph shows that negative SPEI values (drought periods) are more frequent and more intense in recent decades, especially from the early 2000s onwards. This reflects the compounded effect of declining rainfall and increasing evapotranspiration due to rising temperatures in southern Malawi.

Significant drought events are observed around 1992, 2002–2004, 2007–2008, 2012–2016, and 2018–2023, with prolonged negative values indicating severe and recurrent agricultural and hydrological droughts. These years correspond with El Niño events and periods of high temperature anomalies that reduce soil moisture and crop productivity. Positive SPEI values are also visible in years such as 1989, 1997, 2005, and 2010, showing relatively wet conditions; however, their duration is short compared to the persistence of drought periods.

The SPEI analysis reveals that Phalombe is becoming increasingly vulnerable to climate change-driven drought risk, as higher evapotranspiration rates intensify water stress even in years with near-normal rainfall. This indicates reduced groundwater recharge, declining streamflow, and increased threats to food security and livelihoods in the district.

Figure 8

3.7 Standardized Precipitation Drought Index (SPDI)

The Standardized Precipitation Drought Index (SPDI) results for Phalombe between 1980 and 2025 (Figure 9) provide another dimension in assessing drought dynamics, focusing on both precipitation variability and cumulative water balance over time. The graph shows that positive SPDI values dominate during the 1980s and early 1990s, indicating periods of above-normal rainfall that supported water availability and reduced drought risk. However, from the late 1990s onward, negative SPDI values become increasingly frequent and severe, particularly during 2001–2004, 2007–2008, 2012–2016, and 2018–2023. These negative anomalies signify prolonged and intense drought episodes, aligning closely with the major drought events recorded in southern Malawi during those years.

The SPDI analysis also reveals that while short wet periods do occur (e.g., around 1997, 2005, and 2010), they are relatively brief compared to the persistence of dry periods. This imbalance highlights an increasing tendency toward cumulative drought stress, meaning that even after rainfall events, recovery in groundwater, soil moisture, and river flow is limited. Such prolonged drought conditions are critical for Phalombe, where communities rely heavily on rain-fed agriculture and shallow groundwater sources.

SPDI results confirm a long-term shift towards more frequent and extended drought conditions, especially after the year 2000. This underscores the growing vulnerability of Phalombe to climate change impacts, such as rainfall variability, higher temperatures, and cumulative water deficits combine to threaten agricultural production, water resources, and livelihoods.

Figure 9

3.8 SPI Standardized Precipitation Index projections

Figure 10

The projections of the Standardized Precipitation Index (SPI) for Phalombe show significant spatial and temporal variations in drought conditions from 2030 to 2080 (Figure 10). In 2030, the district experiences mixed conditions, with the northern and eastern parts showing moderate to severe drought stress (SPI values between -2.9 and -1.3), while the southern and central areas display relatively wetter conditions (SPI values up to 0.7). By 2050, drought intensity appears less extreme, with most of Phalombe falling within near-normal ranges (-0.6 to 0.4), suggesting a temporary improvement in rainfall distribution, although pockets of dryness remain in the north.

However, by 2080, the projections indicate worsening drought conditions again, with much of the northern and eastern parts under severe drought stress (SPI values between -2.3 and -1.8), while the southern areas retain relatively wetter conditions (up to 1.7). These results suggest that while mid-century may see a short-lived improvement in water availability, long-term projections point toward intensified and spatially uneven drought risks in Phalombe, with significant implications for agriculture, water resources, and livelihoods

3.9 SPEI Standardized Precipitation Evapotranspiration Index Projections

Figure 11

The Standardized Precipitation Evapotranspiration Index (SPEI) projections for Phalombe illustrate changing drought and wetness conditions across the district for the years 2030, 2050, and 2080 (Figure 11). In 2030, the northern part of Phalombe is projected to experience moderate to severe drought stress (SPEI values between -1.5 and -0.5), while the central and southern regions show relatively wetter conditions (0.2 to 0.8), suggesting spatial variability in water availability. By 2050, drought intensity expands slightly across the north (with values reaching -1.6), but much of the central and southern parts retain near-normal to moderately wet conditions (0.3 to 0.8), indicating some resilience in rainfall and water balance in those areas.

Looking further ahead to 2080, the northern and northeastern areas are projected to face more intense and widespread drought stress (SPEI values between -1.9 and -0.7), while the southern and southeastern regions continue to show wetter conditions (0.2 to 0.4). These projections highlight a clear north-south divide in Phalombe's future drought risk, with northern areas becoming increasingly vulnerable to persistent dryness, while the southern regions maintain relatively favorable water balance that could support agriculture and livelihoods

3.10 PDSI Palmer Drought Severity Index Projections

Figure 12

The SPDI projections (Figure 12) for Phalombe District (2030, 2050, and 2080) show how drought severity and wetness conditions are expected to evolve under changing climate scenarios. By 2030, the district is projected to experience a mix of moderate wetness in the southern and central areas (SPDI values 0.3–0.7) while the northern and eastern zones face drier conditions (SPDI values down to –2.9), indicating localized drought risk. By 2050, the patterns shift, with larger portions of the district stabilizing around near-normal to slightly wet conditions (0–0.4), though pockets of dryness persist in the north.

By 2080, the projections suggest a return of more intense variability: significant drought-prone zones emerge again in the northern and northeastern parts (–2.3 to –1.8), while the southern and southeastern regions show relatively wetter conditions (0.2–1.7). Overall, the results indicate that Phalombe will face fluctuating drought and wetness extremes over time, with drought risks remaining most pronounced in the northern zones, underscoring the need for adaptive water management and drought resilience strategies in the district.

3.11 Drought Validation through Borehole Yield Metrics

Figure 13

These results agree with Abiodun (2019) where drought projections (SPDI) and borehole yield data (Figure 13) for the district can be linked as part of a validation process, since both indicators reflect water availability but from different perspectives, surface/atmospheric moisture stress versus groundwater potential. The SPDI maps show that northern and northeastern Phalombe are consistently prone to drought (negative SPDI values), which aligns with the borehole yield map where many areas in these zones record very low yields (0.0–0.42 l/s). Conversely, southern and southeastern parts of the district, which are projected to remain relatively wetter in the SPDI analysis, show clusters of higher borehole yields (0.80–2.40 l/s).

This correspondence between projected drought-prone zones and low-yield groundwater zones validates the reliability of the SPDI outputs, indicating that drought stress reduces groundwater recharge and availability. Therefore, combining drought indices with borehole yield patterns provides a more robust picture of water scarcity risks, confirming that groundwater stress will be most severe in areas with recurrent drought, and highlighting the importance of integrated drought and groundwater management in Phalombe

3.12 Validation of the drought projections towards borehole yield

The SPDI projections in each area were compared to the corresponding borehole yield conditions identified in the study. The results indicated a strong correlation between projected drought severity and observed borehole yields. Areas projected as highly vulnerable to drought by the SPDI projections generally exhibited lower borehole yields, and vice versa. This positive correlation ($R^2 = 0.89$) suggests that the SPDI projections effectively identified areas with a greater risk of groundwater stress within Phalombe District.

It was also observed that different environmental and land use conditions existing in the district could directly influence borehole yields, especially in areas dominated by intensive agricultural activities and high-water demand. Agricultural lands normally under continuous cultivation in some areas have higher groundwater abstraction contributing to lower borehole yields as compared to vegetated and less disturbed areas. The Index figure (Figure 14) show degree of agreement ($d = 0.836$) and Kling-Gupta Efficiency (KGE = 0.907, Figure 15) indicates higher performance metrics of the SPDI projections against the borehole yield conditions.

Figure 14

Figure 15

4 DISCUSSION

The results give evidence that drought vulnerability in Phalombe is induced by a combination of climatic, environmental and hydrological factors.

The study has shown that land degradation negatively affects ecological resilience, and the increase in temperature enhances evapotranspiration leading to intensified moisture deficits. This finding is consistent with Mulungu et al. (2022), who documented higher mean temperatures and drought frequency in southern Malawi compared to the central and northern regions

Siltation is also captured as a contributing factor towards hydrological degradation in Phalombe. These outcomes corroborate findings by Gondwe et al. (2019), who linked soil erosion and riverine siltation in southern Malawi to reduced water storage capacity and increased vulnerability to hydrological drought.

The temporal analysis of SPI, SPEI, and SPDI between 1980 and 2025 confirmed recurrent drought events in Phalombe, particularly during 2002–2004, 2012–2016, and 2018–2023. These coincide with well-documented El Niño years, which are known to suppress rainfall in southern Malawi (Kalisa et al., 2019). Comparable national-level studies by Nyirenda et al. (2020) and Mekonnen et al.

The Sediment Transport Index results showed generally stable soil across much of Phalombe, but higher siltation along river channels. Similarly, Phiri et al. (2021) identified deforestation-driven erosion as a persistent challenge in the Shire Highlands, which parallels the processes observed in Phalombe.

The projections of SPEI and SPDI suggest an emerging north–south divide in Phalombe, with northern areas facing intensified drought risk by 2080, while southern zones may retain relative resilience. This mirrors regional projections by Engelbrecht et al. (2019), who found that climate change will disproportionately increase drought risk in southern Africa, with uneven spatial impacts.

Importantly, this study validated the projections against borehole yield data, showing that drought-prone areas identified by SPDI correspond with low groundwater yields in northern Phalombe. This finding aligns with Nyirenda et al. (2022), who emphasized the importance of integrating groundwater dynamics into climate vulnerability assessments in Malawi.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study concludes that drought vulnerability in Phalombe District is not driven by a single factor but by the combined effects of land degradation, climatic stress, and hydrological constraints, which collectively intensify the susceptibility of communities and ecosystems to drought impacts. Through the integration of composite drought indices and GIS-based spatial analysis, the study identified distinct drought-prone hotspots, demonstrating that vulnerability is spatially uneven across the district. This finding highlights the critical need for location specific drought mitigation and adaptation strategies rather than uniform interventions. Furthermore, the study establishes that geospatial approaches provide an effective framework for drought risk assessment, early warning, and informed decision-making, thereby supporting more targeted resource allocation and enhancing resilience to future drought events in Phalombe District.

5.2 Recommendations

Several remedial actions to address hydrological drought vulnerability in Phalombe District. Priority should be given to strengthening water resources management through the implementation of soil and water conservation measures along riverine systems to reduce siltation, preserve water quality, and enhance water storage capacity. Such interventions can improve the reliability of surface water resources during prolonged dry periods.

Additionally, the study emphasizes the need for sustainable groundwater development and management by strengthening borehole management practices and establishing robust groundwater monitoring systems. These measures will support the efficient utilization of groundwater resources, improve water security for vulnerable communities, and enhance the district's resilience to recurring drought conditions.

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AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation was done by Mathews Mtegha, Harold Wilson Mapoma and Isaac Kamdonu Mwalwimba. Data collection and analysis were performed by Mathews Mtegha. The first draft of the manuscript was written by Mathews Mtegha and all authors commented on previous versions of the manuscript. All authors read and approved this manuscript.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request, subject to participant confidentiality protections.

ETHICAL CONSIDERATION

Ethics Declaration

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki. Ethical approval for the study protocol and data collection instruments was obtained from the Malawi University of Business and Applied Sciences (MUBAS) through the relevant academic committee, school board, and the MUBAS Research Ethics Committee (MUBASREC), which is responsible for reviewing,

578 advising on, and approving research conducted by MUBAS staff and students. In addition, permission to
579 conduct the study at the district level was granted by the District Commissioner for Phalombe district prior
580 to the commencement of data collection. All participants were informed about the study objectives and
581 consented to the data collection tools.

582 **Approval for animal experiments**

583 The study did not conduct any animal experiments.

584 **Approval for human experiments**

585 The study did not conduct any clinical and/ or human experiments. Interaction with human beings was
586 minimal because the study employed GIS and Remote sensing to collect and analyse data. This has very
587 minimal interaction with human beings in the study area.

588 **Consent to publish**

589 Not applicable. This manuscript does not contain any individual person's data, images or other identifiable
590 information; all findings are reported in aggregate or anonymised form, and no individual participant can be
591 identified from the material presented.

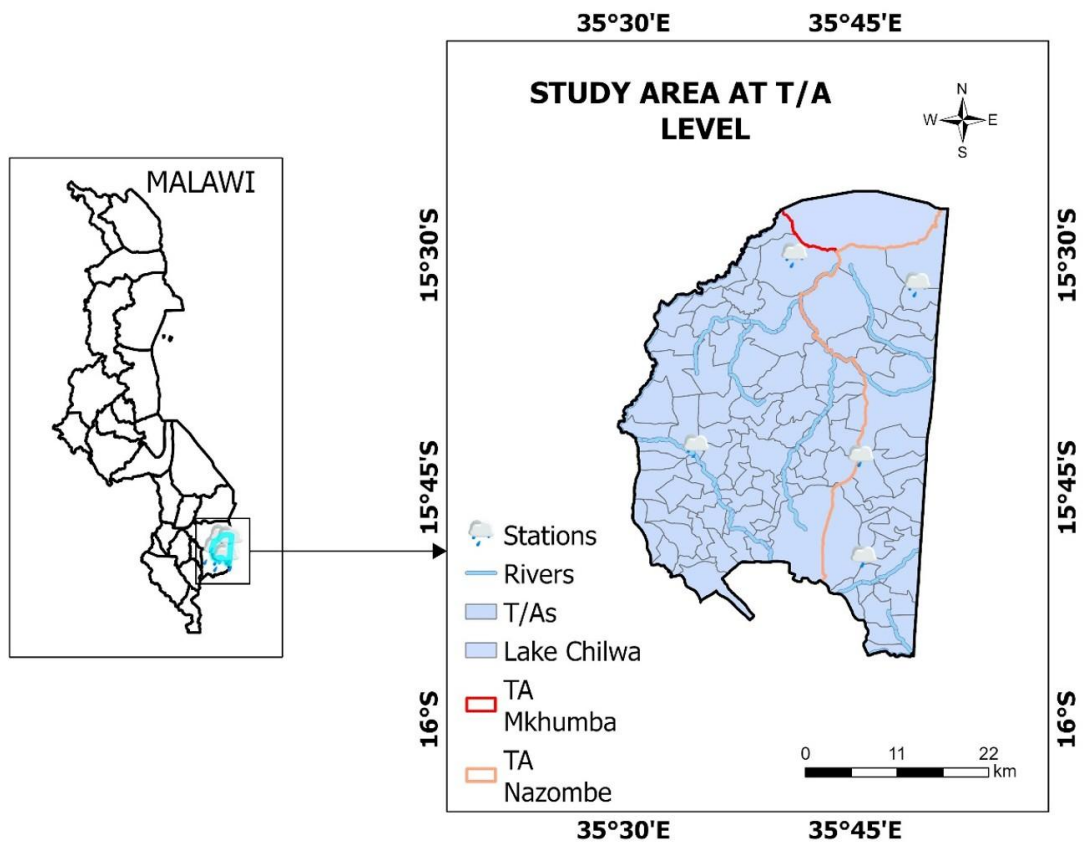
592 **COMPETING INTERESTS**

593 The authors have no relevant financial or non-financial interests to disclose.

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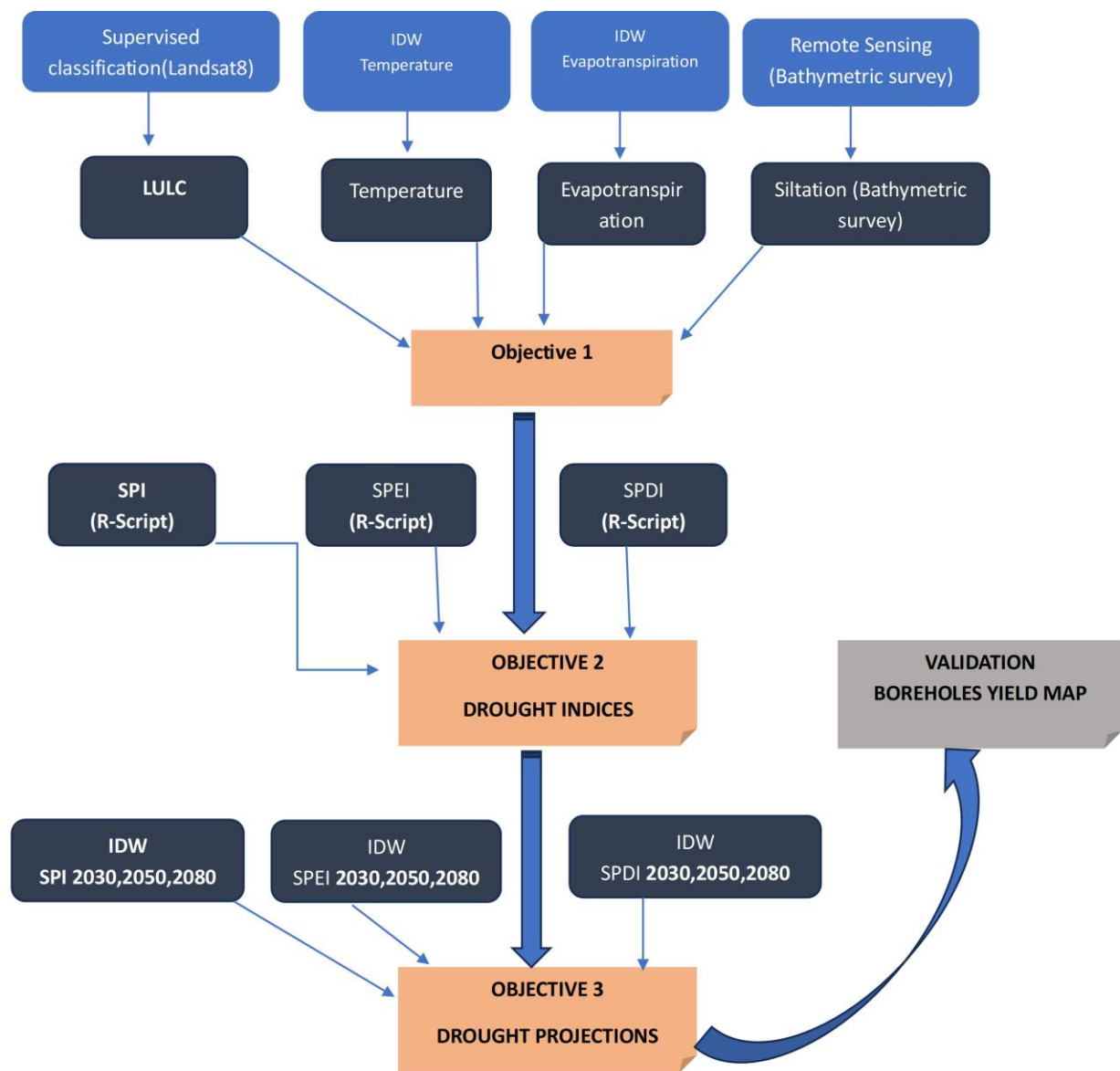
595 **FIGURE LEGENDS**

596 Figure 1: The Geographical location of Phalombe district in the Southern Region of Malawi



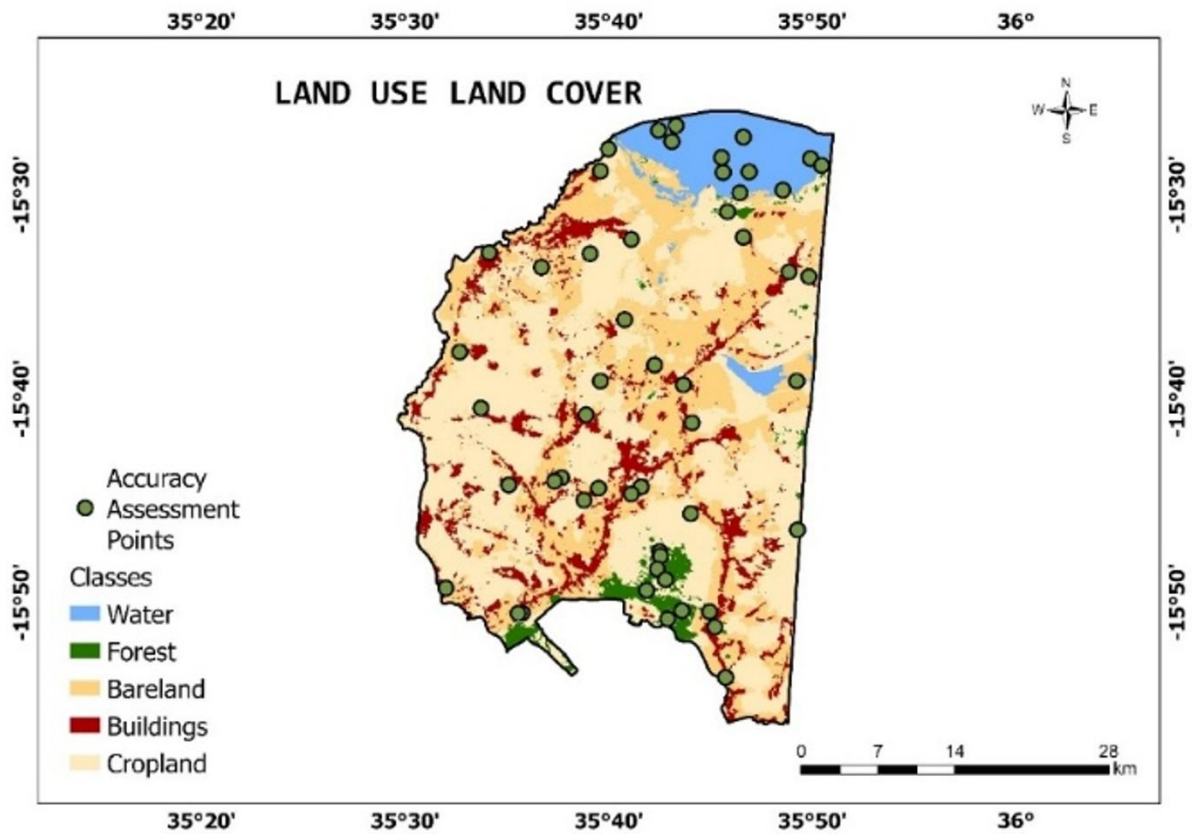
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598 Figure 2: Multi method research approach used in this research.



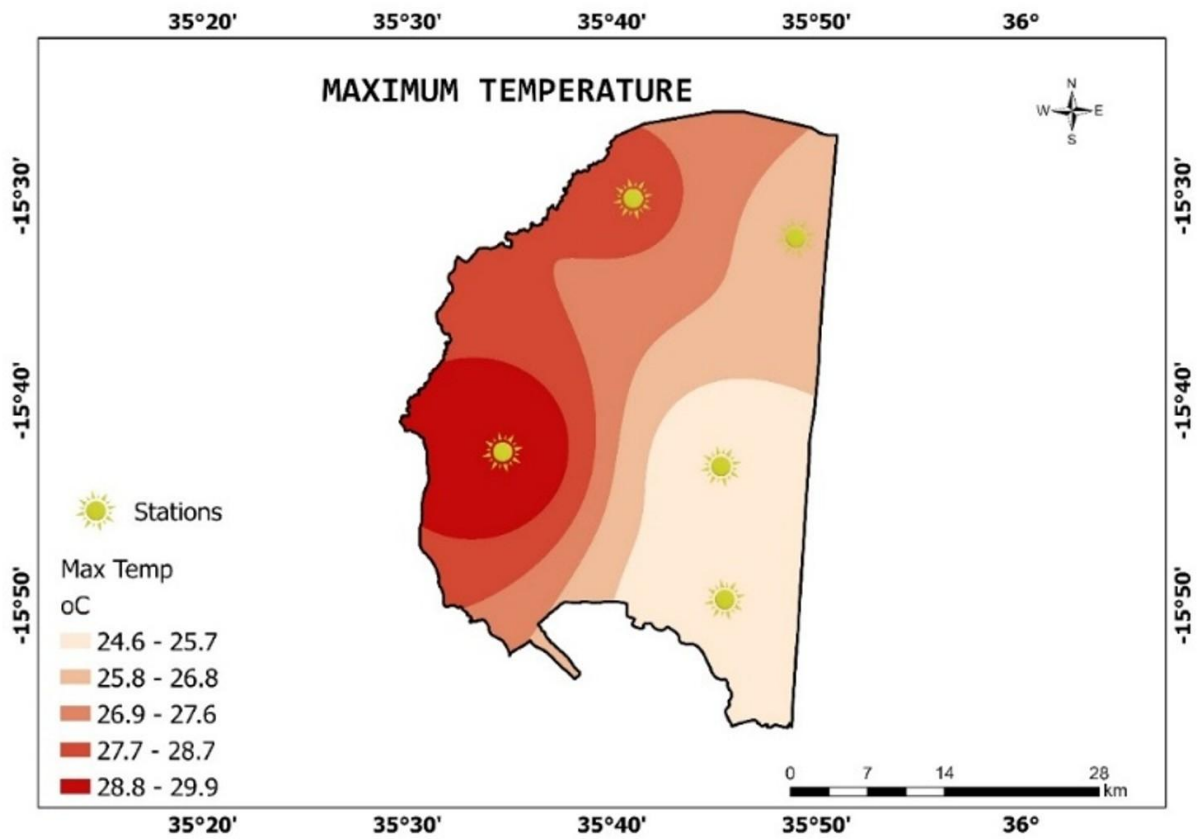
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600 Figure 3: Classification of the surface land cover in the study area



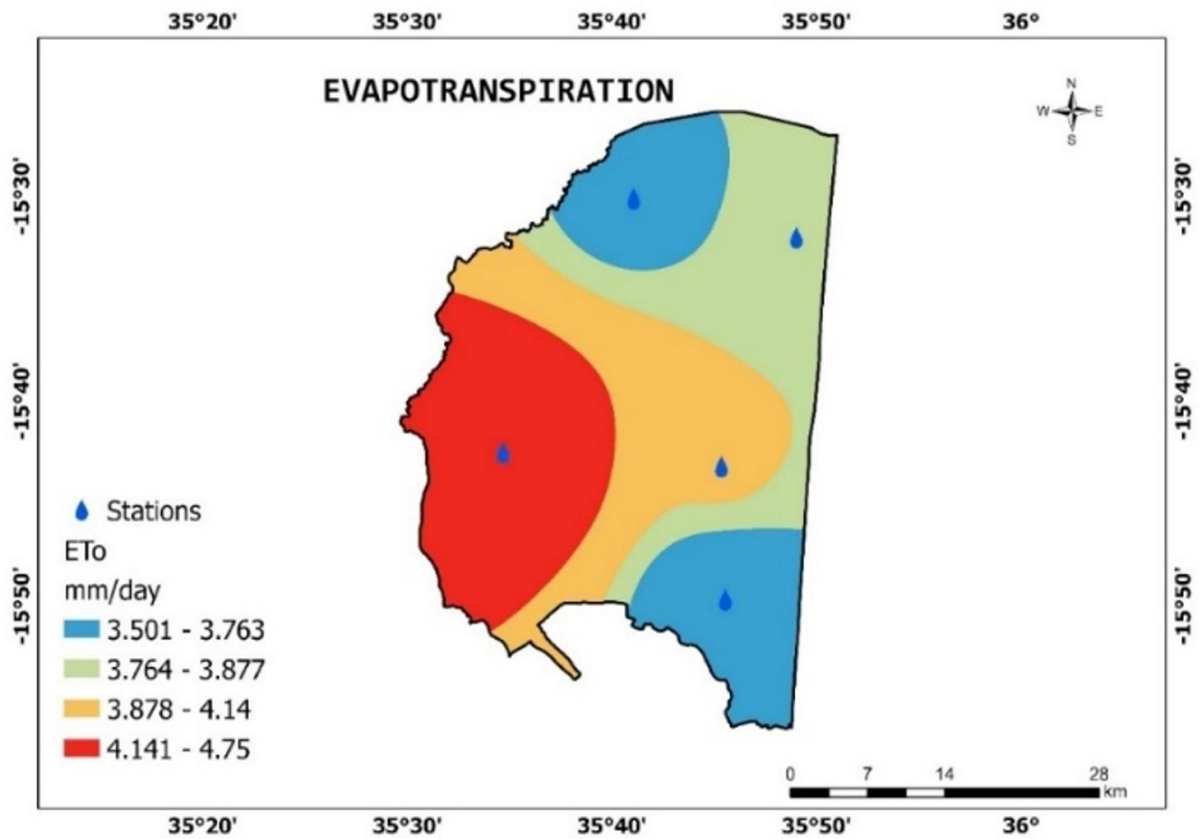
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602 Figure 4: Temperature using An Inverse Distance Weighting (IDW) interpolation



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604 Figure 5: Spatial distribution of Evapotranspiration in Phalombe district



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606 Figure 6: The Sediment Transport Index (STI) map highlighting how siltation is distributed across the
 607 landscape

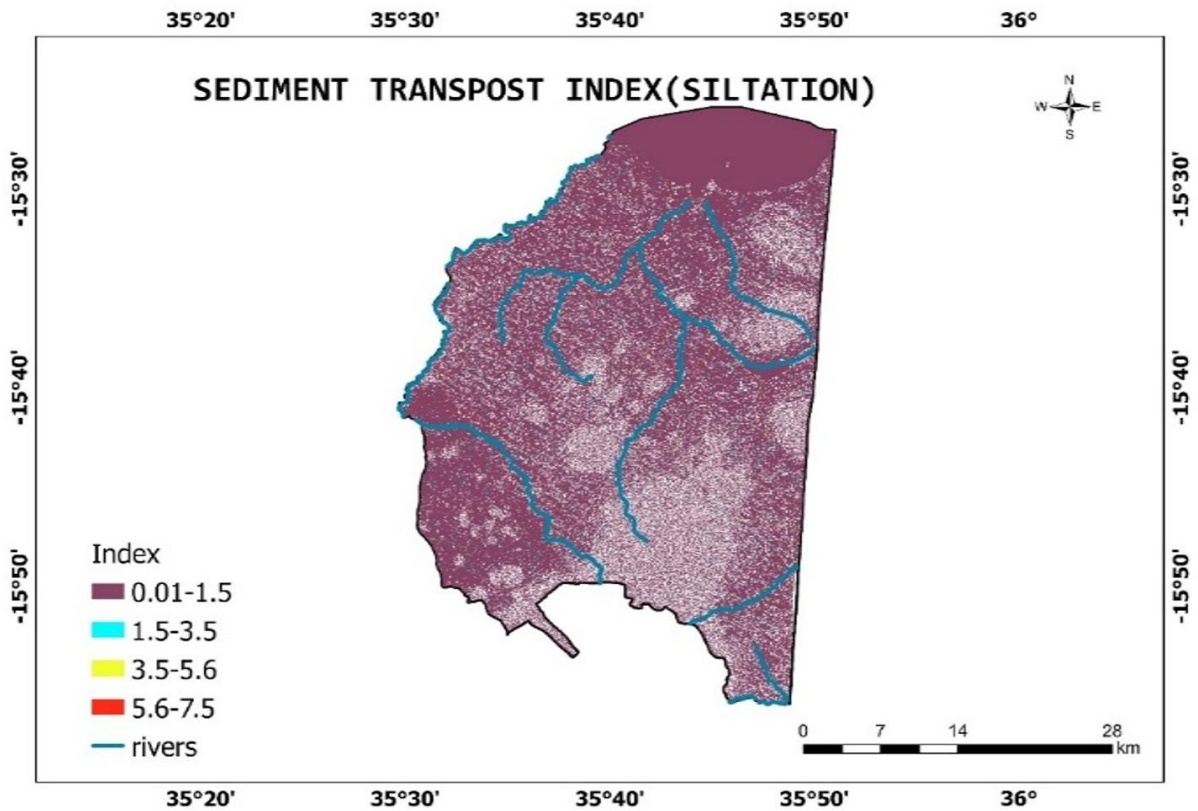


Figure 7: Standardized Precipitation Index (SPI) results for Phalombe from 1980 to 2025 showing how rainfall and drought conditions change over time

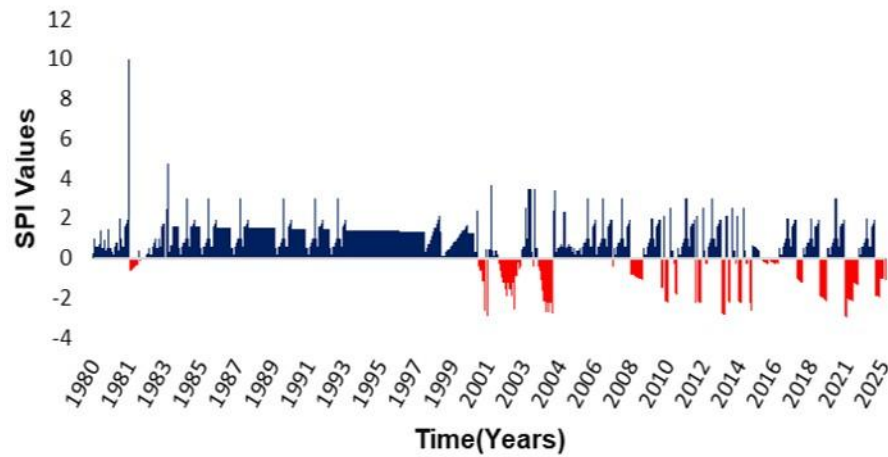
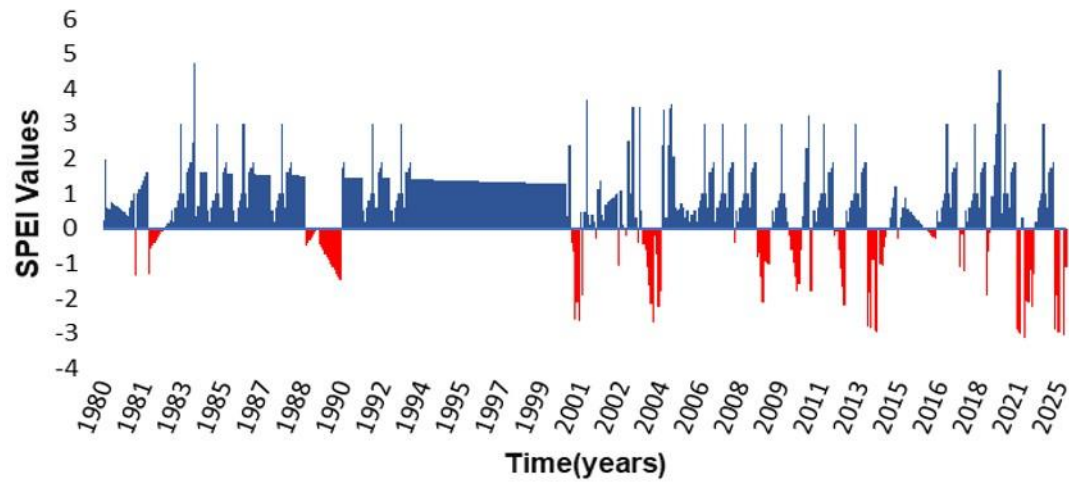
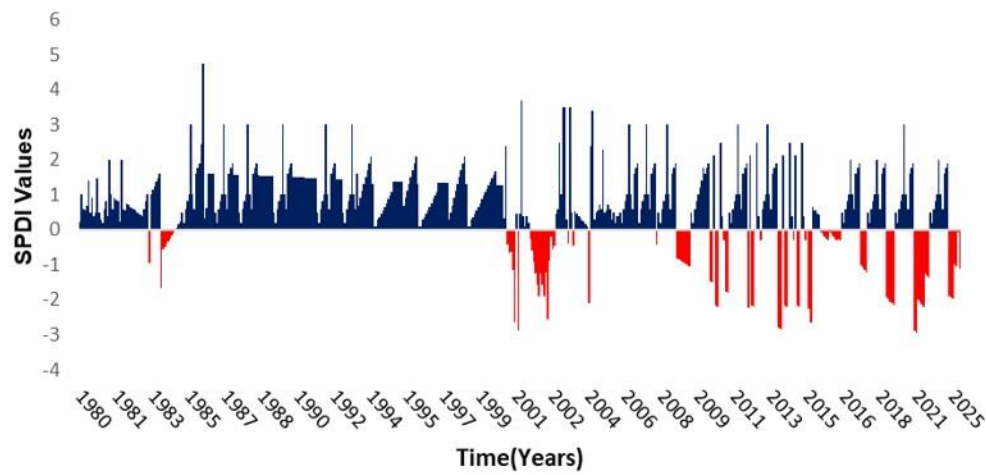


Figure 8: Standardized Precipitation Evapotranspiration Index (SPEI) results for Phalombe from 1980 to 2025



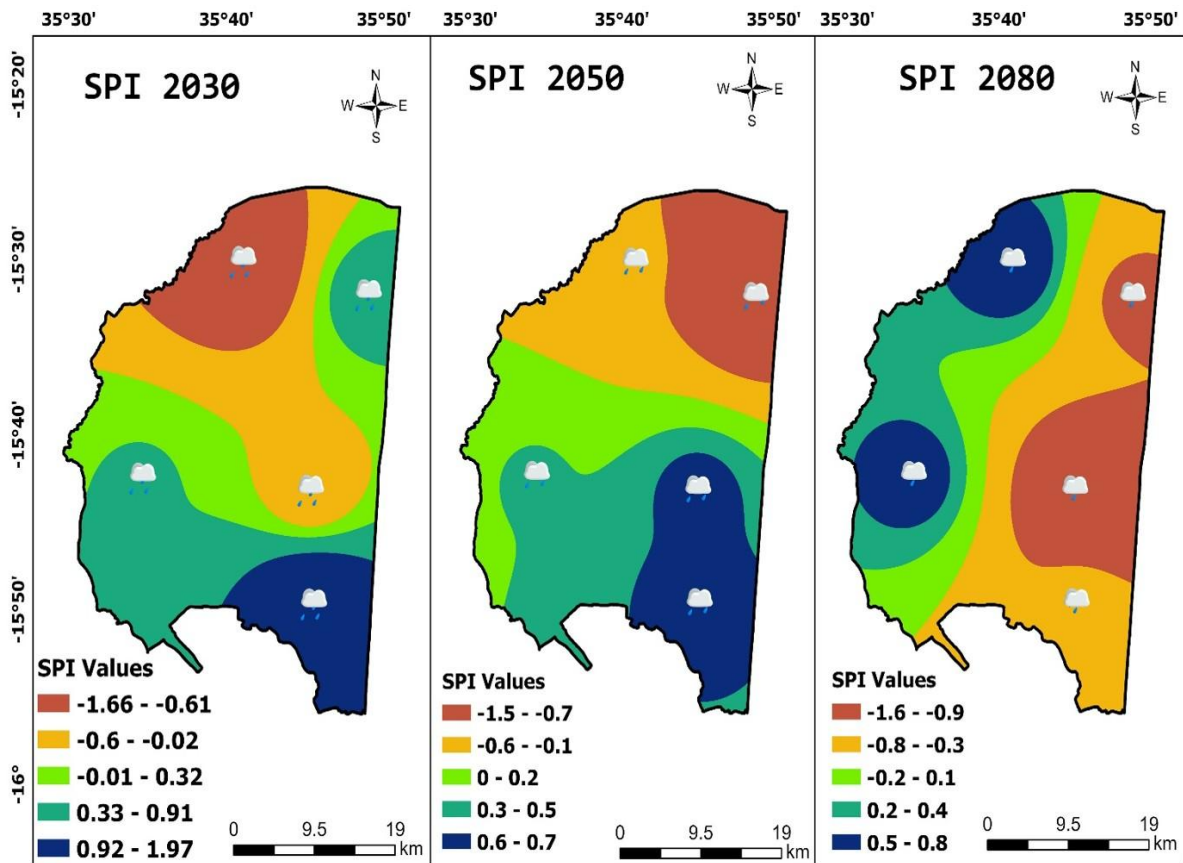
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615 Figure 9: Standardized Precipitation Drought Index (SPDI) results for Phalombe between 1980 and 2025



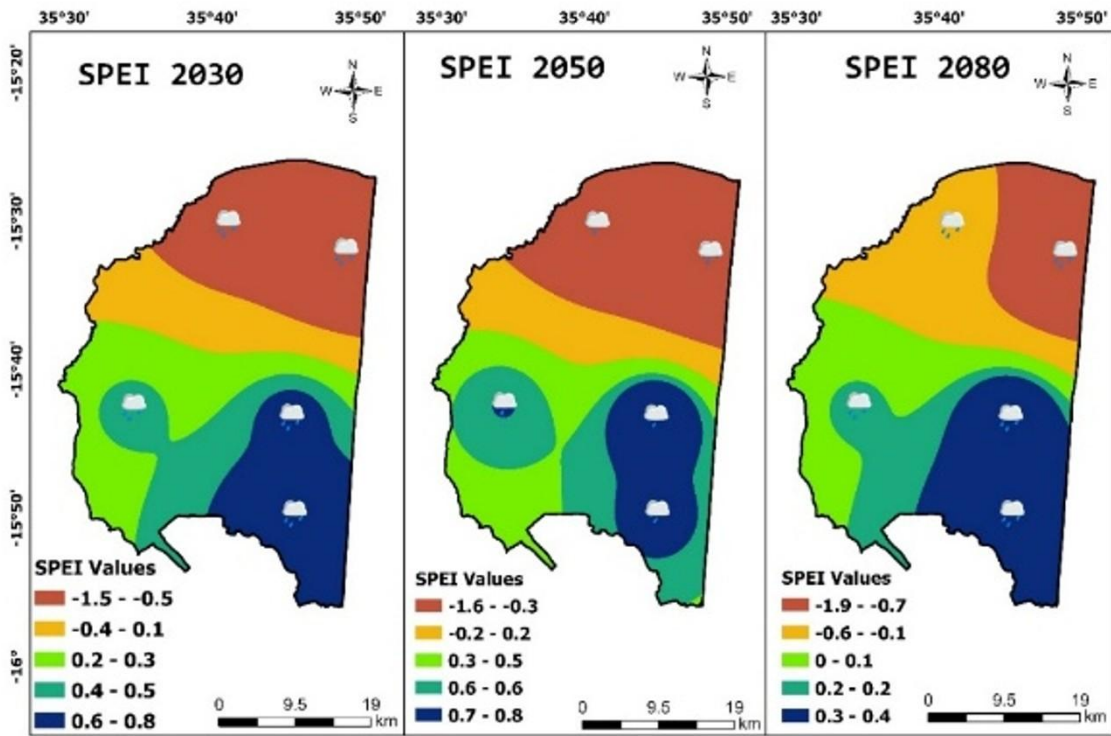
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617 Figure 10: The Standardized Precipitation Index (SPI) for Phalombe showing significant spatial and
 618 temporal variations in drought conditions from 2030 to 2080



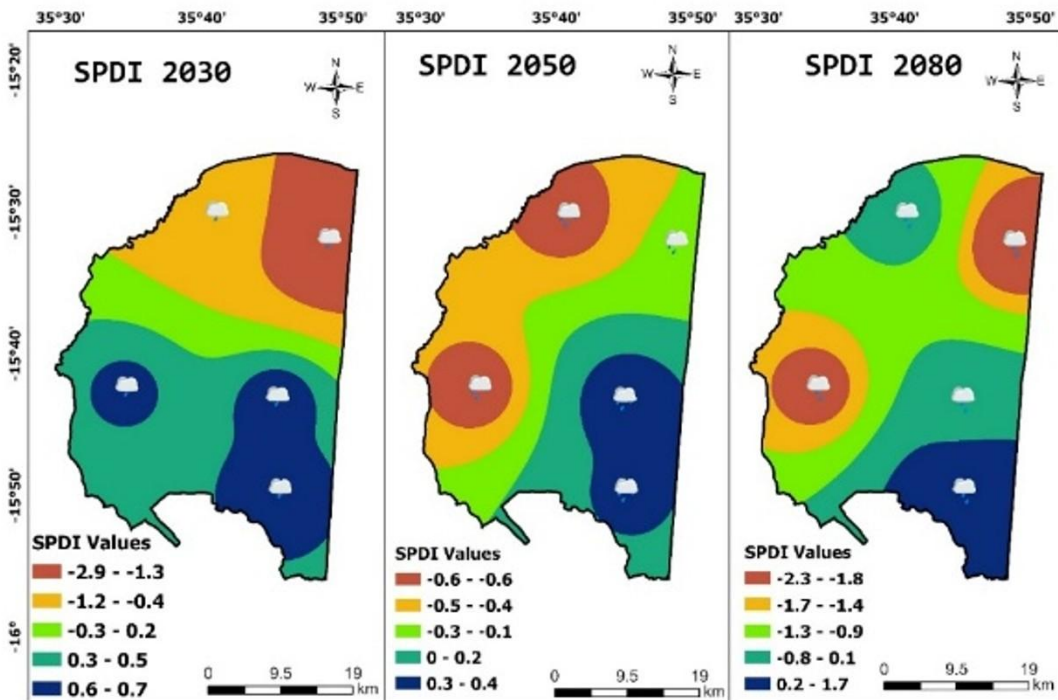
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620 Figure 11: The Standardized Precipitation Evapotranspiration Index (SPEI) projections for Phalombe
 621 illustrating changing drought and wetness conditions across the district for the years 2030, 2050



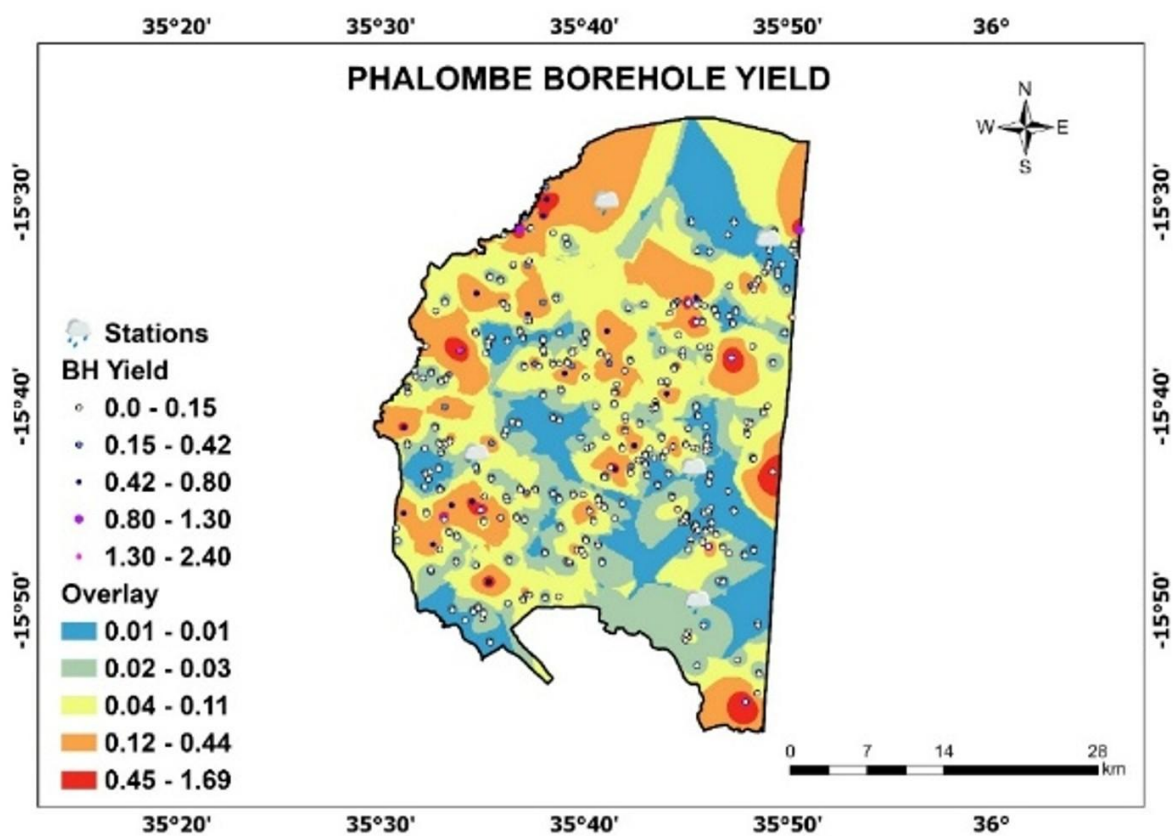
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623 Figure 12: The SPDI projections for Phalombe District (2030, 2050, and 2080) showing evolution of drought
 624 severity and wetness conditions.

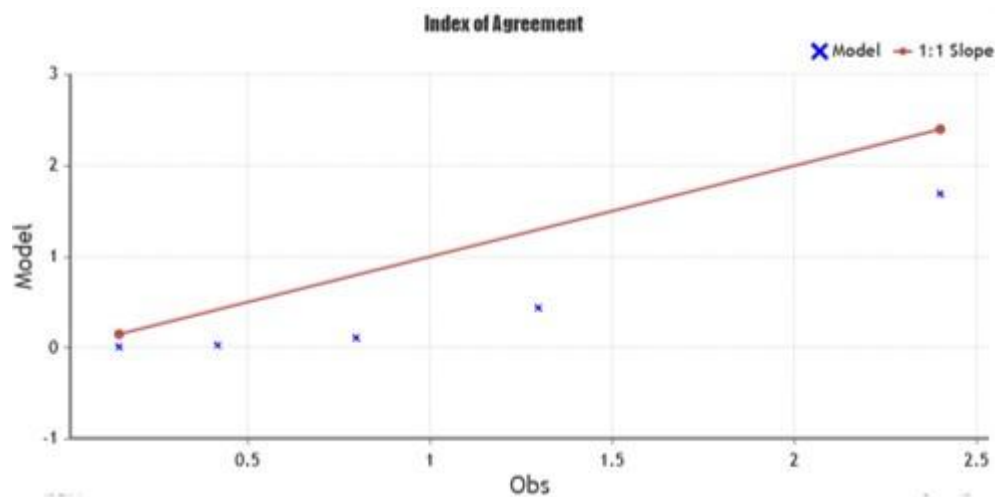


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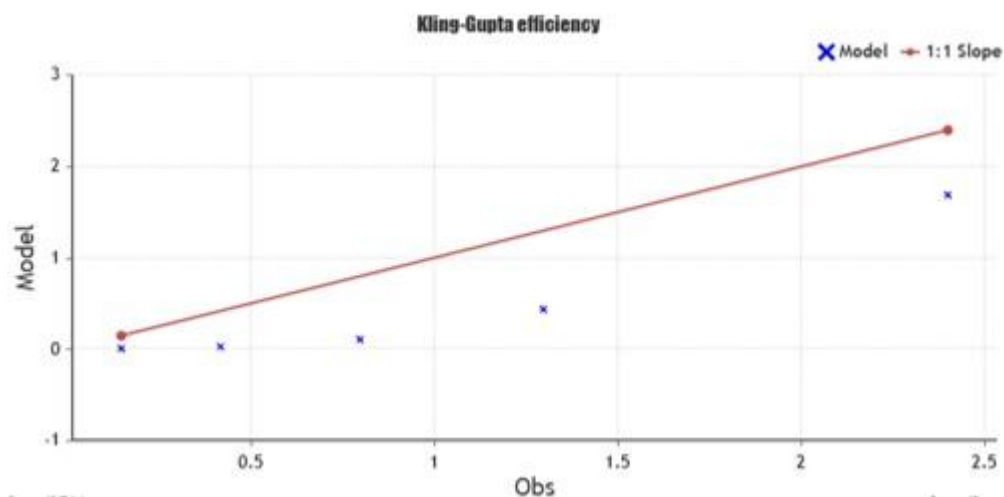
626 Figure 13: Phalombe borehole yields



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628 Figure 14: Index of Agreement between PDSI and Borehole yield



629
630 Figure 15: KGE between PDSI and Borehole yield



TABLES

Table 1: Matrix confusion for accuracy assessment of LULC

	C_1	C_2	C_3	C_4	C_5	Total	U_Accuracy	Kappa
C_1	9	0	1	0	0	10	0.9	0.0
C_2	0	9	1	0	0	10	0.9	0.0
C_3	0	1	9	0	0	10	0.9	0.0
C_4	0	0	0	10	0	10	1.0	0.0
C_5	0	0	0	0	12	12	1.0	0.0
Total	9	10	11	10	12	52	0.0	0.0
P_Accuracy	1	0.9	0.8	1	1	0	0.9	0.0
Kappa	0	0	0	0	0	0	0.0	0.9

Note: C_1=Water, C_2=Forest, C_3=Bare land, C_4=Buildings, C_5=Cropland