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Research Article

Hydro-Climatic Variability and Drought Patterns in the Thal Desert, Pakistan: An Integrated Drought Assessment

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Abstract: Drought is a major hydro-climatic hazard in arid and semi-arid regions. In the Thal Desert of Punjab, Pakistan, limited rainfall, high temperature, and dependence on groundwater can increase drought vulnerability. This study assessed drought patterns in the region by integrating rainfall, temperature, groundwater conditions, and the Standardized Precipitation Index (SPI-12) using Geographic Information System (GIS) techniques from 1995 to 2024. Rainfall and temperature data from six PMD stations were analyzed, while groundwater records from 79 monitoring stations were examined for pre- and post-monsoon periods from 2003 to 2019. Spatial patterns were assessed using inverse distance weighting (IDW), whereas long-term trends were evaluated using the Mann-Kendall test and Sen's slope estimator. A Composite Drought Index (CDI) was developed and standardized on a 1.0 - 1.5 scale and weighed using Analytical Hierarchy Process (AHP) values. Mean annual rainfall ranged from 465 to 517 mm and showed weak decreasing trends at all six stations, although none of the trends was statistically significant. Temperature trends varied across the study area, with both increasing and decreasing patterns observed. Mean groundwater depth ranged from 2.55 - 21.79 m during the pre-monsoon period and 3.05 - 21.59 m during the post-monsoon period, with no significant long-term trends at most monitoring stations. The CDI classified the study area into five drought hazard classes rather than independently validated risk categories. High and moderate hazard classes covered 34.6% and 26.6% of the study area, respectively. The findings highlight the spatial variability of drought hazard and the importance of integrating climatic and groundwater indicators for regional drought assessment.

Keywords: Thal Desert, Drought Assessment, SPI-12, Groundwater, Rainfall Variability, Temperature Variability, GIS, Composite Drought Index.

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1. INTRODUCTION

Drought is a natural phenomenon with a long development pathway that occurs when there has been a prolonged lack of adequate precipitation along with rising temperatures, increased evapotranspiration, reduced soil moisture, and reduced groundwater recharge. Drought is a gradual process of change which takes place over a longer period, and has effects on agriculture, water availability, ecosystem stability, food security, and rural livelihoods, as compared to sudden-onset natural disasters [1-2]. The impact of climate change on climatic systems, water resources, ecosystems, agriculture, and socio-economic development makes it one of the most far-reaching challenges faced by the global environment in the 21st century. The scientific evidence shows that the rise in greenhouse gas concentrations from human activities has increased global warming and altered atmospheric circulation, precipitation patterns, and the frequency and intensity of extreme climatic events. In arid and semi-arid areas, water resources are naturally limited and highly susceptible to climatic variations. Among these events, drought has become one of the most persistent and devastating natural hazards [3].

Such problems exist especially in the Thal Desert, where agricultural output and basic potable

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water sources largely rely on seasonal rainfall, canal irrigation, and underground water. The average rainfall in the Thal Desert is low, irregular and very unevenly distributed and thus the occurrence of droughts is one of the main factors controlled by rainfall in the region. A significant improvement in the methods for assessing meteorological droughts was the development of the Standardized Precipitation Index (SPI). Because of its statistical simplicity, flexibility across a range of temporal scales, and its suitability for comparing drought across different climatic regions, from the time it was introduced, SPI has been one of the most accepted drought indices. Drought influences, however, can also be manifested in warming or changes in groundwater levels. Seasonal monsoon rainfall plays an important role in agricultural production, and the amount or distribution of precipitation is closely coupled with groundwater recharge [4-6]. When drought assessment relies solely on precipitation, it may not adequately represent groundwater resource stress, particularly during prolonged dry periods.

Mann-Kendall and Sen's slope estimator are statistical methods of trend detection that can be used to detect monotonic increases and decreases and estimate their magnitude without assuming that the observations are normally distributed [7]. GIS also allows mapping these observations at points, updating those to a continuous surface, and merging them for a regional hazard assessment.

Regional-scale drought assessment in Thal desert and adjoining arid region is constrained by sparse meteorological observations, while precipitation-based drought study may not fully represent the combined effects of temperature, precipitation, and groundwater conditions. Previous studies have examined groundwater separately from precipitation and temperature, while drought patterns, agricultural drought, and climate-related drought assessments have largely relied on remote sensing data [8]. To address this limitation, groundwater data are integrated with meteorological and precipitation data, particularly during prolonged dry seasons, to assess the ground water stress more effectively [9]. Composite drought index is developed by an integrated framework covering long-term rainfall and temperature variability, groundwater conditions, SPI-12, spatial interpolation, trend analysis, and weighted overlay based on AHP for the present study. The goal of this study is to develop a drought hazard map and provide scientific evidence to support drought management and groundwater planning in the Thal Desert.

2. MATERIALS AND METHODS

2.1. Study Area and Data

This study was conducted in five districts of Punjab, Pakistan, namely, Bhakkar, Khushab, Layyah, Jhang and Mianwali within Thal Desert (Figure 1). The analysis was based on monthly rainfall and temperature data from six Pakistan Meteorological Department (PMD) stations (Bhakkar, Jhang, Jauharabad, Layyah, Mianwali and Noor Pur Thal) for the period from 1995 to 2024 [10]. Groundwater data were available from 79 monitoring stations for the period from 2003 to 2019, as obtained from the Irrigation Department, Punjab. Therefore, groundwater analysis was restricted to 2003 to 2019, whereas the meteorological analysis covered 1995 to 2024, because the rainfall and temperature records from the Pakistan Meteorological Department were available for the longer period. The datasets were preprocessed and screened for consistency and uniformity before analysis.

2.2. Temperature Analysis

For the six meteorological stations, mean annual, maximum, minimum, and average temperatures were calculated. Inverse distance weighting (IDW) was used in ArcGIS 10.4.1 to generate spatial distribution maps of temperature variables [11]. The Mann-Kendall test was used to test long-term trends, and a p-value < 0.05 was considered statistically significant; Sen's slope was applied to describe the rate of change. Pre-testing for serial autocorrelation was performed before applying the Mann-Kendall trend test [12].

2.3. Groundwater Analysis

The groundwater data were analyzed separately for the pre-monsoon and post-monsoon periods. Spatial variability was described using mean, min, max, standard deviation, and coefficient of variation. To determine trends, whether increasing, decreasing, or neither statistically significant, the Mann-Kendall trend analysis was used at the

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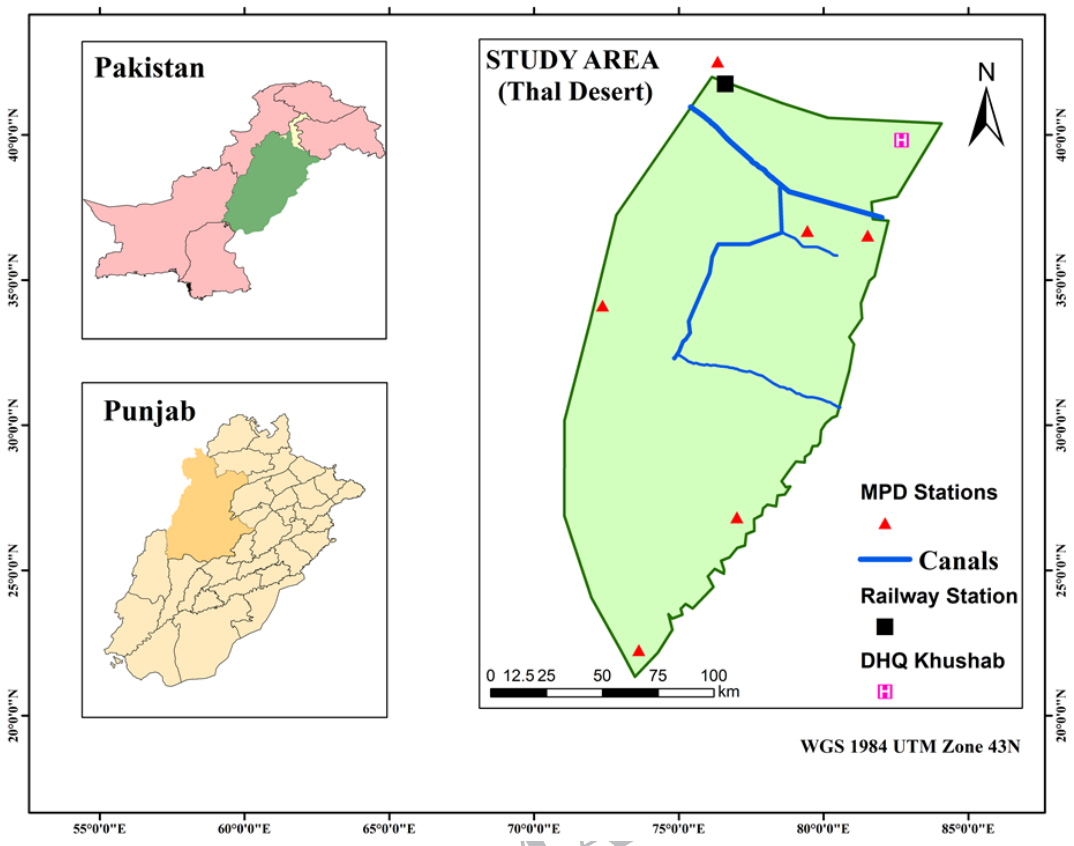


Fig. 1. Study area and meteorological stations.

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monitoring stations, and Sen's analysis was used to determine the rate of change.

2.4. SPI-12 and Drought Frequency

The monthly precipitation series was processed using the R package SPEI to calculate SPI-12 [13, 14]. The accumulation scale for the past 12 months was chosen to reflect longer-term meteorological moisture conditions important to water resources and drought assessment. The SPI values were then interpolated following the same process as the other data in GIS and categorized into drought-frequency classes for better understanding of the spatial pattern of meteorological drought.

2.5. Composite Drought Index

To create the Composite Drought Index, the indicator layers selected were standardized and then overlaid through a GIS-based weighted overlay. The drought indicators were weighted for SPI-12, annual mean temperature, and groundwater conditions, while precipitation was input as rainfall [15]. Weights for indicators were derived by applying the AHP method and then implemented in ArcGIS for relative indicator weights. The final CDI raster has been classified into five hazard categories: Very Low, Low, Moderate, High, and Very High (1-0, 2-1, 3-2, 4-3, 5-4). Area statistics have been generated for each class. The advantage of using AHP for structured multi-criteria weighting is that it transforms the relative importance judgments into normalized weights and can be checked for consistency [16]. The normalized AHP weights were 0.50 for SPI-12, 0.30 for annual mean temperature, and 0.20 for groundwater depth. The normalized weights were used in the GIS-based weighted overlay to drive the Composite Drought Index. The AHP (Analytic Hierarchy Process) was established for relative weights of three criteria, and a pairwise-comparison matrix was created for specific weights of 0.5, 0.3, and 0.2, while the reported consistency ratio was below 0.10.

Each indicator layer X is normalized to the range 0-1 before overlay.

For indicators positively correlated with drought severity (e.g., temperature, groundwater depth):

$$X_{norm} = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

For indicators negatively correlated with drought severity (e.g. SPI-12):

$$X_{norm} = \frac{X_{\max} - X}{X_{\max} - X_{\min}}$$

For the pairwise comparison matrix A, the weight vector $W = [0.50,\ 0.30,\ 0.20]^T$ (normalized so that $\sum W_i = 1$) satisfies:

$$AW = \lambda_{\max} W$$

with $\lambda_{\max}$ estimated as:

$$\lambda_{\max} \approx \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i}$$

Consistency Index:

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \qquad n = 3$$

Consistency Ratio:

$$CR = \frac{CI}{RI} < 0.10$$

where $RI = 0.58$ is the random index for $n = 3$ criteria.

3. RESULTS

3.1. Rainfall Variability and Trend

Annual rainfall ranged from 465 - 517 mm during the 1995 to 2024 study period. The greatest rainfall classes were mainly towards the northern and north-central areas of the study area, while lower rainfall classes were mainly distributed along the western and south-eastern margins (Figure 2). Rainfall generally decreased towards the southern and peripheral areas of the region.

The seasonality is evident in rainfall cycle of Thal, demonstrates the clear distinction in dry (Pre-monsoon) from February to April and wet season (Monsoon) during July and August (Figure 3). While rainfall patterns were consistent on the annual time scale, water availability depended heavily on a short period of variable wet seasons rainfall.

The annual rainfall trends were negative at all six stations, although the trends were weak and statistically non-significant. Sen's slope estimates ranged from -3.173 mm year^{-1} to -0.083 mm year^{-1}. Noor Pur Thal recorded the maximum negative slope (-3.173 mm year^{-1}), while the minimum negative slope (-0.083 mm year^{-1}) was recorded at Mianwali. The findings show that the recorded trend during the study period is not statistically significant at the annual scale, but the slight negative trends and high concentration of rain over the seasons could lead to drought susceptibility. These station-level trend results are summarized in Table 1.

3.2. Temperature Variability and Trend

Annual mean temperature across the study area ranged from around 24.22 to 25.15 °C, with the higher values in the central-western part of the study area and relatively lower values toward the north (Figure 4). The spatial pattern shows that there is a definite thermal gradient in the Thal Desert. The calculated underlying maximum temperature values were within the range of 31.18 to 33.10 °C while the minimum temperature values ranged from 17.13 to 17.35 °C.

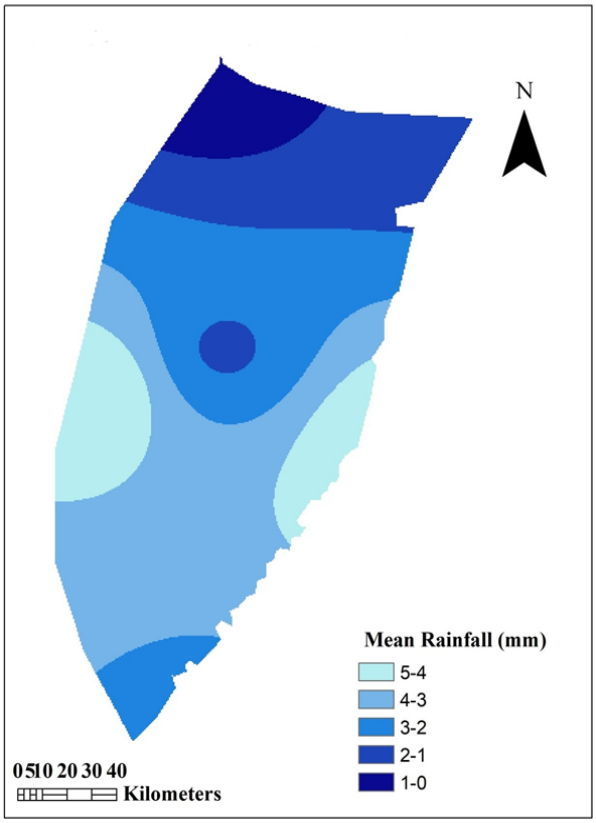


Fig. 2. Spatial distribution of mean annual rainfall (1995-2024).

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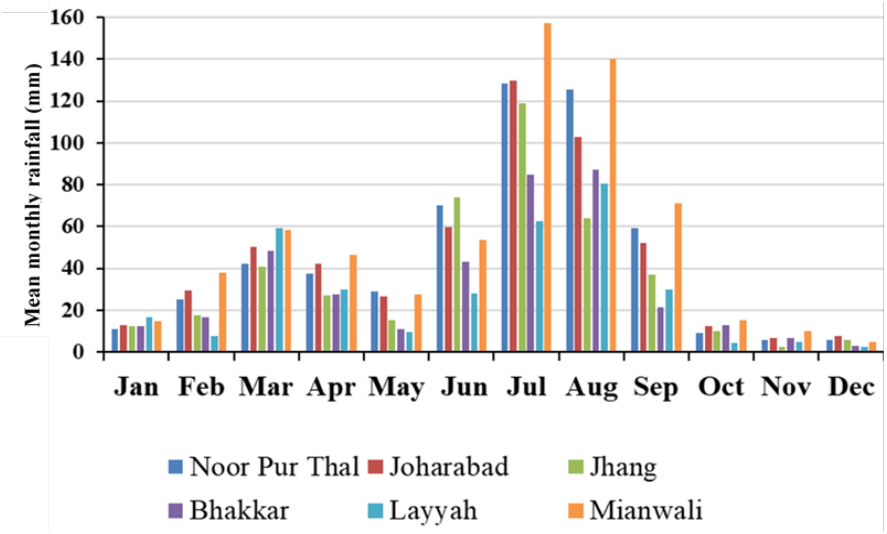


Fig. 3. Mean monthly rainfall of different station data.

Table 1. Annual rainfall trends.

Station	Kendall's τ	p-value	Sen's slope (mm yr^{-1})
Bhakkar	-0.100	0.6204	-1.844
Jhang	-0.200	0.2043	-0.775
Jauharabad	-0.137	0.4487	-0.800
Layyah	-0.028	1.0000	-0.208
Mianwali	-0.014	0.9289	-0.083
Noor Pur Thal	-0.216	0.2255	-3.173

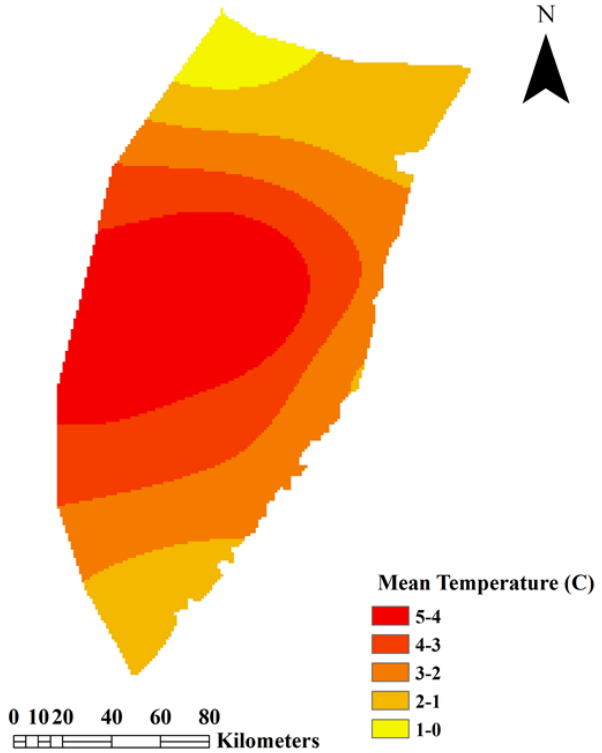


Fig. 4. Spatial distribution of mean annual temperature (1995-2024).

The trend analysis results showed mixed temperature trends among the individual stations rather than a regionally consistent trend. A statistically significant positive trend in annual maximum temperature was observed at Jauharabad ($\tau = 0.354$ and $p = 0.0445$) with a Sen's slope of 0.0267 °C year^{-1}. In contrast, the trends at Bhakkar, Jhang, Mianwali, Layyah and Noor Pur Thal were not statistically significant ($p > 0.05$). The annual maximum-temperature trend statistics are presented in Table 2. Overall, the results demonstrate spatial variability in temperature trends across the Thal Desert, suggesting that the contribution of temperature to drought conditions should be evaluated together with rainfall and groundwater characteristics.

3.3. Groundwater Conditions and Trends

The depth of groundwater during pre-monsoon was 2.55 - 21.79 m and during post-monsoon was 3.05 - 21.59 m. The mean groundwater depth showed

Table 2. Annual maximum-temperature trends.

Station	Kendall's τ	p-value	Sen's slope (°C yr^{-1})
Bhakkar	-0.068	0.7517	-0.0012
Jhang	0.022	0.9100	0.0000
Jauharabad	0.354	0.0445	0.0267
Layyah	0.087	0.8315	0.0006
Mianwali	-0.109	0.4115	-0.0050
Noor Pur Thal	0.040	0.8495	0.0008

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some improvement in groundwater condition from 14.53 m before the monsoon season to 14.30 m after the monsoon season. The standard deviations of the two measurements were 5.53 m and 5.35 m, and the coefficients of variation for the two measurements were 38.07% and 37.39%, respectively. For both seasons, the similar variability suggests the overall spatial pattern of groundwater depth did not change significantly since the monsoon [17]. These groundwater depth statistics are summarized in Table 3.

The density of water stations suggested that, in most cases, there was no statistically significant long-term trend at the groundwater stations. During the pre-monsoon, 17 stations had increasing trend, 12 decreasing trend and 50 had no trend. 15 stations reported an increasing trend, 8 stations decreasing trend and 56 stations no trend in the post-monsoon season. These results indicate that groundwater behavior was spatially heterogeneous across the study area rather than uniform. The station-level trend categories are summarized in Table 4.

3.4. Meteorological Drought

The SPI-12 analysis was used to identify recurrent meteorological drought conditions during 1995-2024 and revealed significant variability in drought frequency. The drought frequency surface showed relatively favorable conditions in the northern part of the study area, while higher drought frequency occurred in central, southern, and peripheral areas (Figure 5). The pattern was generally consistent with the expected precipitation gradient. Temperature and groundwater conditions were subsequently incorporated into the composite drought index (CDI) to provide an integrated assessment of drought hazard.

Table 3. Groundwater depth statistics.

Statistic	Pre-monsoon (m)	Post-monsoon (m)
Mean	14.53	14.30
Minimum	2.55	3.05
Maximum	21.79	21.59
Standard deviation	5.53	5.35
Coefficient of variation (%)	38.07	37.39

Table 4. Groundwater trend categories.

Trend category	Pre-monsoon	Post-monsoon
Increasing	17	15
Decreasing	12	8
No trend	50	56
Total	79	79

3.5. Composite Drought Hazard

The CDI incorporated standardized climatic and groundwater indicators into one dataset that was used to provide spatial representation of drought hazard. The final map showed a gradient from north to south and from central-western to eastern/north-eastern. high and very high hazards were more prevalent in the central and south-west of the Thal Desert while very low and low hazards were generally confined to the northern section (Figure 6). There were transitional areas between these extremes, where the hazard rating was moderate.

The high drought hazard class was the largest, covering 7,212 km² (34.6%) of the CDI area, followed by the moderate class, which covered 5,541 km² (26.6%). Together these two classes accounted for 61.2% of the CDI area. The very high low, and very low hazard classes accounted

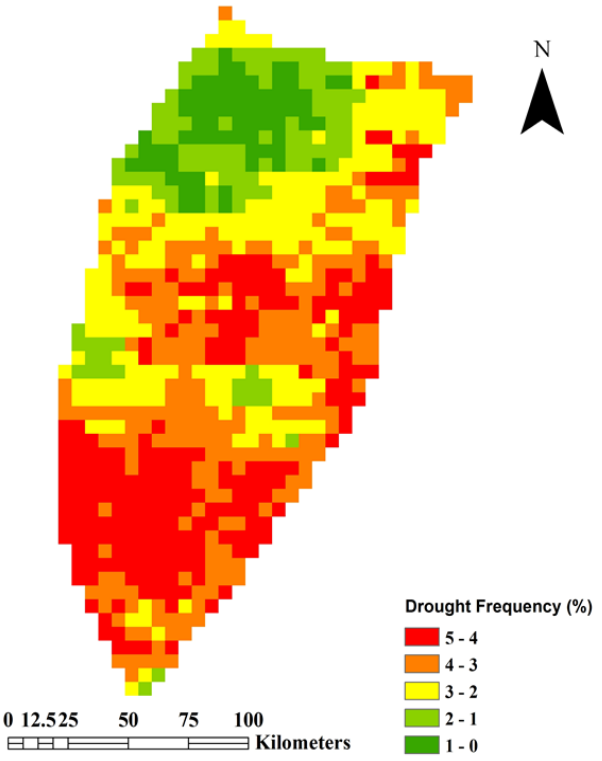


Fig. 5. SPI-12 drought frequency (1995-2024).

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for 13.8%, 13.7%, and 11.3% of the total area respectively. The area statistics for the CDI classes are presented in Table 5.

4. DISCUSSION

The results indicate that annual rainfall alone may not fully capture drought conditions in the Thal Desert. Annual rainfall showed slightly decreasing trends at all six stations, but none of the trends was statistically significant at the 95% confidence level. The region-wide non-significant decrease in rainfall is in line with rainfall assessments across Pakistan, where Punjab has also shown a decreasing tendency in rainfall, although the trend was not statistically significant. Such regional variability indicates that changes in annual rainfall may be relatively weak while seasonal and spatial variability remain important for drought assessment [18]. Studies in arid and semi-arid Punjab have similarly highlighted strong spatial variability in precipitation and the importance of prolonged dry spells, particularly in the southern part of the province [19]. This combination is important because seasonal water stress may occur even when annual rainfall totals remain relatively low but are concentrated within a short-wet season. Another dimension of drought stress is caused by temperature.

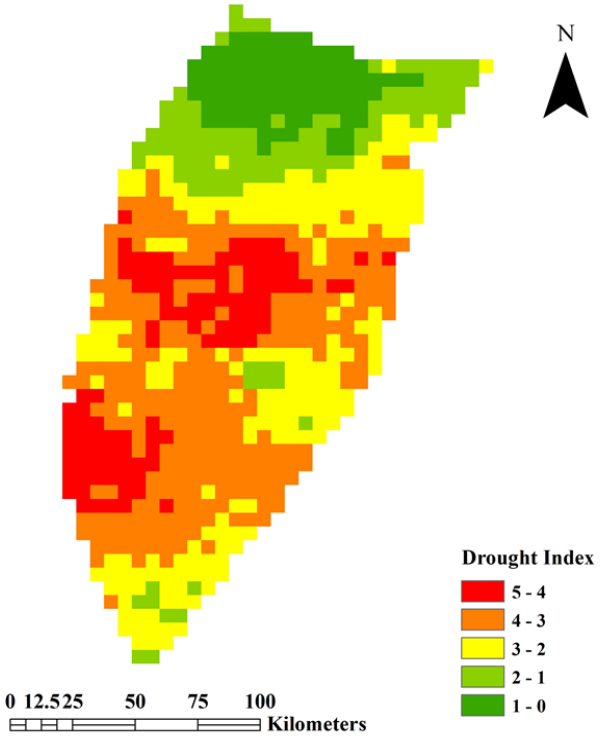


Fig. 6. Composite drought hazard index (1995-2024).

Table 5. Composite Drought Index classes.

CDI class	Area (km²)	Area (%)
Very Low	2,351	11.3
Low	2,858	13.7
Moderate	5,541	26.6
High	7,212	34.6
Very High	2,877	13.8
Total	20,839	100.0

Spatial analysis revealed higher thermal conditions in the central-western and southern areas, and the trend analysis indicated thermal change for selected stations. In warmer conditions, increased evaporative demand may reduce effective water availability even when precipitation remains relatively stable. However, temperature trends in Punjab have also shown spatial and temporal heterogeneity, with different temperature variables exhibiting varying trends across individual stations [20]. This finding is consistent with evidence summarized by the Intergovernmental Panel on Climate Change and the World Meteorological Organization, which shows that climate change is increasing hydro-climatic risks through interacting changes in temperature and precipitation. The groundwater results provide an important hydrological perspective. The small difference between mean pre-monsoon and post-monsoon depth suggests that recharge during the monsoon season was mostly localized, and the broad dominance of stations where there was no significant change suggests that groundwater behavior was not uniform nor generally declined. This could be because of the greater Thal canal and its tributaries, along with an unconfined Quaternary alluvial and eolian aquifer system primarily composed of interlayered sand, gravel, silt, and a very small amount of clay, in addition to the influence of bordering Jhelum and Indus rivers. The northern side of the study area depicted less inter-seasonal variation in comparison to the southern side, plausibly due to the canal, yet the rate of abstraction is also higher in the same area. The spatially heterogeneous groundwater response observed in the present study is consistent with previous investigations in Punjab and the Thal region. Previous investigations in Punjab and the Thal region have reported that groundwater is influenced by rainfall, canal-water conveyance, and

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irrigation, with groundwater levels showing seasonal variations between the Kharif and Rabi periods. Similarly, isotopic investigations in the Thal Doab demonstrated spatial differences in groundwater recharge sources, with rainfall contributing more strongly in some areas while surface-water sources dominated in others [4]. These findings support the interpretation that groundwater responses in the Thal Desert may vary spatially according to recharge sources, canal influence and local hydrogeological conditions. Therefore, groundwater is an important drought indicator because groundwater responses may differ from precipitation-based drought signals across locations. This interpretation is consistent with previous research showing that groundwater responses can differ substantially from precipitation-based drought signals because groundwater integrates climatic forcing with recharge processes, aquifer characteristics, and human water use [21]. This highlights the importance of incorporating groundwater responses into integrated drought assessment.

The CDI is an integrated spatial synthesis of selected drought indicators with limited meteorological and groundwater data (uneven coverage) and lacking the anthropogenic factor of climate change without the support of simulation or modelling. These factors may constrain the effectiveness of CDI. The high and very high hazard zones are where more than one stressor is present, while the low hazard zones to the north match more closely the comparatively good climatic and groundwater conditions. The integrated spatial pattern identified by the CDI is consistent with previous research showing that combining multiple drought indicators provides a more comprehensive assessment than using individual indicators alone [22]. The high and very high hazard zones in the present study therefore reflect the combined influence of multiple hydro-climatic stressors. Since drought is a complex phenomenon, a composite approach can be beneficial as it captures different facets of water stress that a drought index may miss [23]. Similar findings have been reported in recent multi-indicator drought assessments, where combining meteorological, hydrological, and other environmental indicators provided a broader representation of drought conditions than single-index approaches. The spatial patterns also illustrate how GIS can be used to project observations from stations and statistical information in the form of geographical information about a drought. GIS-based approaches have been widely used to identify spatial variations in drought hazard and vulnerability. These studies support the use of GIS for converting station-based and environmental observations into spatially explicit drought assessment. These results should be interpreted in the context of the available observations. Thirty years of meteorological data were available for analysis, while groundwater data covered 17 years from 79 monitoring locations. The selected indicators and the AHP weighting scheme are also important components of the CDI; during this study the weights used were normalized: 0.50 for SPI-12, 0.30 for temperature and 0.20 for groundwater depth. The results of the study are meant to be read as indicative of hydro-climatic variability and drought/prolonged wetness over time, and do not explicitly attribute observed changes to anthropogenic climate change, since the study does not use formal detection and attribution, or detection and attribution from climate-modeling experiments. Therefore, the map is not to be used as an exact indicator of drought risk, but rather as a regional drought-hazard assessment. The framework would be strengthened with the inclusion of soil moisture, vegetation health, land use change, and socio-economic vulnerability indicators in future assessments; for example, future climate change projections, and sensitivity/validation analyses of the CDI could be included.

5. CONCLUSIONS

This study proposed a multivariate drought assessment study of the Thal Desert, utilizing groundwater conditions, statistical trend analysis, SPI-12 and GIS based multi-criteria evaluation. The annual rainfall for the period from 1995-2024 showed spatial variation with a weak, statistically non-significant decreasing trend, and the precipitation had a strong monsoon concentration. Selected stations showed spatial variability and significant trends in temperature, which has been shown to be an important component of drought stress. Conditions in groundwater exhibited a wide range across the 79 monitoring stations, with few exhibiting an apparent long-term trend, supporting relatively high spatial variability of aquifer response. The SPI analysis identified recurrent meteorological drought conditions, with higher drought frequency observed in the central and southern parts of the study area. The

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integrated CDI classified 34.6% of the study area as high drought hazard, 26.6% as moderate drought hazard, and 13.8% as very high drought hazard. The observed spatial patterns indicate that drought hazard is unevenly distributed across the region, reflecting the combined influence of climatic and groundwater conditions. The resulting hazard map can support the prioritization of drought monitoring, groundwater resource management and irrigation planning in the Thal Desert.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Pakistan Meteorological Department (PMD) and the Punjab Irrigation Department for providing the meteorological and groundwater-related data used in this study.

7. FUNDING

No funding was received to conduct this research.

8. ETHICAL STATEMENT

This study did not involve human participants, human subjects, or animals. Therefore, ethical approval was not required.

9. AUTHOR CONTRIBUTIONS

Muhammad Waseem Haidar: Conceptualization, methodology, data analysis, investigation, visualization, and writing original draft. Shakir Hussain: Supervision, methodology, and critical review of the manuscript. Omar Riaz: Data interpretation, review, and editing. Muhammad Imran: Data analysis support, review, and editing. All authors read and approved of the final manuscript.

10. DECLARATION

The authors declare that the results presented in this manuscript are original and that the same material has neither been published previously nor is currently under consideration for publication elsewhere. All authors have approved the final version of the manuscript and agree to its submission for publication. In case the article is accepted for publication, its copyright will be assigned to the Pakistan Academy of Sciences. The authors confirm that, where necessary, permission has been obtained to reproduce copyrighted material from other sources and that no copyrights have been infringed.

11. DATA AVAILABILITY

The rainfall, climatic temperature, groundwater, and spatial data used in this article were also used in the M.Phil. research of Muhammad Waseem Haidar at the University of Sargodha, Sargodha, Pakistan. The availability of these data is dependent on the permissions and conditions of the data providers.

12. CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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