Future Intensification of Drought and Heatwaves in Quetta Valley Based on SSP Pathways

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Abstract

Quetta Valley is increasingly vulnerable to climate-induced droughts and heatwaves, as indicated by historical observations and future climate projections. The Standardized Precipitation Index (SPI-12) shows values ranging from approximately 0 to –2.5, reflecting frequent moderately to severely dry conditions over the study period. Trend analysis using the Mann-Kendall test indicates a weak negative slope of –0.00013 for observed data (p = 0.736), suggesting a slight tendency toward drier conditions; however, the trend is not statistically significant. Similarly, future projections under SSP245 and SSP585 scenarios show small negative slopes (–0.000075) with p-values of 0.483 and 0.495, respectively, indicating no statistically significant drying trend. These results suggest that drought conditions are likely to persist with minor variations rather than intensify significantly. Heatwave analysis reveals no events in the observed dataset based on the defined thresholds, whereas future projections indicate a substantial increase in both moderate (>40 °C) and severe (>45 °C) heatwaves. The frequency of 5-day heatwave events is consistently higher than 7- and 10-day events, highlighting the increasing persistence of short-duration heat stress. These findings suggest that while drought conditions may remain relatively stable, heatwave intensity and frequency are expected to increase significantly under future climate scenarios, particularly under SSP585. The combined occurrence of droughts and heatwaves poses serious risks to water resources, agriculture, and public health in Quetta Valley. The study highlights the urgent need for climate-resilient water management strategies and adaptive planning to mitigate the impacts of future climate extremes.

keywords: Quetta Valley, Drought, Heatwaves, Standardized Precipitation Index**,** Shared Socioeconomic Pathways.

Introduction

Climate change is a significant worldwide concern, intensifying the frequency and severity of extreme weather events such as droughts and heat

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waves (Change, 2022). These processes pose a threat to the ecosystems, human health and socio-economic stability especially in the weak areas with low adaptive capacity. Worldwide, dry seasons and extreme heat waves have caused tremendous loss in agriculture, shortage of water, and elevated death rates with arid and semi-arid areas being particularly affected owing to their dependency on scarce water supply (Change, 2022; Mukherjee & Mishra, 2021). In combination, the cumulative effects of occurrences such as heat waves that worsen the effects of droughts by enhancing evapotranspiration, create a considerable challenge to sustainable development globally.

South Asia which harbors more than a fifth of the population of the world is highly inclined towards the extremes of climate due to the great numbers, dependence on agriculture practices relying on monsoons, and socio-economic issues (Mondal et al., 2022; Naveendrakumar et al., 2019). Extreme cases of droughts and heatwaves have been witnessed in the area, and events such as the 2015 heatwave in India and Pakistan led to the death of thousands of people (Im et al., 2017). These natural disasters cause disturbance to food security, overburdening of water resources and endanger livelihood, especially by rural communities that are depending on rain-fed agriculture (Mishra et al., 2020). The projections of the changes in climate include hotter and more severe heat waves, and longer. dry seasons which will cause further aggravation of the situation in South Asia (Mondal et al., 2024).

In Pakistan, climate change has been reported to increase due to increased droughts and heat waves in the southern and western parts of Pakistan (Rasul et al., 2012). It is also one of the most climate-sensitive countries, and such incidents as the Karachi heat wave in 2015, when over 2,000 individuals died in the heat, reveal the disastrous effects of high temperatures (Khan et al., 2022). There have been frequent droughts and severe drought most of which have impacted negatively on agricultural production and lowered the level of water supplies and arid areas such as Balochistan have not been spared (Ahmed et al., 2018). These climate extremes are a serious issue in Pakistan that has come to depend on agricultural production that absorbs about 43 percent of the population in the country (Afzal et al., 2021).

Balochistan, the largest province of Pakistan, is marked by an arid environment with limited precipitation, rendering it especially vulnerable to droughts and increasingly to heat waves (Ahmed et al., 2018). The province experienced severe drought between 1998 and 2002, which devastated agriculture, decimated livestock, and undermined rural livelihoods (Naz et al., 2020). In recent years, temperatures have risen markedly, with Balochistan recording one of the highest in Pakistan, 54 °C in Turbat in 2021 (Khan et al., 2022). These situations enhance water shortages and pose danger to the socio-economic stability in the province, and drastic climate adaptation policies are required there.

Quetta, the capital of Balochistan, presents particular challenges due to its location in a high-altitude valley and reliance on limited groundwater resources. The city has a history of severe droughts, with major episodes in 2000, 2004, and 2008, driven by a statistically significant decline in precipitation (Naz et al., 2020). Such droughts have resulted in the drying up of important water sources such as Hanna Lake, which has dried up severally since 2001 as there was a decline in rain, and temperature was raised (Sarwar et al., 2019). Nonetheless, according to the predictions of the climate, moderate heat waves, when temperatures are above 40 o Celsius, will be significantly more frequent and intense in the next several decades, which would also become newly dangerous to health and infrastructure (Ali et al., 2019).

Several studies have investigated drought variability and temperature trends in Pakistan and Balochistan. For instance, drought assessments using indices such as Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Reconnaissance Drought Index (RDI) have identified recurring drought events and increasing precipitation variability across the region (Ahmed et al., 2018; Naz et al., 2020) . Similarly, temperature-based studies have reported a consistent rise in warm days, tropical nights, and extreme heat events in arid regions of Pakistan, including Quetta (Khan et al., 2022) . Recent advancements in climate modeling further highlight that Couple Model Intercomparison Project Phase 6 (CMIP6) models reasonably capture precipitation variability over Pakistan, particularly in arid and semi-arid regions, providing a reliable basis for future projections (Abbas et al., 2025; Sarwar et al., 2019). Additionally, studies comparing satellite and ground-based datasets emphasize the importance of robust dataset selection and validation for accurate drought assessment, showing that different indices and datasets can significantly influence drought characterization outcomes.

Recent regional studies have also highlighted the increasing variability of precipitation extremes and their implications for water resources in South Asia and Pakistan, particularly using CMIP6-based projections (Ibrahim et al., 2024a). Furthermore, evaluation of CMIP6 simulations over Pakistan demonstrates their capability in reproducing precipitation patterns and future climate variability, supporting their application in climate impact studies (Ibrahim et al., 2024b; Ullah et al., 2025). These findings underline the growing importance of integrating advanced climate models and multiple datasets in regional climate assessments.

Despite these contributions, existing studies predominantly analyze droughts and heatwaves independently, without addressing their compound interaction. However, droughts and heatwaves often occur simultaneously or sequentially, amplifying their impacts through increased evapotranspiration, reduced soil moisture, and declining groundwater recharge. This interaction is particularly critical in arid environments such as Quetta Valley, where water scarcity is already severe. Moreover, most previous studies are limited to historical observations and do not incorporate bias-corrected CMIP6 projections under multiple Shared Socioeconomic Pathways (SSPs) to evaluate future risks comprehensively.

Therefore, a clear research gap exists in understanding the combined behavior of droughts and heatwaves under future climate scenarios in Quetta Valley. Addressing this gap is essential for developing effective climate adaptation strategies and improving regional resilience.

To address the identified research gap, the proposed research study aims to analyze historical and future drought and heatwave characteristics in Quetta Valley using observed data and bias-corrected CMIP6 simulations under SSP245 and SSP585 scenarios. The study evaluates drought conditions using the Standardized Precipitation Index (SPI-12) and assesses heatwave characteristics based on threshold-based definitions. Furthermore, it examines the compound impacts of these climate extremes on water resources, agriculture, and human health. The present research study uniquely evaluates the compound interaction of droughts and heatwaves in Quetta Valley using bias-corrected CMIP6 projections, which has not been comprehensively addressed in previous regional studies.

Methodology

Study Area Description

Quetta District is geographically bordered by Pishīn District to the north, Afghanistan to the west, Ziārat and Harnāi Districts to the east, and Mastung and Nūshki Districts to the south. Located in a land area of about 2653 square kilometers (Figure 1), the Quetta is encompassed by four major mountains which naturally surround the area, acting as a wall to the area. The district's climate is arid yet temperate, characterized by low winter rainfall and high summer evapotranspiration. The geographical extent of the Quetta Valley study area spans approximately from 30°06′N to 30°18′N latitude and 66°52′E to 67°07′E longitude. The region has elevation of 5,577 feet to 10,500 feet above sea level, which makes it mainly dry, and winters extremely cold. Precipitation in the region is scarce and irregular due to its elevated topography, which lies beyond the influence of the monsoon belt (Mahar et al., 2018).

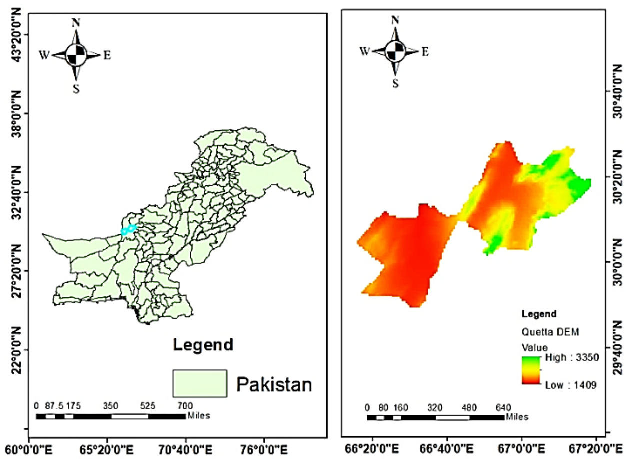

Figure 1: Location of the study area showing Quetta District within Pakistan.

Data Collection

As Pakistan faces limitations in data availability, meteorological records were gathered from diverse sources to achieve complete regional coverage. The Pakistan Meteorological Department (PMD) provided historical precipitation and mean temperature data over the years 1982 to 2018 station at Sibbi, which is the closest reliable station providing long term records. To supplement this dataset, daily maximum and minimum temperature observations were obtained from online sources, including the Global Precipitation Climatology Centre (GPCC; https://www.psl.noaa.gov), National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resources (POWER; https://power.larc.nasa.gov/), National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC; https://www.cpc.ncep.noaa.gov), and the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS; https://www.chc.ucsb.edu/data/chirps3). The GPCC dataset provides gauge-based precipitation data at 0.5° resolution from 1891 to present, NASA POWER offers daily maximum and minimum temperatures at 0.5° resolution from 1981 onward, NOAA CPC supplies daily temperature and precipitation at 0.5° resolution from 1979 to present, and CHIRPS delivers precipitation estimates at 0.05° resolution from 1981 to present, all selected for their reliability, validation in previous studies, and global coverage. The choice of these datasets is based on their reliability and worldwide coverage, which means the data is solid to analyze.

For future climate predictions, we extracted daily temperature and precipitation data from eight Global Climate Models (GCMs) in the CMIP6 repository: NorESM2-MM (Norway), CMCC-ESM2 (Italy), CNRM-CM6-1 (France), EC-Earth3-Veg-LR (Europe), INM-CM4-8 (Russia), INM-CM5-0 (Russia), MIROC6 (Japan), and MRI-ESM2-0 (Japan). These models were selected based on their performance in accurately simulating historical climate patterns, including seasonal temperature and precipitation variability, over South Asia. For this study, two SSPs were applied: SSP245, representing a moderate greenhouse gas emission scenario, and SSP585, representing a high greenhouse gas emission scenario. These scenarios depict different future trajectories of radiative forcing and socio-economic development, allowing assessment of drought and heatwave risks under varying levels of climate mitigation and adaptation. The methodology of the current project is depicted by Figure 2. Firstly, climatic data was preprocessed. Secondly, anomaly, drought index and heat waves was assessed for historical and future climatic conditions.

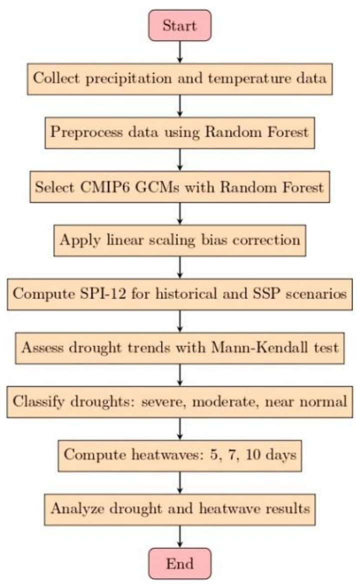

Figure 2: Flowchart of Methodology for Analyzing Drought and Heatwave Trends in Quetta Valley.

Data Pretreatment

Pakistan is a data-scarce country, where limited data availability poses a significant challenge (Moazzam et al., 2022). Due to not present PMD station in Quetta Valley, the Sibbi station data was used as a reference to rank satellite datasets and GCMs in terms of reliability. A Random Forest regression model was trained using observed daily precipitation and temperature from Sibbi as the target, and candidate satellite products or GCM outputs as input features (Ahmed et al., 2019). Feature importance scores derived from the Random Forest allowed quantitative ranking of each dataset based on its contribution to accurate prediction of observed conditions. The top-ranked satellite product and GCM, identified as the most consistent with historical observations at Sibbi, were subsequently used for Quetta Valley analysis. All data were used at daily temporal resolution. While Sibbi data was used for ranking and bias correction, the final analysis was conducted using Quetta-specific daily data obtained from the selected top-ranked datasets.

Drought Index

The SPI is a drought indicator that reflects how recorded rainfall differs from the average climatic value over a defined duration. The SPI evaluates the shortfall or excess in precipitation over different time scales. It is particularly useful for understanding and monitoring drought conditions across various climatic regions. While short-term indices such as SPI-3 or SPI-6 capture agricultural drought, the focus of this study is on long-term water availability for water resource planning (Hoylman et al., 2022). The SPI is calculated using below equation:

$$SPI = x - {}^{\mu}/_{\sigma}$$

Here "x" refers to the recorded precipitation amount for a specific time frame (e.g., monthly, seasonal). "μ" represents the average precipitation for the identical duration. "σ" standard deviation representing the variability of long-term rainfall distribution. In the current project, SPI-12 was estimated. SPI-12 assesses long-term precipitation patterns and is useful for understanding hydrological conditions, including groundwater levels, reservoir storage, and long-term agricultural impacts (Mishra & Nagarajan, 2011). This longer-term perspective helps to identify drought conditions that persist over a year, impacting water supply systems and broader environmental conditions. It is applicable in water resource management, hydrology, and the knowledge of long-term. The effects of drought are on the supply infrastructure and ecosystems.

Drought Indicators

Severity of a drought is calculated by dividing the severity of the event by length of time. A drought is considered more severe when its intensity value is higher. The drought peak represents the lowest SPI recorded during the event. The length of a drought is measured by the total number of months it continues. Drought severity equals the cumulative SPI values during a drought period. The equations are:

$$Ds = \left|\sum_{J=1}^{DD} index\ j\right|$$

$$Di = \frac{D_S}{D_D}$$

Where J stands for a month, index J shows value of SPI in J month, and D_D, D_S, and D_i represent the length, severity, and intensity of a dry period, respectively (Abu Arra et al., 2024).

Drought Classification

The categorization of drought events according to SPI metrics ranges from extremely moist (SPI scores ≥ 2.0) to extremely arid (SPI scores ≤ -2.0). SPI scores from 1.5 to 1.99 are labeled as very wet, while those from 1.0 to 1.49 are considered moderately wet. SPI values ranging from -0.99 to 0.99 reflect near-normal conditions. Mild drought is defined by SPI readings from -1.0 to -1.49, while severe dryness corresponds to SPI values between -1.5 and -1.99 (Lin et al., 2020). The details of various classes are provided in Table 1.

Table 1: Classification of drought conditions as per SPI values.

SPI Values	Classification
2.0+	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

Heat Waves Assessment

In this project heat waves were computed for 5, 7 and 10 consecutive days for observed and SSP scenarios. Heat waves were classified as moderate or severe, with threshold maximum temperatures of 40 °C and 45 °C, respectively (Smith et al., 2013). This study facilitates the comparison of present and future heat wave conditions in the Quetta District.

Results

Data Preprocessing

In this project, the Random Forest algorithm was used to assess the relevance of different online data sources. On analysis of precipitation, the dataset of GPCC had the utmost applicability as shown in Figure 3. In the case of temperature, POWER NASA collection was found as the most significant data source. In cases where ground-based meteorological data was unavailable, these models proved highly useful.

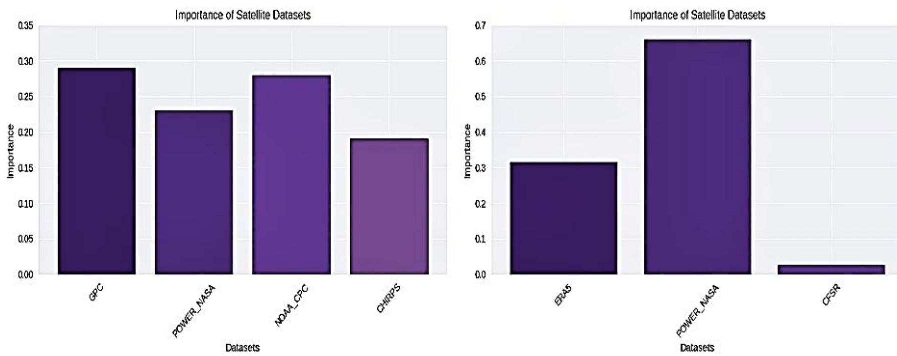

Figure 3: Selection of optimal datasets using Random Forest analysis: (a) precipitation datasets and (b) temperature datasets, showing relative importance of each source.

Meteorological Forcing

Bias correction refers to the highly common statistical technique of correcting the results of globally known GCMs which are complicated models that are meant to illustrate the atmospheric, marine, and land climate actions. Although GCMs are advanced computer models, their outputs often contain systematic errors due to inherent limitations. Bias correction addresses these discrepancies by statistically adjusting GCM outputs to align with observations, thereby making climate projections more reliable for impact assessment and decision-making.

Statistical downscaling is a useful version of dynamic downscaling, with similar empirical relationship between observed climate data and GCM simulations and provides an effective and resource-intensive alternative to Dynamic downscaling. Its relative ease, the ease of computation has led to the adoption of this method by many in climate and hydrological studies. Linear Scaling approach to bias correction was implemented in a multiplicative and additive manner While linear scaling effectively adjusts the mean of temperature and precipitation to align with observations, it does not fully correct extreme events, which may introduce some uncertainties in SPI and heatwave analysis. These limitations are acknowledged, and the results should be interpreted with caution, particularly regarding the frequency and intensity of extreme events. The correctness of the bias correction was tested using the GCM outputs with bias correction, and also using the observed historical data of the baseline period. Statistical performance metrics, including the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Bias Error (MBE), were calculated for both precipitation and temperature datasets. These indicators ensured that the corrected outputs effectively reproduced the magnitude, variability, and distribution patterns of the observed climate variables, thereby enhancing the reliability of subsequent drought and heatwave assessments.

In addition, the relative importance of eight GCMs used in the study was measured following the Random Forest algorithm. The CNRM-CM6-1 model (France) achieved the highest feature importance score, as shown in Figure 4, indicating a stronger association with observed climate patterns compared to other models, including its counterparts.

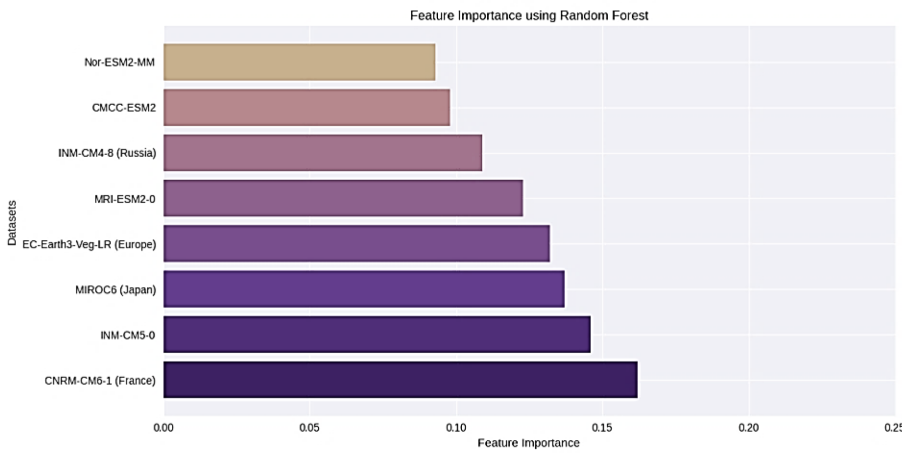

Figure 4: Relative importance of CMIP6 GCMs derived from Random Forest analysis, highlighting the most suitable models for climate projections in the study area.

Drought Assessment

Drought Trend Assessment

In this project SPI-12 was computed for historical and future conditions using two CMIP6 scenarios namely SSP245 and SSP585. The SPI-12 values for observed data vary between 0 and -2.5. Majority of the drought values are less than -2 which falls in severely dry, moderately dry and near normal drought categories. For SSP245 and SSP585, majority of the drought values are less than -2 which falls in severely dry, moderately dry and near normal drought categories as shown in Figure 5, Figure 6, and Figure 7. While SPI-12 captures long-term hydrological drought affecting water resources and agriculture, short-term agricultural drought could be better assessed using SPI-3 or SPI-6. Future studies should incorporate these shorter time scales for a more complete understanding of agricultural water stress.

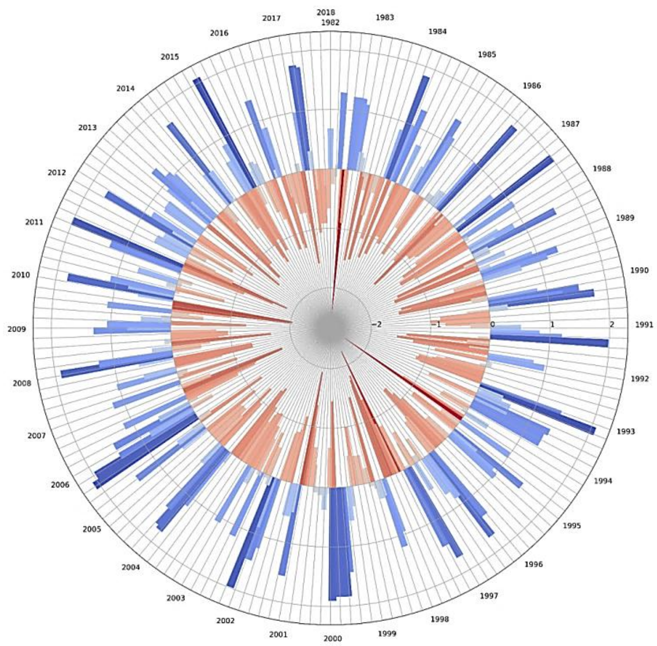

Figure 5: SPI-12 values for historical observations showing temporal variability of drought conditions in Quetta Valley.

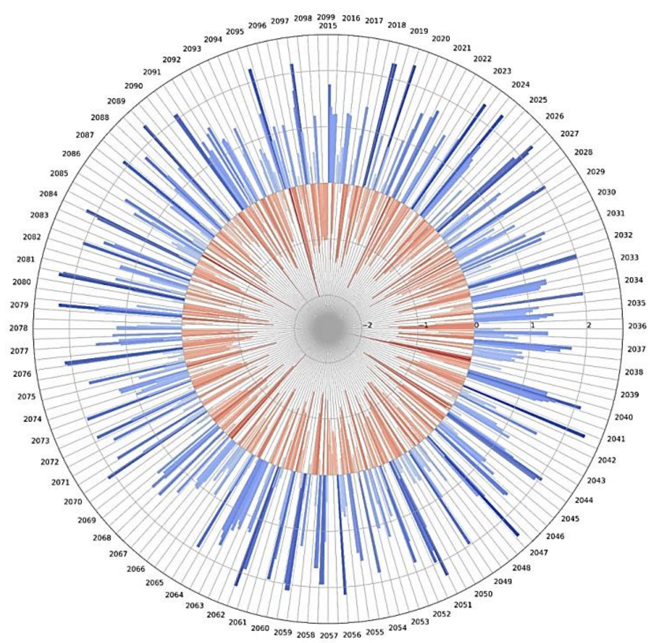

Figure 6: SPI-12 values for future projections under SSP245 scenario showing expected drought variability and persistence.

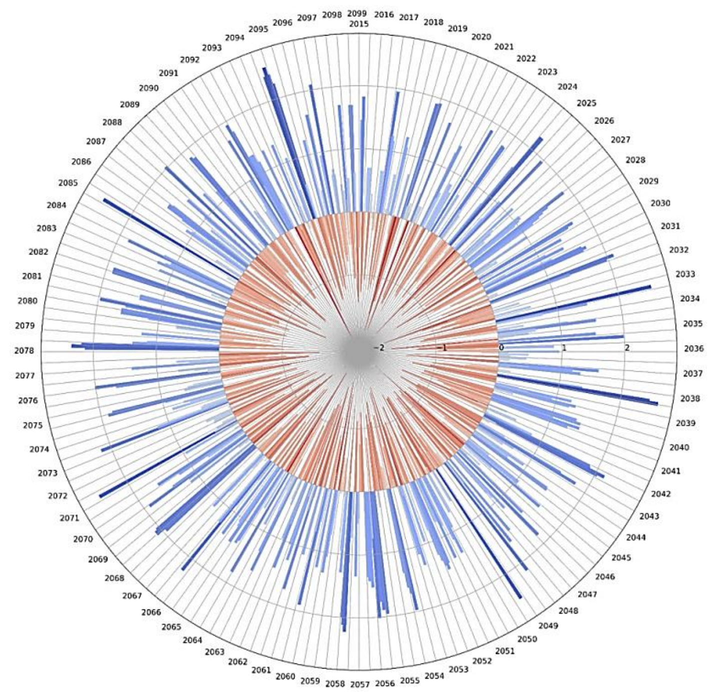

Figure 7: SPI-12 values for future projections under SSP585 scenario indicating intensified variability and persistence of dry conditions.

The SPI-12 time series illustrates significant interannual variability in drought conditions across Quetta Valley. Periods of negative SPI values indicate prolonged dry conditions, while positive values reflect relatively wet phases. The figure highlights the recurring nature of droughts in the region and emphasizes the increasing variability in long-term precipitation patterns.

Table 2: Mann–Kendall trend analysis and Sen's slope estimation of SPI-12 for observed and projected scenarios.

Station	Observed/SSP scenario	Z value	p value	Tau	Slope
Quetta	Observed	-0.336	0.736	-0.0108	-0.00013
	SSP 245	-0.700	0.483	-0.0147	-0.000075
	SSP 585	-0.682	0.495	-0.014	-0.000075

Note: Z-value represents the standardized test statistic of the Mann–Kendall test used to detect monotonic trends. "Tau" (Kendall's Tau) indicates the strength and direction of the trend (positive or negative association). The "p-value" represents statistical significance ($p < 0.05$ indicates significant trend). "Slope" refers to Sen's slope estimator, representing the magnitude of change in SPI-12 per time step.

The Mann-Kendall test was applied to evaluate trends in SPI-12 values. Observed data exhibit a slope of –0.00013, with a p-value of 0.736, indicating that the trend is not statistically significant, as shown in Table 2 (above). Similarly, the SSP245 and SSP585 scenarios show slopes of –0.000075 (p-values 0.483 and 0.495, respectively). These results suggest a slight tendency toward drier conditions, but the small magnitude and lack of statistical significance indicate that a strong drying trend cannot be confidently claimed. Wet periods are becoming slightly less intense, while dry periods show minor increases in intensity, consistent across both historical and projected datasets.

Drought Classification

SPI is classified according to Table 1. Notably, the frequency of occurrence increases from extremely dry to near-normal conditions in both the observed data and the SSP scenarios, as shown in Figure 8, Figure 9, and Figure 10. Across all datasets, moderately dry events are the most common, followed by severely dry and then extremely dry conditions, with the latter being comparatively rare. This pattern indicates that, while extreme droughts occur infrequently, moderate and severe droughts have a more sustained impact on the region's water resources and agricultural activities.

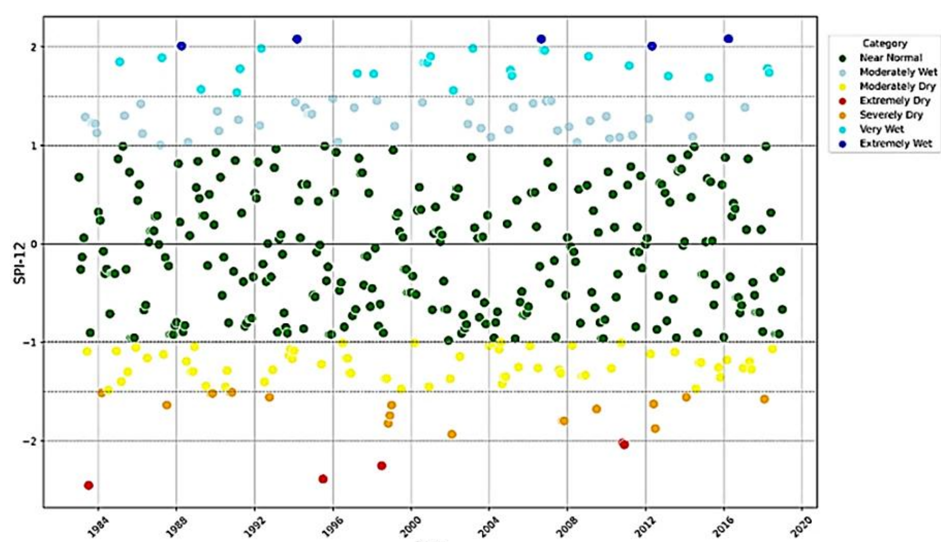

Figure 8: Distribution of drought categories based on SPI classification for observed data, showing the frequency of near-normal to extremely dry conditions.

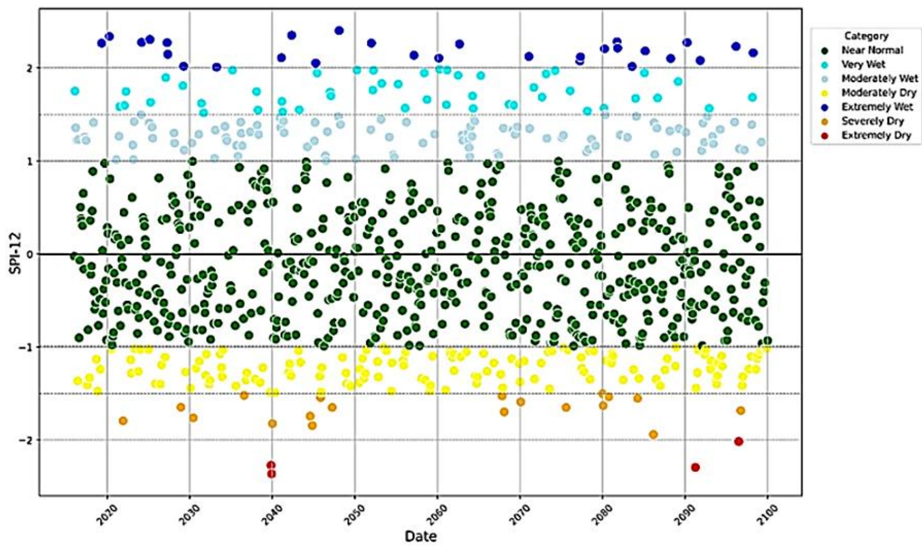

Figure 9: Distribution of drought categories based on SPI classification for SSP245 scenario, illustrating projected frequency of near-normal to extremely dry conditions under moderate emission pathway.

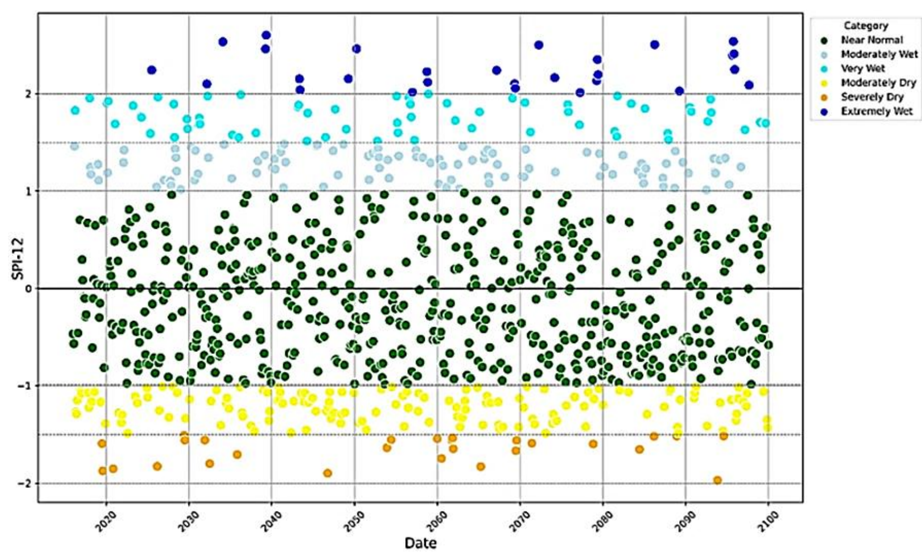

Figure 10: Distribution of drought categories based on SPI classification for SSP585 scenario, illustrating projected frequency of near-normal to extremely dry conditions under high emission pathway.

Drought Indicators

As observed from Figure 11, the maximum drought duration for observed data was 5 months with drought severity being 8. Droughts of various durations and severity level frequently occurred throughout study period. Drought peaks are observed throughout the study period. The frequency of extremely dry < severely dry < moderately dry.

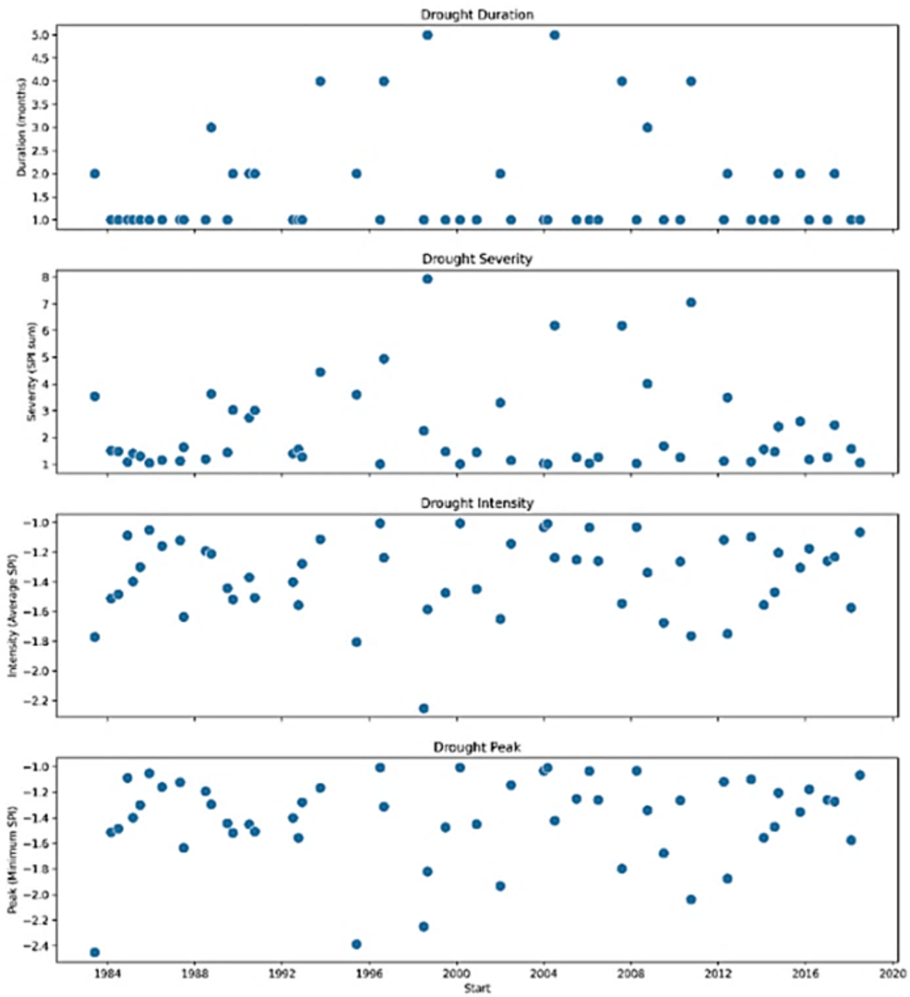

Figure 11: Drought characteristics (duration, severity, and intensity) derived from observed SPI-12 data, illustrating historical variability and temporal behavior of drought events in the study area.

As shown in Figure 12, the maximum drought duration under SSP245 was 5 months with a severity of 10. Droughts of varying durations and severities occurred frequently throughout the study period, with severely dry peaks persisting until 2100. The frequency pattern followed the same trend observed in other datasets, with moderately dry events being most common, followed by severely dry and then extremely dry events.

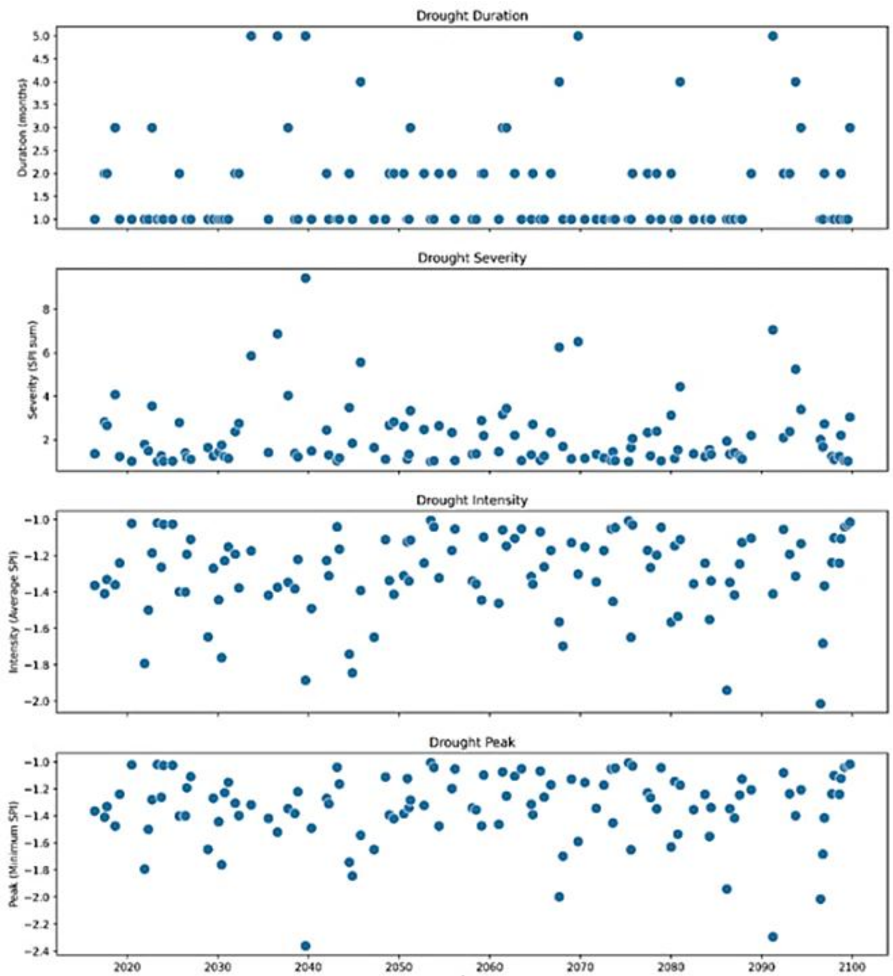

Figure 12: Projected drought characteristics (duration, severity, and intensity) under SSP245 scenario, showing moderate climate change impacts and variability in future drought behavior.

As shown in Figure 13, the maximum drought duration for SSP585 was 4 months with drought severity being 6. Droughts of various durations and severity level frequently occurred throughout study period. A similar frequency pattern was observed for droughts of varying durations and severities.

The figure illustrates a clear intensification of drought characteristics under the SSP5-8.5 scenario. Both duration and severity show an increasing trend, indicating more prolonged and severe drought events in the future. This reflects the stronger climate forcing associated with high-emission pathways, leading to greater variability and higher drought intensity compared to historical conditions.

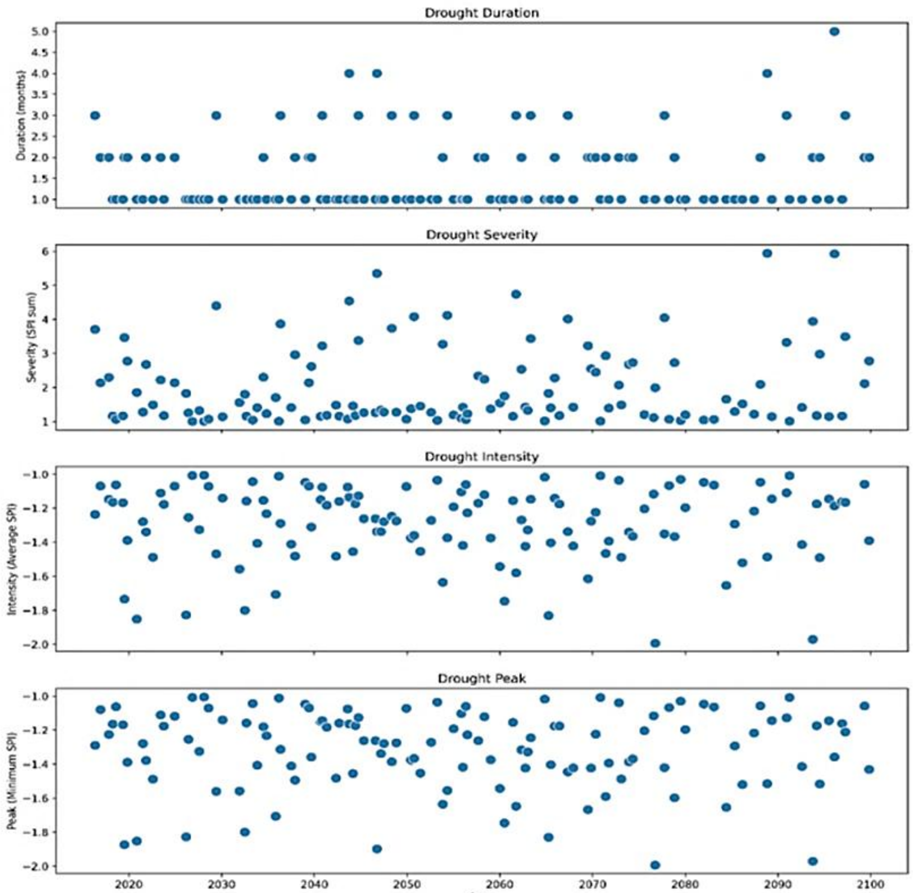

Figure 13: Projected drought characteristics (duration, severity, and intensity) under SSP585 scenario, indicating stronger climate forcing and increased variability and intensity of future drought events.

As obvious from Figure 14, the frequency of SSP585, SSP245 and observed is approximately same. This shows that the drought condition will remain consistent in the future.

Heat Waves

Climate extremes lead to heat waves which are getting more powerful and common in many parts of the world during summer. They not only result in death of living organisms but also modify the rates of evapotranspiration and the amount of soil moisture thus resulting in crop failure. The high temperatures are expected to raise occurrence of heat waves in the future. The timeframe of heat waves is critical to their harmful effects because it may interfere with water cycle by increasing the speed of convection, evapotranspiration, condensation, and precipitation.

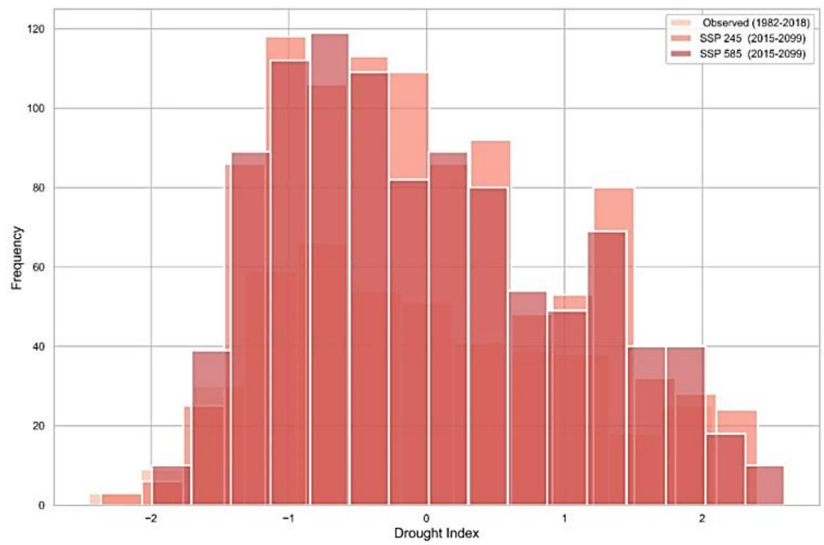

Figure 14: Comparison of drought frequency across observed data and SSP scenarios, indicating similar patterns of drought occurrence under current and future conditions.

In this research, heat waves for consecutive 5, 7, and 10 days were computed for observed and SSPs scenarios. Heat waves were categorized into two main classes namely moderate and severe based on temperature maximum threshold value of 40°C and 45°C respectively. It is important to note that the observed record is free from heat waves as shown in Figures 15, 16, 17, 24, 25, and 26. Moreover, Figures 18, 19, 20, 21, 22, 23, 27, 28, 29, 30, 31, and 32 show the frequency of 5-day heatwaves is greater than that of 7-day heatwaves, which is in turn greater than that of 10-day heatwaves. It is worth notable that the frequency of heat waves for SSP scenarios is greater than observed data. Moreover, the frequency of severe heatwaves is lower than that of moderate heatwaves. These findings suggest that residents of the Quetta District will face more frequent heat waves in the future, primarily due to rising mean temperatures and reduced soil moisture from prolonged dry periods. This could increase heat-related health risks, strain water supply systems, and raise irrigation demands in an already water-limited environment.

Figures 15, 16, 17 confirm that no moderate heatwave events occurred in the observed record (1982–2018) for any duration threshold (5, 7, or 10 consecutive days). This absence reflects Quetta Valley's high-altitude, temperate-arid climate, where maximum temperatures historically remained below the 40 °C threshold despite regional warming trends. Likewise, Figure 18 shows the highest frequency among all durations, with events concentrated in mid-century (2040–2060) and late-century (2080–2100). In addition, Figure 19 shows that there is a lower frequency than 5-day events, with similar temporal clustering. In Figure 20, there is a rarest moderate event, indicating that prolonged heatwaves remain uncommon even under moderate warming. Similarly, Figures 21 and 22 show substantially higher frequencies than SSP245, with events spanning the entire projection period (2020–2100). Peak occurrences shift toward late-century as radiative forcing intensifies. Additionally, Figure 23 illustrates the duration hierarchy clearly—5-day > 7-day > 10-day—confirming that shorter heatwaves dominate future projections. The visual comparison underscores that SSP585 projects roughly 2–3× more events than SSP245 for equivalent durations.

In Figures 24, 25, and 26, no severe heatwave events were detected in observed data across all durations. The 45 °C threshold was never breached, indicating that extreme heat stress of this magnitude was historically absent in Quetta Valley. On the other hand, Figure 27 shows sparse events, primarily late-century, suggesting that 45 °C thresholds are occasionally exceeded only under sustained warming. Figures 28 and 29 show extremely rare or absent, indicating that multi-day severe heat stress is unlikely under moderate emissions. Also, Figure 30 shows a clear increase in severe events, with clusters in 2050–2070 and 2080–2100. The frequency, while lower than moderate heatwaves, represents a qualitative shift from historical absence. Finally, Figures 31 and 32 present a rare particularly late-century. These prolonged severe events pose critical risks to human health, agriculture, and infrastructure given Quetta's limited adaptive capacity.

To counter the predicted rise in heat waves there should be strong mechanisms on how to achieve a stable supply of water. The policy makers should concentrate on more water conservation, efficiency of the current water supply systems, and development of superior water technologies like recycling of waste water. Another way of ensuring water resources is by implementing effective irrigation systems, encouraging the use of drought resistant crops and establishment of infrastructure to collect rainwater. Also, developing policies that promote the sustainable use of water and minimizing the losses in the distribution systems will be crucial in ensuring the sustainability of water during the extreme heat periods.

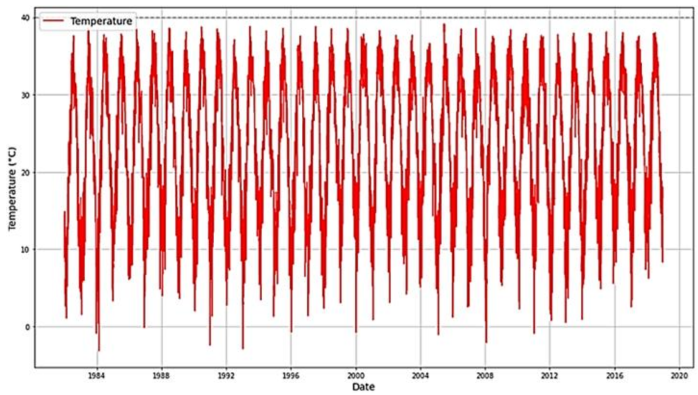

Figure 15: Moderate heatwave events (≥40 °C) for 5-day durations in observed data, showing absence of heatwave events under defined thresholds.

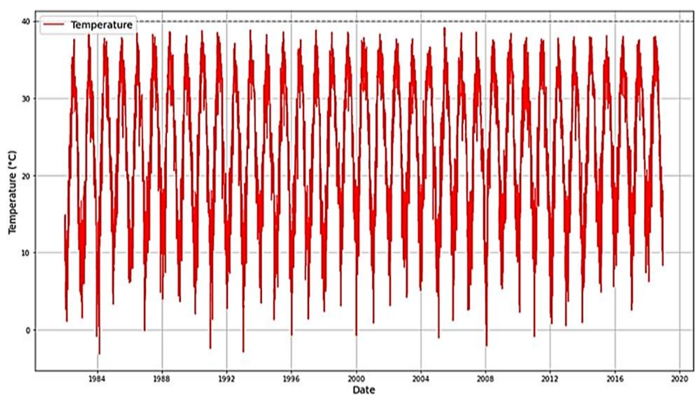

Figure 16: Moderate heatwave events (≥40 °C) for 7-day durations in observed data, showing absence of heatwave events under defined thresholds.

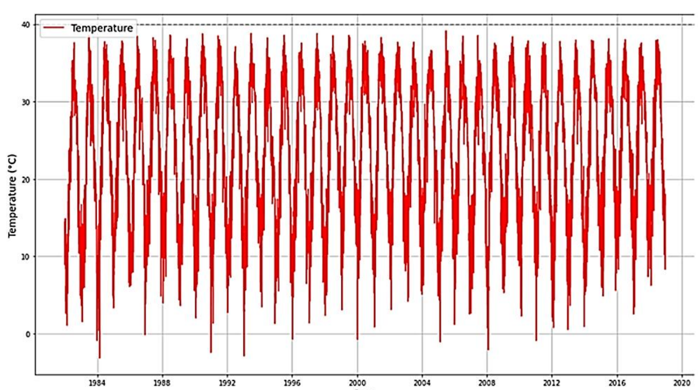

Figure 17: Moderate heatwave events (≥40 °C) for 10-day durations in observed data, showing absence of heatwave events under defined thresholds.

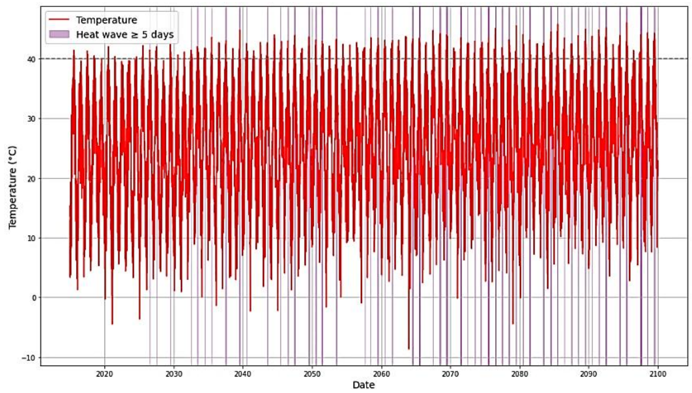

Figure 18: Projected moderate heatwave events (≥40 °C) for 5-day duration under SSP245 scenario.

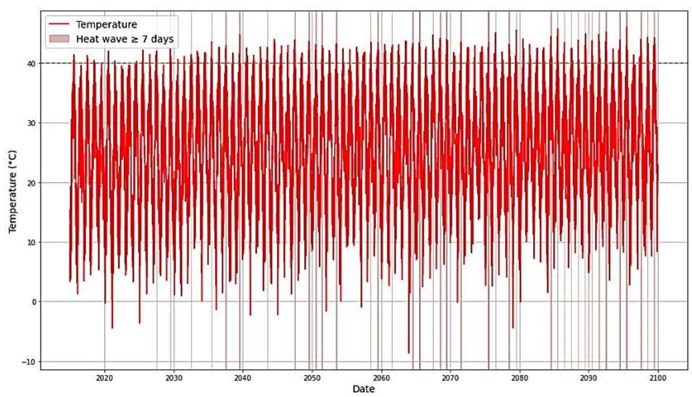

Figure 19: Projected moderate heatwave events (≥40 °C) for 7-day duration under SSP245 scenario.

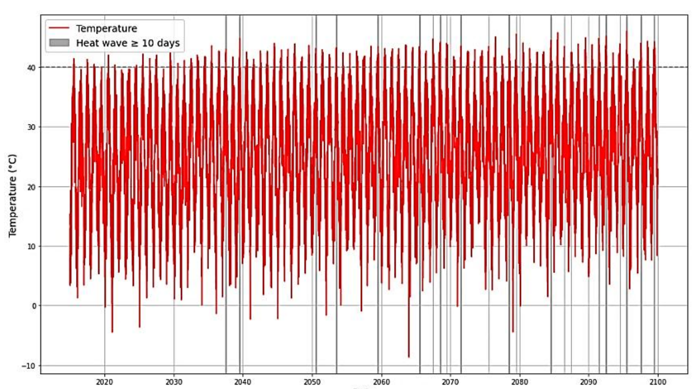

Figure 20: Projected moderate heatwave events (≥40 °C) for 10-day duration under SSP245 scenario.

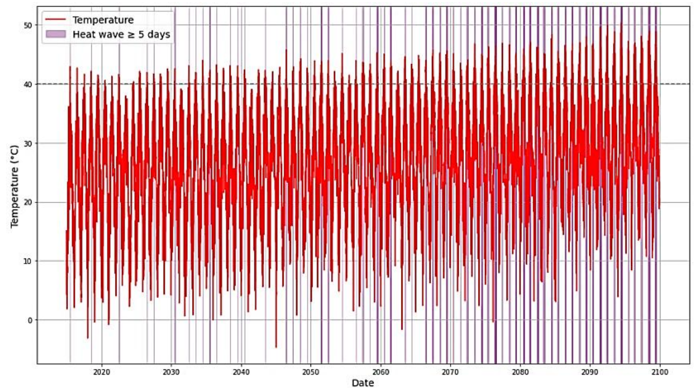

Figure 21: Projected moderate heatwave events (≥40 °C) for 5-day duration under SSP585 scenario.

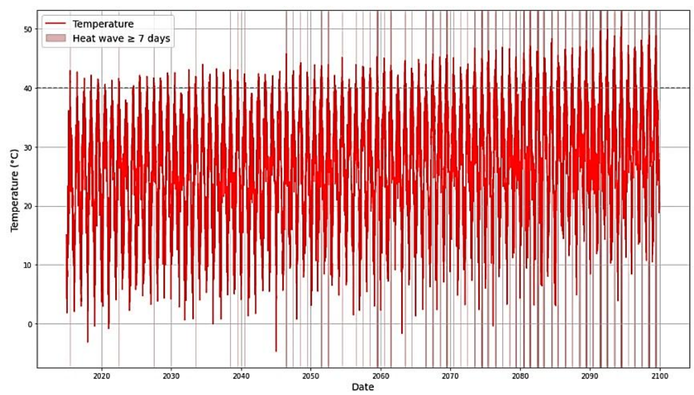

Figure 22: Projected moderate heatwave events (≥40 °C) for 7-day duration under SSP585 scenario.

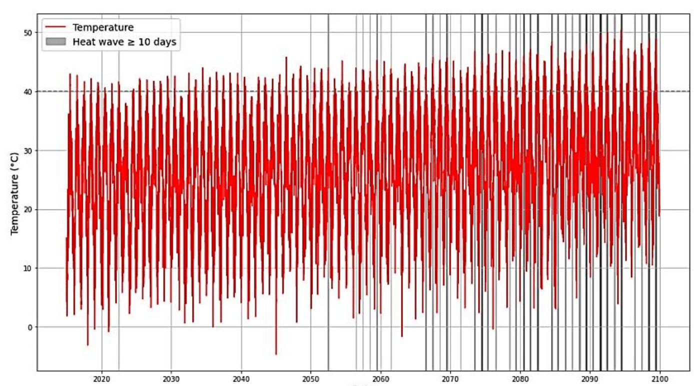

Figure 23: Projected moderate heatwave events (≥40 °C) for 5-, 7-, and 10-day durations under SSP585 scenario.

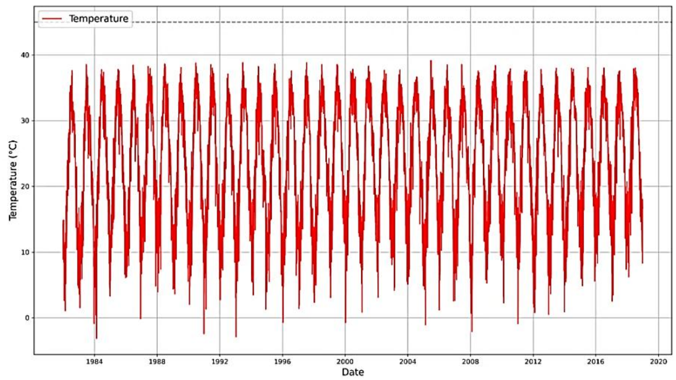

Figure 24: Severe heatwave events (≥45 °C) for 5-day duration in observed data, showing absence under defined thresholds.

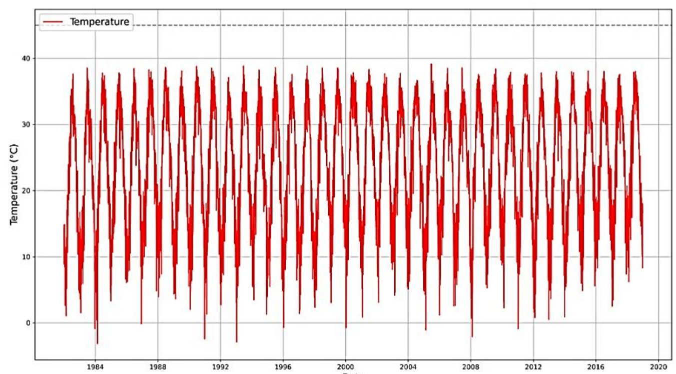

Figure 25: Severe heatwave events (≥45 °C) for 7-day duration in observed data, showing absence under defined thresholds.

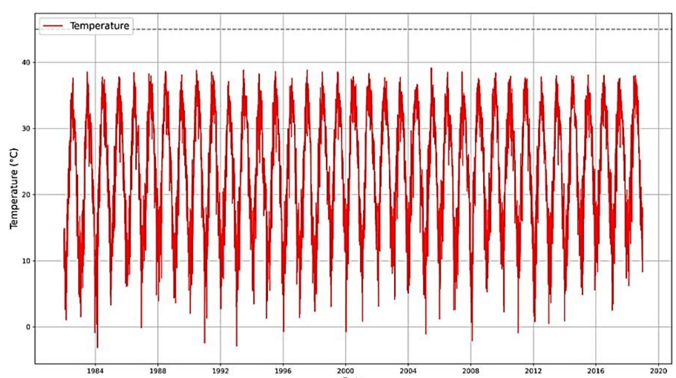

Figure 26: Severe heatwave events (≥45 °C) for 10-day duration in observed data, showing absence under defined thresholds.

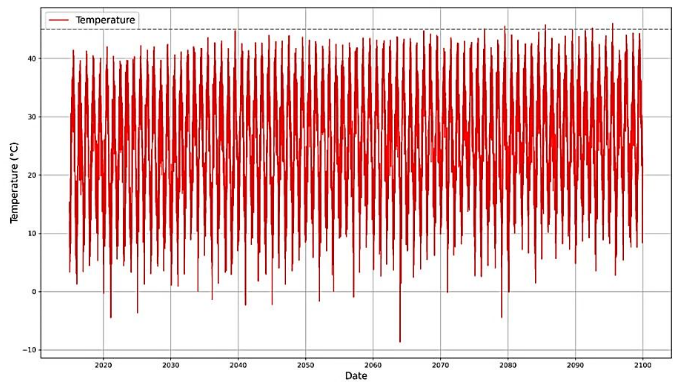

Figure 27: Projected severe heatwave events (≥45 °C) for 5-day duration under SSP245 scenario.

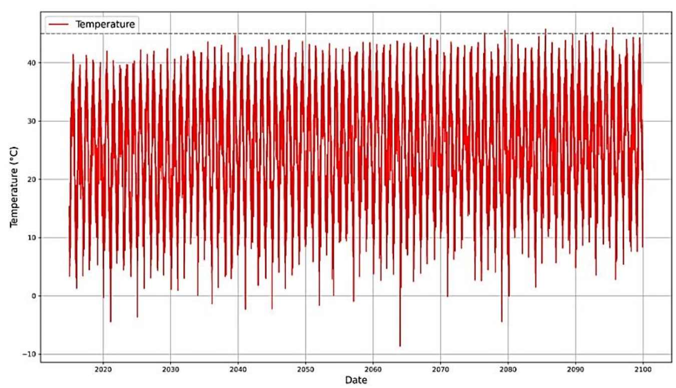

Figure 28: Projected severe heatwave events (≥45 °C) for 7-day duration under SSP245 scenario.

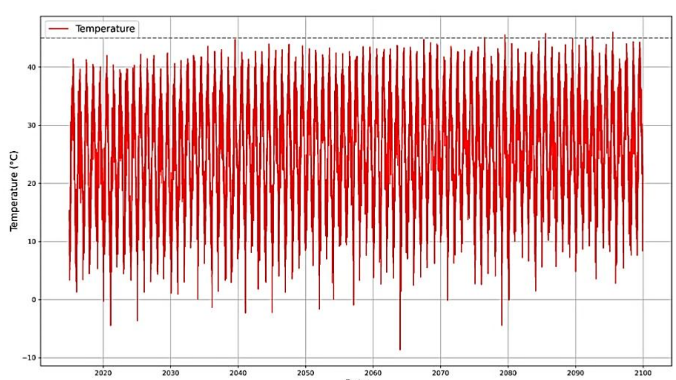

Figure 29: Projected severe heatwave events (≥45 °C) for 10-day duration under SSP245 scenario.

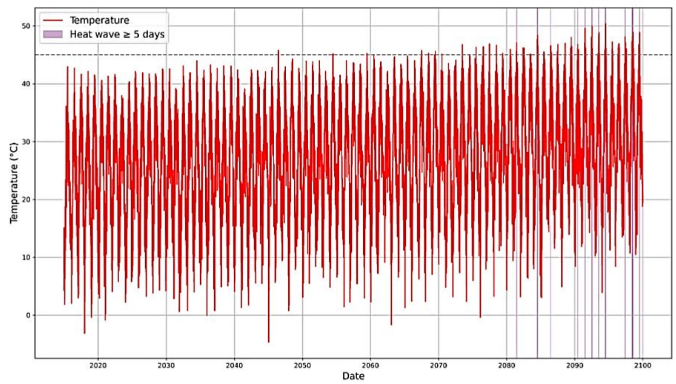

Figure 30: Projected severe heatwave events (≥45 °C) for 5-day duration under SSP585 scenario.

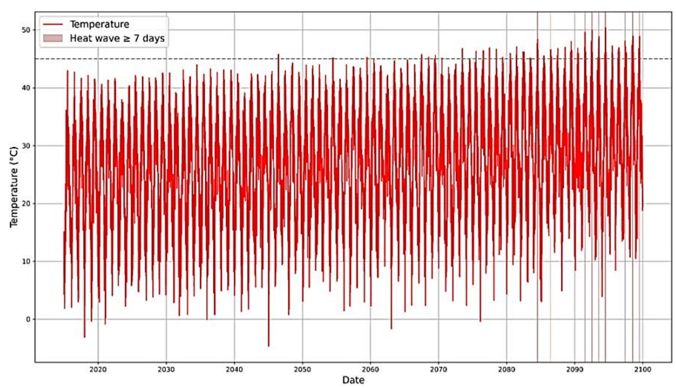

Figure 31: Projected severe heatwave events (≥45 °C) for 7-day duration under SSP585 scenario.

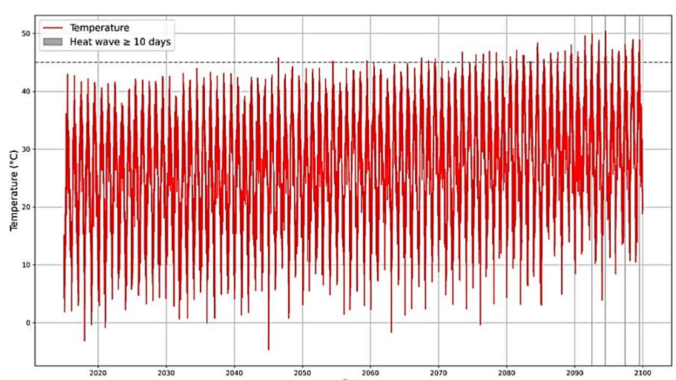

Figure 32: Projected severe heatwave events (≥45 °C) for 10-day duration under SSP585 scenario.

Discussion

The findings of this research indicate a slight warming trend and a minor tendency toward drier conditions in Quetta Valley, rather than a statistically significant drying trend. The SPI-12 analysis revealed that the moderate to severe drying spells occurred intermittently in the historical record. while climate projections under SSP245 and SSP585 suggest a continuation of this pattern into the future, though with small magnitude and non-significant trends. Such results are homogenous with other climatic trends observed in Balochistan. In particular, the study by (Ashraf et al., 2022) have discovered a statistically significant downward trend in the amount of precipitation in Quetta (p-value 0.039), and periods of extreme droughts were recorded in 1996, 2001, 2002, 2004, 2009, and 2014. Likewise, a research examining the recurrence of droughts in Balochistan in 1986, to 2021 using the Reconnaissance Drought Index (RDI) and standardized precipitation and evapotranspiration (SPEI) found severe drought events in 1986, 1988, 1998,2000-2002, 2004, 2006, 2010, 2018-2019 and 2021 (Rafiq et al., 2024). The consistency across these studies highlights the persistent challenge of water scarcity in Quetta, driven by declining precipitation and rising temperatures.

In addition to rising drought risk, climate models project a considerable increase in the frequency and magnitude of extreme heat events in Quetta, a region formerly unused to prolonged heatwaves. By the mid to late 21st century, mild heatwaves lasting 5 to 10 days with maximum temperatures above 40 °C are projected to occur. Although rare, temperatures over 45 °C can have significant implications on human health, agriculture, and infrastructure.

Observed temperature trends further support these projections. According to study (Durrani et al., 2021), the steep rise of 1.9 warm days per 10 years and 5.3 tropical nights per decade with an increase in the daily maximum temperatures was observed with the rate of 0.28 o C per decade in Quetta city. On a larger scale, the IPCC Sixth Assessment Report (AR6) predicts that the occurrences of heatwaves in South and Central Asia will increase in frequency, raising the threats of heat stress, agricultural losses, and exposures to an urban environment (Change, 2022). In a similar vein, it was pointed out by the United Nations Environment Program (UNEP, 2021) that water-stressed areas, including Balochistan, will be subjected to a higher rate of increases in temperature, which will ultimately cause an increase in evapotranspiration, droughts, and irrigation needs in said regions (Programme, 2022).

The combine effects of recurring droughts and potential risks of heatwaves have indicated acute social-economic and environmental obstacles in the Quetta Valley. It has already caused the loss of much agricultural produce, death of livestock and socio-economic impacts such as unemployment and migration due to droughts (Ashraf et al., 2021). Compounding of increase in temperatures causes additional problems through more decrease of soil moisture availability and the increase in evapotranspiration. The forecast of more rising moderate heatwaves poses a dire challenge to the security of the humans, especially those who are already vulnerable like outdoor workers, children and the aged, making it even worse through lack of cooling places and electricity-related infrastructure (Rasool et al., 2024).

To address the escalating risks of drought and heatwaves in Quetta Valley, urgent adaptation strategies are essential. Key measures include the implementation of groundwater management policies to prevent over-extraction and secure long-term water sustainability, alongside the promotion of drought- and heat-tolerant crop varieties and optimized irrigation techniques. Establishing early warning systems for extreme heat and drought events can enhance preparedness, while urban planning interventions, such as creating green spaces and cooling centers can reduce heat exposure in urban populations. Additionally, capacity building and public awareness programs are critical to reducing the vulnerability of at-risk communities and enhancing local adaptive capacity.

However, this study has several limitations that warrant caution in interpreting the results. The use of linear scaling for bias correction may underrepresent extreme precipitation and temperature events, introducing uncertainty into SPI and heatwave projections. Observational data in Quetta are limited, and while high-resolution satellite data were validated using Random Forest-based model selection, some biases may persist. The analysis focuses on SPI-12 for long-term drought assessment, omitting short-term indices (SPI-3, SPI-6) that could better capture agricultural drought impacts. Moreover, heatwave thresholds were fixed at 40°C and 45°C, without accounting for regional acclimatization or urban heat island effects, potentially affecting local risk estimates. Future studies should integrate socio-economic data, short-term drought indices, and dynamic heatwave thresholds to refine vulnerability and resilience assessments in the region.

Conclusion

Climate change is a pressing issue which has profound impacts on various sectors. Climate change is causing human deaths, as well as social, environmental, and economic consequences. This study illustrates Quetta Valley's increasing vulnerability to climatic extremes, particularly droughts and heatwaves. The SPI-12 values for observed data vary from 0 to -2.5, with the majority of readings falling below -2, suggesting very dry, moderately dry, or near-normal circumstances. Similar trends are visible in future estimates. For SSP245 and SSP585, the majority of drought values are less than -2, indicating severe, moderate, or near-normal drought. The observed record is free from heat waves while SSP scenarios predict heat waves in the future. The frequency of severe heat waves < moderate heat waves. The frequency of 5 days heat waves > 7 days heat waves > 10 days heat waves. To address these challenges, urgent adaptation measures are required. Recommended strategies include sustainable groundwater management, rainwater harvesting, recycling wastewater, promotion of drought- and heat-tolerant crops, optimized irrigation, and urban planning interventions such as green spaces and cooling centers. Early warning systems, community awareness programs, and health preparedness can further reduce vulnerability. Limitations of this study include the use of linear bias correction (which may underrepresent extremes), the focus on SPI-12 without short-term drought indices, and fixed heatwave thresholds; future research should integrate socio-economic data, SPI-3/6 indices, and dynamic temperature thresholds to refine risk assessments.

Acknowledgments: We thank the PMD for providing historical meteorological data and the GPCC, NASA POWER, NOAA CPC, and CHIRPS for additional datasets. This research was supported by the University of Engineering and Technology Peshawar.

Authors contribution: All authors contributed significantly: Fayaz Ahmad Khan designed the study, Muhammad Ahmad and Syed Furqan Ahmad collected and analyzed data, Syed Furqan Ahmad wrote the manuscript, and Syed Furqan Ahmad, Atif khan, Muhammad Qasim, performed simulations. All authors approved the final manuscript.

Declaration: This manuscript has not been previously published and is not under consideration by any other journal.

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