Spatio-Temporal Analysis of Meteorological Drought in Lahore (1995–2024)

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Evaluating urban meteorology is essential for efficient water resource management, especially considering climate change and an increase in Urban population. It helps to understand the severity and scope of drought conditions, which enables improved planning and execution of drought response measures. This research paper examines long-term patterns of rainfall variability and drought situations in Lahore, spanning a period of 30 years (1995- 2024). Monthly rainfall data taken from the UCSB-CHG/CHIRPS dataset, along with potential evapotranspiration (PET) information from the TERRACLIMATE dataset, are being analyzed using the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). The whole dataset is processed by Google Earth Engine (GEE), with Lahore's administrative boundaries used to define the Area of Interest (AOI). The analysis recognizes significant annual and spatial variability, with the mean annual Precipitation recorded at 65.35mm. Extreme years included 2021, with 184.77 mm, and 2019, in this year precipitation was only recorded at 13.06 mm, which highlights growing climatic inconsistencies. SPI values dipped as low as -2.6 in 2015 in the southern part of Lahore, indicating severe drought conditions, while northern Lahore experienced values as high as 1.7, denoting extreme wetness. SPEI values exhibited a similar pattern, with the southern region recorded -2.3 in 2024, reflecting ongoing moisture stress, contrasted by northern Lahore reaching 1.2 to 2, a marked improvement in hydrological balance. These results show that Lahore is becoming more and more vulnerable to both drought and flooding because of urban growth and changes in the monsoon. According to the findings, localized, data-driven climate adaptation policies that prioritize drought resistance, water conservation, and efficient urban planning are essential.

Keywords: Urban Resilience, Meteorological Drought, SPI & SPEI, Precipitation Variability

Introduction:

The ongoing phenomenon of global warming, along with increasingly frequent and severe weather and climatic extremes, is mostly attributed to the human-induced effects of greenhouse gases, mainly due to the overconsumption of fossil fuels. According to IPCC 2021, there are significant inequalities in precipitation patterns. Various methodologies and indices are utilized to more accurately analyze variations in precipitation. The Palmer Drought Severity Index (PDSI), the Standardized Precipitation Index (SPI), and the Standardized Precipitation Evapotranspiration Index (SPEI) are included in typical indicators for assessing meteorological and hydrological drought [1]. SPEI is often used to evaluate the accessibility of water resources. SPEI considers both potential evapotranspiration (PET) and precipitation, making it a more accurate measure than SPI. Drought is a common climatic extreme that can lead to significant costs [2]. An extended absence of rainfall provokes drought, which can last for months or even years. Due to increasing temperatures and climate change, droughts are more likely to happen with greater frequency, intensity, and duration [3]. The Standardized Precipitation Index (SPI) is a commonly utilized drought indicator created by [4] to estimate precipitation shortages over different timescales, such as from 1 to 72 months, facilitating the evaluation of both short-term and long-term drought situations [4]. SPI makes it more convenient to analyze drought and wet conditions across various climates by converting precipitation information into a standardized normal distribution, making it a useful tool for meteorological, agricultural, and hydrological purposes. (Svoboda et al., 2022).

Literature Review:

Urbanization has become a ubiquitous phenomenon in recent decades, and it is widely regarded as the most distinguishing element of climate change. The average size of cities has doubled in comparison to the urban population increase, resulting in a fast shift of global land cover and land-use patterns. Although urban areas account for only 2% of the world's surface, they are responsible for 70% of climate change. [5]

Climate change will drastically affect the pattern and distribution of global water supplies, and more than 2 billion urban dwellers are expected by 2030. This tendency will keep increasing the severity of urban drought, putting cities under severe water stress and drought hazards. [6] South Asia has recently faced significant drought due to changes in temperature and vegetation, impacting water supplies, energy generation, and crop yields.[7]. The summer monsoon in South Asia, which accounts for 78% of annual precipitation and serves as a crucial source of water for billions, is primarily the cause of meteorological droughts in the area. [8]. SPEI is frequently used at both global and regional levels to predict and observe drought, as it is responsible for changes in precipitation over time. [9][10]. [11]. In addition to learning more about drought conditions in light of climate change, the SPEI was used to analyze rainfall and PET.

It is projected that rising temperatures in South Asia will cause PET values to rise. [12]. Drought conditions can result from little rainfall, and plant growth can be impacted by heat stress caused by high temperatures. [13]. [14] Reports indicate that freshwater reserves are depleting throughout around two-thirds of the planet's surface. This information must be included in drought evaluations so that appropriate policies and actions may be developed. [15][10]. Recent widespread drought events in South Asia have been primarily brought on by changes in rainfall patterns, which have a substantial impact on local water supplies, energy generation, and agricultural yield. [16]. Since the Standardized Precipitation Index (SPI) is only dependent on precipitation data, it is a widely used tool for detecting drought and is especially useful in regions where rainfall variability has a major impact on drought occurrences. [17]. The SPI's adaptability over several timeframes, short-term (1-3 months) for agricultural droughts and long-term (up to 24 months) for hydrological droughts, enables complete evaluations of drought conditions. [18][19]. In drought-prone locations, such as South Asia, the Standardized Precipitation Index (SPI) has proved critical for identifying and quantifying the severity of drought. For instance, [20] demonstrated the SPI's ability to detect both mild and severe meteorological droughts in several climatic zones. South Asian droughts are profoundly tied to variations in monsoon rainfall, which are increasingly affected by climate change-induced alterations in atmospheric patterns. [21]. Reductions in precipitation have not only diminished groundwater recharge but have also greatly decreased levels in reservoirs and rivers, creating severe threats to water security [22]. The goal of this research is to use SPI and SPEI indices to examine long-term changes in drought severity and precipitation patterns in Lahore from 1995 to 2024, identify spatial differences in rainfall and drought intensity with a focus on the north-south gradient. The study's distinctive contribution is the finding of a north-south gradient in drought intensity across urban zones, as well as the integration of hydrometeorological data into practical lessons for climate-resilient urban planning and sustainable water management.

Materials and Methods:

Standardized Precipitation Evapotranspiration Index:

Lahore is the administrative hub of Punjab, Pakistan. It is located at latitudes 31.5497° N and 74.3436° E. With hot summers, moderate winters, and monsoon precipitation from July to September, the city has a subtropical semi-arid climate. Lahore's water resources are under a lot of strain due to the city's fast urbanization and population increase, which calls for better drought situation evaluations.

The source of the rainfall data was www.weatherandclimate.eu. Long-term precipitation trends were examined by calculating annual averages and utilizing graphs to visually represent. The research used daily precipitation information sourced from UCSB-CHG/CHIRPS/DAILY. This provides global daily precipitation estimates with a spatial resolution of 0.05°. Additionally, it incorporated monthly global Potential Evapotranspiration (PET) data from IDAHO_EPSCOR/TERRACLIMATE, calculated using the Penman-Monteith equation and featuring a spatial resolution of roughly 4 km.

The whole data analysis was conducted using Google Earth Engine (GEE), Google Earth Engine is a cloud-based platform designed for extensive geospatial analysis of climate data. The methodology involved several stages: Initially, the Area of Interest (AOI) was identified by utilizing the Lahore administrative boundaries from the USDOS/LSIB_SIMPLE/2017 dataset to differentiate it from the broader Punjab region and facilitate a more concentrated examination. Following that, daily precipitation measurements were compiled to produce yearly totals for the selected study years (1995, 2005, 2015, and 2024), and monthly PET data were similarly combined to create annual PET values for those same years.

The yearly water balance was then calculated using the difference between total annual precipitation and PET [23].

Water Balance: P – PET:

Where;

"P" is the total annual precipitation

"PET" is the annual potential evapotranspiration

The Standardized Precipitation-Evapotranspiration Index for 12 months (SPEI-12) was then calculated by standardizing the annual water balance using the mean and standard deviation over four years to generate z-scores that successfully measure variations from the mean and indicate wetness or dryness conditions [24].

Standardized Precipitation-Evapotranspiration Index for a 12-month scale, $SPEI_{12}$, is calculated by standardizing the water balance:

$$\mathbf{SPEI} = \frac{WB-\mu}{\sigma}$$

Where;

"WB" annual water balance

"μ" means water balance over a reference period

"σ" is the standard deviation of the water balance

Finally, the resulting SPEI-12 raster layers were visualized using color-coded classification based on standardized intervals, and these classified raster datasets were exported in GeoTIFF format with a 250-meter spatial resolution, ensuring precise spatial representation for subsequent high-quality spatial analysis.

Table 1. Wet and dry classification scales of standardized

Grade	Classification	SPEI Values
1	Extremely wet	≥ 2.0
2	Severely wet	1.5 ≤ SPEI < 2.0
3	Moderate wet	1.0 ≤ SPEI < 1.5
4	Normal	-0.99 ≤ SPEI ≤ 0.99
5	Moderate dry	-1.49 ≤ SPEI < -1.0
6	Severely dry	-1.99 ≤ SPEI < -1.5
7	Extremely dry	≤ -2.0

Source: [25], [24].

Standardized Precipitation Index (SPI):

This analysis relied on daily precipitation data from the UCSB-CHG/CHIRPS/DAILY dataset, which provides global daily precipitation estimates at a spatial resolution of 0.05. All data processing was performed using Google Earth Engine (GEE)**,** a cloud-based geospatial analysis platform designed to handle large-scale climatic and environmental datasets. First, the Area of Interest (AOI) was determined using the USDOS/LSIB_SIMPLE/2017 dataset's Lahore administrative boundary to focus the analysis specifically on Lahore, effectively distinguishing it from the larger Punjab region. Next, daily precipitation data were averaged to yearly totals for the chosen study years (1995, 2005, 2015, and 2024).

The Standardized Precipitation Index (SPI) was then calculated by standardizing the annual precipitation using the mean and standard deviation of precipitation values for the year to produce z-scores, which represent how much the annual precipitation deviates from the mean [4].

The formula for SPI is:

$$\text{SPI} = \frac{P-\mu}{\sigma}$$

Where:

P is the total annual precipitation,

μ is the mean precipitation over the reference period,

σ is the standard deviation of the precipitation.

In this demonstration, the reference period was approximated using precipitation data from the years 1995-2024, acknowledging that a longer climatological baseline (e.g., 30+ years) is generally preferred for operational drought monitoring. Finally, the resulting SPI raster layer was visualized in GEE using color-coded classification based on standardized intervals, with colors representing categories from extreme dry to extreme wet conditions. The SPI raster was then exported as a GeoTIFF file with a spatial resolution of **250 meters**, ensuring precise spatial representation suitable for high-quality mapping and subsequent analysis. Table 2 presents the drought classification based on SPI, modified after [4].

Table 2. Drought class classification of SPI (modified from [4])

Code	Drought Classes	SPI Values
1	Non-Drought	SPI ≥ 0
2	Near Normal	-1 < SPI < 0
3	Moderate	1.5 < SPI ≤ -1
4	Extreme/Severe	SPI ≤ -1.5

Results and Discussion:

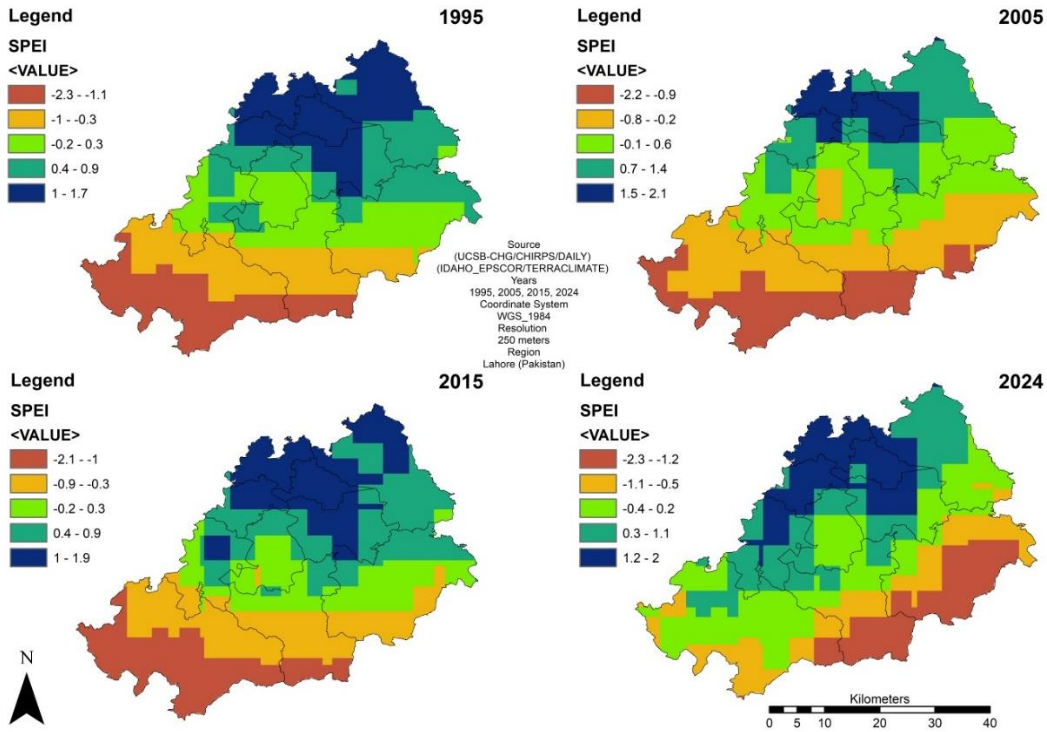

Figure 1. Annual Potential Evapotranspiration of Lahore for the years 1995, 2005, 2015, and 2024.

As per Figure 1, in 1995, Lahore had near-normal climatic conditions, with the bulk of SPEI-12 values ranging from -0.3 to 0.3. This range indicated that moisture availability was balanced, and there were no big drought or wetness occurrences across much of the city. However, severe to extreme drought conditions were seen on the southern and southwestern outskirts of Lahore, with SPEI-12 values as low as -2.3. These regions experienced large moisture shortages, which were most likely caused by low precipitation or high evapotranspiration rates. In contrast, northern Lahore showed isolated pockets of moderate wetness, indicating microclimatic variability and local effects such as unequal land use and topography. These findings show that, whereas central Lahore remained constant in 1995, geographical differences in moisture availability were already present in the urban environment.

By 2005, areas in northern and central Lahore had started to bounce back from the earlier drought. SPEI-12 scores in these regions ranged from 0.4 to 0.9, signifying a gradual shift towards moderate wetness and an improved moisture equilibrium. This favorable trend indicates either an increase in rainfall or a reduction in PET, which may be attributed to changing weather patterns or enhanced water management practices in certain areas. However, the southern regions continued to experience mild drought, with SPEI-12 values between -1.2 and -0.6. These spatial differences indicate that the recovery from climatic changes was not consistent across the city, with certain regions remaining vulnerable to moisture shortages. Factors related to urban environments, like the heat island effect and groundwater depletion, could have intensified these inequalities, highlighting the necessity for climate resilience strategies tailored to specific locations.

The variability of meteorological conditions across Lahore became greater in 2015. The northern part of Lahore experienced a significant increase in wetness, with SPEI-12 values climbing to 1.1. This pattern indicates that the northern areas received either increased rainfall or reduced evapotranspiration, potentially as a result of improved land cover or favorable climatic conditions.

In contrast, the southern region of Lahore has been facing moderate to severe drought levels, as shown by SPEI-12 readings between -2.1 and -1.0. This ongoing moisture deficiency highlights the continuing challenges in these areas, even with the overall climatic enhancements observed in the north. The various trends within Lahore's administrative limits demonstrate the impact of rapid urban growth and evolving land-use practices on local microclimates, suggesting that city-wide climate adaptation strategies need to consider these intra-urban differences. In 2024, northern Lahore experienced the most pronounced moisture conditions, with SPEI-12 values between 1.2 and 2. These positive moisture anomalies suggest considerable rises in precipitation or reductions in PET, likely resulting from beneficial meteorological changes or effective water management practices.

Central Lahore experienced near-normal to moderate rainy weather, with SPEI-12 values ranging from -0.3 to 0.9, indicating a reasonably balanced hydrological environment. In contrast, the southern zones remained under moderate to severe drought conditions, with SPEI-12 values ranging from -2.3 to -1.2, indicating a lack of significant recovery in these areas.

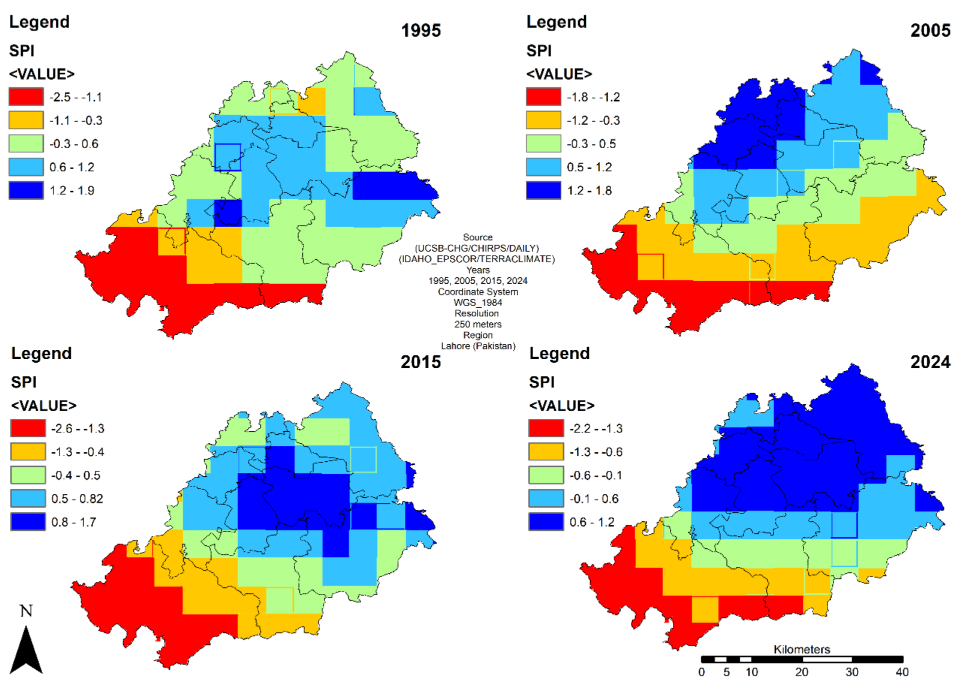

Figure 2. Annual Standardized Precipitation Index of Lahore for the years 1995, 2005, 2015, and 2024.

As per Figure 2, in 1995, Lahore exhibited near-normal climatic conditions, with the bulk of SPI-12 values ranging from -0.3 to 0.3. This range indicated balanced moisture availability across much of the city, with no pronounced drought or excess wetness. However, the southern and southwestern outskirts of Lahore experienced severe to extreme drought, where SPI-12 values fell as low as -2.5. These regions faced substantial moisture deficits, likely driven by low precipitation or high evapotranspiration rates. In contrast, northern Lahore showed localized areas of moderate wetness, indicating microclimatic variations driven by factors such as land use, topography, or urban design. Although central Lahore remained consistent, these spatial differences emphasized the initial occurrence of moisture variability within the urban area.

By 2005, northern and central Lahore exhibited signs of hydrological improvement following previous droughts. SPI-12 values in these areas varied from 0.5 to 1.2, indicating a movement towards moderate wetness and enhanced moisture balance. This favorable trend may be due to heightened rainfall or decreased PET, possibly associated with alterations in weather patterns or water management strategies. Still, the southern areas continued to show mild drought conditions, with SPI-12 values ranging from -1.8 to -0.5, highlighting ongoing moisture shortages. These geographical differences demonstrated that recovery was inconsistent throughout the city, with elements like urban heat islands and groundwater depletion probably intensifying local drought pressures and stressing the importance of specific adaptation strategies. In 2015, the variation in climatic conditions across Lahore became more evident. The northern part of Lahore experienced significant wetness, with SPI-12 values soaring to as high as 1.7, indicating either a notable increase in precipitation or a decrease in PET, potentially due to enhanced land cover or favorable climate patterns. In contrast, the southern region of Lahore continued to endure moderate to severe drought, with SPI-12 values ranging from -2.6 to -1.3, reflecting ongoing moisture stress. The results emphasized that while there have been general advancements in the northern areas, the southern regions continue to face ongoing water shortages, probably due to elements like urban growth, alterations in land use, and insufficient water management practices. This underscores the importance of targeted and fair climate adaptation strategies.

By 2024, northern Lahore reached the highest levels of positive moisture conditions, with SPI-12 values between 1.2 and 2, signifying notable precipitation surpluses or lower evapotranspiration rates. This change may be attributed to favorable meteorological conditions or improved water management practices. Central Lahore experienced near-normal to moderately wet conditions, as evidenced by SPI-12 values ranging from -0.3 to 0.9, indicating a balanced hydrological situation.

The southern regions continued to experience moderate to severe drought, with SPI-12 values ranging from -2.2 to -1.3, highlighting ongoing moisture shortages and a failure to achieve significant recovery. These trends underscore the uneven distribution of climatic conditions in Lahore and the urgent requirement for localized climate resilience strategies that consider intraurban differences and tackle the enduring vulnerabilities in the city's southern areas.

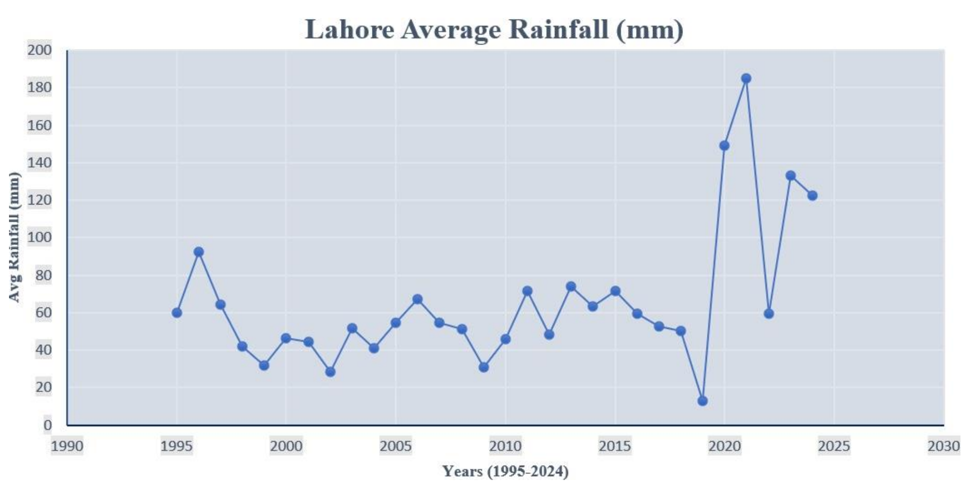

Figure 3: Mean annual rainfall, Lahore 1995-2024)

Figure 3 provides a visual representation of the annual average rainfall in Lahore from 1995 to 2024 is based on monthly precipitation data. This data depicts major variations annually, reflecting not only natural climatic variations but also potential human impacts. The annual average precipitation was measured to be 65.35 mm over the period of 30 years, which highlights that Lahore receives moderate rainfall. Even so, the city is facing hydrological insecurity due to its substantial variability, which makes it vulnerable to both hazards, droughts and floods, depending on the specific year. The lowest annual rainfall is measured to be just 13.06 mm, which occurred in 2019. This is alarming as this kind of arid year leads to water scarcity, which will not only affect agriculture but also reduce urban greenery and lead to bad air quality due to less natural dust suppression.

Conversely, the highest average precipitation was noted in 2021, with a peak of 184.77 mm, which can likely be attributed to a vigorous monsoon season or extreme weather phenomena, potentially influenced by broader climate change factors like increased moisture in the atmosphere and altered wind patterns.

The graph aids in illustrating the rising climatic unpredictability in Lahore. With increasing urban development and deforestation in nearby regions, the city may experience heightened impacts from climate extremes, including urban flooding, water stress, and degradation of ecosystems.

Discussion:

The spatial and temporal analysis from 1995 to 2024 supports the study's goal by finding a strong north-south gradient in drought intensity using SPI and SPEI indices. Northern Lahore is getting more rain, but southern Lahore is suffering from a protracted drought caused by urbanization and microclimatic changes. These findings support the goal of detecting spatial disparities while also emphasizing the importance of climate-resilient urban development and sustainable water management. These inequalities are not a coincidence as they have a strong connection with increasing urbanization, unplanned land use changes, and variations in microclimatic dynamics within the metropolitan landscape. These modifications have led to extended periods of drought and an increased risk of rapid urban floods, highlighting the dual characteristics of the climate extremes that Lahore is facing now. These results are backed by standardized drought indicators such as the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI). In 1995, Central Lahore faced fairly dry conditions, with SPI-12 levels ranging from -0.3 to 0.3, whereas the southern areas experienced extremely low SPI values of -2.5, signifying severe drought. By 2024, this gap had grown significantly. But the southern Lahore continued to suffer from extreme droughts, with SPI values ranging from -2.2 to -1.3; northern Lahore's SPI increased to about +2.0, signifying a surplus of moisture. This ongoing trend illustrates how urban inequality manifests in climate susceptibility as well, where some regions are advancing while others are still falling further behind.

We could draw a comparison with Mumbai, another significant South Asian metropolis with a coastline environment, to further our knowledge of this. According to Mishra S.(2016), Mumbai's rainfall variability has also led to recurrent drought episodes. According to their research, 74% of the years from 1994 to 2013 saw some kind of drought at Mumbai's Santacruz station. While Colaba reported -1.89 in 2000, the most severe was in July 2002, when SPI fell to -1.94. Interestingly, these droughts happened during the monsoon season, which is typically thought to lessen dryness but is increasingly characterized by unpredictable rainfall and strain on water infrastructure. [26]

Research from Afghanistan and Central Asia, where seasonal drought trends reveal similar climate-induced stressors, further emphasizes the issue's regional relevance. SPEI levels in the southwest decreased during Afghanistan's wheat-growing season as a result of rising temperatures and decreased rainfall. In the meantime, moderate SPEI advances were brought about by slight increases in rainfall in the northeast. A more miserable picture was portrayed during the rice and maize seasons, when 60% of the research region saw steady temperature increases, which led to a persistent fall in SPEI over numerous grid sites. Similarly, drought return periods (RPs) decreased, indicating an increase in the frequency of extreme droughts.

Studies like the one conducted in Pakistan by Ahmed et al. (2021) again linked drought intensification to rising temperatures, demonstrating a marked increase in drought severity throughout the Rabi and Kharif seasons, especially in desert and semi-arid zones. These patterns are reflected in Central Asia, where Uzbekistan and Turkmenistan were found to be most sensitive, and where the frequency of droughts exceeded 42.87%.[27]

Conclusion:

The spatial and temporal analysis of SPEI-12 and SPI for Lahore from 1995 to 2024 reveals a consistent moisture gradient from north to south, with northern regions showing wetter conditions while southern areas experience persistent drought. These findings highlight the significant influence of urbanization, changes in land use, and fluctuations in microclimates on the local water balance. The Rainfall Pattern of Lahore from 1995 to 2024 shows significant annual variation. This variability is pointing towards the increasing climate instability and showing the high risk of both droughts and floods. The findings emphasize the significance of implementing targeted and localized water management strategies to address intra-urban climate inequalities and enhance the overall climate resilience of Lahore city.

Recommendations:

To address the persistent drought conditions in Southern Lahore, targeted mitigation strategies such as rainwater harvesting, improved irrigation efficiency, and groundwater recharge projects must be implemented immediately. Green belt expansion, urban forestry, and the use of permeable surface materials, especially in drought-prone areas, to control evapotranspiration and stabilize local microclimates are all necessary to improve urban resilience. Additionally, modern climate indices like SPI and SPEI, in conjunction with high-resolution satellite imagery, can aid in the creation of early warning systems, allowing for more proactive and data-driven drought risk management in quickly expanding cities like Lahore.

Involving community members, urban planners, and policymakers in climate education and awareness campaigns is crucial to establishing long-term resilience against climate-induced water stress. At the institutional and household levels, this kind of involvement not only encourages shared accountability but also supports sustainable water management techniques. Furthermore, to guarantee ongoing climate monitoring and data-driven decision-making, cooperation between governmental organizations, academic institutions, and non-governmental groups should be strongly promoted.

Author's Contribution:

Fatima Nazir and Nimra Arshad led the conceptualization, methodology, and data analysis, conducted the overall analysis, and wrote the manuscript. Nausheen Mazhar supervised the research and provided resources, and Fatim Rani provided technical inputs for the research, edited, and reviewed the paper.

Availability of data and materials:

Data utilized in this research are available from the corresponding author upon reasonable request.

Declarations: This research paper has been presented orally at "Nexus of Climate Change and DRR: An Anticipatory Action", held at Baragali Summer Campus of the University of Peshawar, 1-3 August 2025.

Ethics approval and consent to participate:

The authors declare that they followed the ethics in scientific research.

Consent for Publication:

Not applicable

Competing Interests:

The authors declare no competing interests

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