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Assessment of Spring Distribution across Pakistan: Implications for Water Security

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ABSTRACT

Springs play a vital role in Pakistan's water security, particularly in remote regions where they serve as a lifeline for agriculture, livestock, and domestic needs. However, increased pressure on spring resources from climate change, population growth, deforestation, and land degradation has significantly declined their availability. Springs have been largely overlooked in both research and policy formulation in Pakistan. This study assesses the distribution and status of springs across Pakistan's main provinces and regions. Focusing on the springs data from the 2023 Survey of Pakistan, along with population data from the 2023 census and climatic data from the nearest stations of Pakistan Meteorological Department, this study maps the spatial distribution of springs and examines the influence of environmental parameters, such as rainfall, temperature, elevation, and slope on their existence. The findings highlight that 81% of the nation's springs are concentrated in Khyber Pakhtunkhwa (KP) and Baluchistan provinces, with substantial regional dependency on these resources. The Hindu Kush Himalaya (HKH) region of Pakistan host 5051 springs (28%) for the 21 million people in Pakistan. Approximately 114 million people live in 108 spring districts with an average of 26,252 persons per spring, while the average spring density is around three springs per hectare. Through province-level mapping, this study underscores the urgent need for sustainable policies to conserve springs and improve water security. This study emphasized on the need for sustainable water management policies and their urgent field implementation that prioritize spring conservation and adaptation to climate change impacts.

Keywords*: Springs, Climate Change, Water Security, Pakistan, Livelihoods*

1. Introduction

Springs are natural discharge points of groundwater [1] and are essential water sources, particularly in rural, hilly and mountainous regions of Pakistan. These springs, which emerge from underground aquifers, are critical for sustaining communities in high-altitude, remote and semi-arid areas, where alternative water sources are limited. Pakistan's diverse climate and topography, ranging from the arid plains of Sindh and Baluchistan to the mountainous regions of Khyber Pakhtunkhwa (KP), Gilgit-Baltistan (GB), and Azad Jammu and Kashmir (AJ&K), makes springs a crucial water resource, especially in areas with limited water availability. In KP, AJ&K, and GB, spring-fed gravity water channels built on contour lines, known as the Kuhl irrigation system, are vital for agriculture and domestic use, particularly where canal irrigation is impractical due to challenging terrain [2]. Springs are also important for sustaining agriculture, ecology, and livelihoods in these regions, playing a pivotal role in balancing the hydrological cycle and replenishing aquifers to ensure sustainable water availability.

The sustainability of springs has been largely threatened by climate change [3, 4], with its impacts particularly more evident in northern Pakistan. Key climate change factors, including unpredictable and extreme rainfall patterns, rising temperatures, land degradation, urbanization, and glacier retreat, have disrupted the recharge of aquifers that feed springs [5]. These trends also mirror global observations in the Hindu Kush-Himalayan (HKH) region, where traditional spring-based water supply systems are also being affected by climate change [3, 6]. The combined impacts of glacier retreat and frequent droughts are severely impacting spring water availability, particularly in the Malakand and Hazara regions. As a result, the livelihoods of spring-dependent communities, and livestock survival, are increasingly threatened [7].

The HKH region in northern Pakistan in particular, encompassing GB and KP, is home to numerous springs that serve as the primary water source for human, animal, and agricultural needs. The construction and maintenance of spring-fed Kuhl irrigation channels rely on traditional knowledge and community involvement [7]. However, this system faces numerous challenges, including the direct diversion of spring water through pipes for household use, frequent damage to channels from climate change-induced storms and flooding, and the growing use of deep tubewells, which has led to the drying up of springs in some areas. These issues threaten ecosystems downstream, hinder agricultural productivity, and undermine the livelihoods of communities reliant on spring-fed water systems [8]. Moreover, changing weather patterns, such as altered snowmelt timing and shifting monsoon rainfall, causes variability in spring flows, further affecting water security for both humans and livestock.

Water quality is another critical concern that negatively impacts the health and well-being of spring-dependent communities [9-12]. Poor water quality is often attributed to mismanagement of spring catchment areas, including deforestation, land-use changes, and urbanization, which reduce water infiltration, increase surface runoff, and increase water pollution particularly in KP and Punjab [13]. The chemical composition of spring water is influenced by both human activities involving untreated sewage disposal and natural processes, such as the mineralization of rocks [14, 15]. In KP and AJ&K, deforestation and rock drilling for groundwater extraction through deep tubewells pose significant challenges to both the quality and quantity of spring water. The loss of ground cover due to deforestation reduces the land's ability to absorb and retain water,

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leading to increased runoff, soil erosion, and land degradation, which further compromises spring sustainability [16].

Despite the growing importance of springs for water security and livelihoods, the management of springs has been largely neglected in Pakistan's water, climate, and food security policies. This highlights the urgent need for targeted research and policy interventions to safeguard these vital resources. This study aims to address this gap by undertaking the first comprehensive assessment of spring distribution across Pakistan and analyzing their correlation with environmental variables such as rainfall, temperature, elevation, and slope. By providing a detailed understanding of spring distribution and the population's dependency on these water sources, this research seeks to inform researchers, policymakers and planners, guiding the development of future programs to conserve and manage these critical water resources effectively.

2. *Materials and Methods*

2.1 *Study Area*

This study area is comprised of KP, Punjab, Sindh, Baluchistan, AJ&K, GB, Islamabad capital territory and the HKH region that fall in Pakistan. The study area represents variable topographies, from the mountainous north to the plains of Sindh and Punjab, providing a wide range of geographical and climatic conditions. All these factors may influence the distribution and occurrence of springs.

2.2 *Data Collection*

The data of springs distribution across the country was obtained from the Survey of Pakistan recorded during 2023. The weather and geographical information comprising (rainfall, temperature, elevation, and slope) were obtained from the Pakistan Meteorological Department (PMD) and other online resources. Population data from the 2023 census was used to calculate spring dependency rates for the various districts. The spatial analysis of spring distribution was conducted using Geographic Information System (GIS) software to generate maps for each province.

2.3 *Statistical Analysis*

To assess the distribution of springs across Pakistan, the total number of springs along with relevant climatic and geographical data for spring-bearing districts in each province was compiled into an Excel spreadsheet (2021). The statistical analysis aimed to establish the relationship between the number of springs in each district (dependent variable) and selected climatic and topographic parameters (independent variables).

A correlation and regression analysis was performed to quantify the influence of climatic and geographical factors on spring distribution. The statistical model was set at a 95% confidence level, and the correlation coefficient (r), coefficient of determination (R^2), and significance level (p-value) were computed using built-in statistical functions in Microsoft Excel. The strength and direction of associations between variables were assessed using Pearson's correlation coefficient (r), while the predictive capability of independent variables was evaluated through linear regression analysis.

The computed values of r, R^2, and p were systematically presented in tabular form to illustrate the statistical relationships between spring availability and climatic and geographical parameters. The significance of these relationships was interpreted based on conventional statistical thresholds ($p < 0.05$ for statistical significance).

3. **Results**

3.1 *Overview of Spring Distribution*

The results indicate substantial variation in spring distribution across Pakistan, as given in Figure 1. Our analysis identified 18,114 springs across Pakistan, with approximately 81% located in KP and Baluchistan, highlighting significant clustering in regions with favorable climatic and geographic conditions. Lower elevation and arid regions, such as southern Punjab and Sindh, showed limited spring presence. On average, about 26,225 people rely on each spring in the 108 spring bearing districts containing springs, underscoring the critical role these resources play in regional water security.

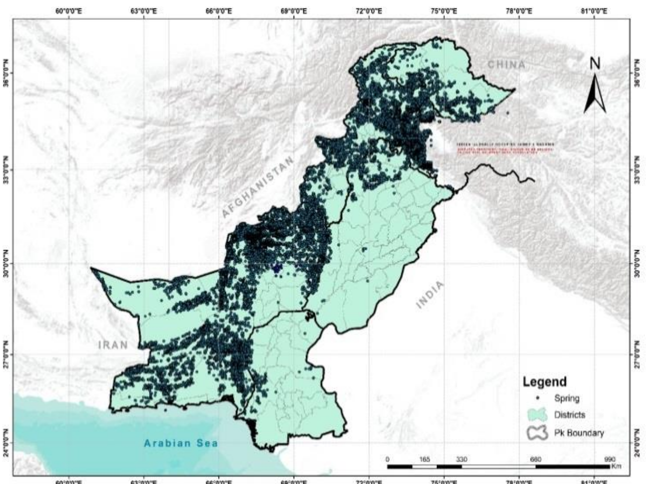

Fig. 1: Spatial distribution of springs across Pakistan

Table 1 presents a summary of the total number of districts, total number of springs, average rainfall, temperature, average elevation, and slope for each province.

The total number of springs per province and the number of persons per spring based on the cumulative population of all spring's districts in each province are summarized in Figure 2. The number of springs in the HKH region that fall in Pakistan is 5051 (28%) of the total springs (18114) in the country. Generally, dependence on springs is larger in the northern part of the country.

Table 1: Spring Distribution and Annual Climatic Variables and Topographic Parameters for the Different Districts in different Provinces and Regions Across Pakistan

Province	Total Districts	Total Springs	Avg. Rainfall (mm)	Avg. Temp. (°C)	Avg. Elev. (m)	Avg. Slope
Khyber Pakhtunkhwa	37	4501	789	12-22	851	Steep
Punjab	14	1285	507	20-30	250	Flat
Sindh	8	215	294	30-40	103	Flat
Balouchistan	29	10047	310	20-30	1036	Moderate
Azad Jammu & Kashmir	10	943	1088	10-20	1350	Steep
Gilgit-Baltistan	8	1095	600	5-15	2155	Steep
Islamabad	1	28	800	15-25	500	Flat
Hindukush Himalaya	37	5051	892	10-22	1590	Steept

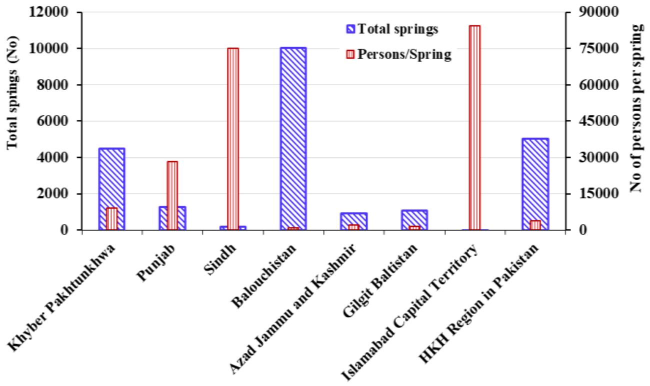

Fig. 2: Comparative analysis of the number of springs and number of persons per spring

The number of springs per unit area of respective districts in each province and the cumulative population of respective spring districts in each province is summarized in Figure 3. The average number of springs per hectare is around 3 in the spring districts of the country. However, the spring densities are 39%, 170% and 24% higher in KP, AJ&K and HKH region of Pakistan respectively than the country's average value.

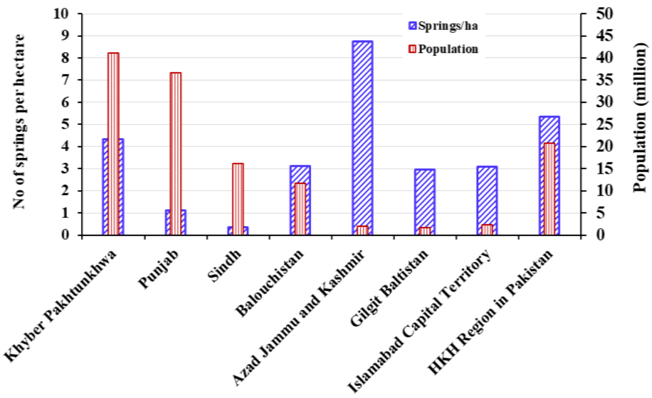

Fig. 3: Spring density and population of respective districts of provinces of Pakistan

3.2 Detailed Analysis of Key Regions

3.2.1 Khyber Pakhtunkhwa

Khyber Pakhtunkhwa (KP) has the highest density of springs showing presence in 37 districts, particularly in Malakand and Hazara divisions, as indicated in Figure 4, where factors such as higher rainfall, moderate elevation, and clay-rich soils support spring formation. Districts such as Abbottabad, Swat, and Lower Dir have a high spring density, where rainfall is high and elevation is moderate.

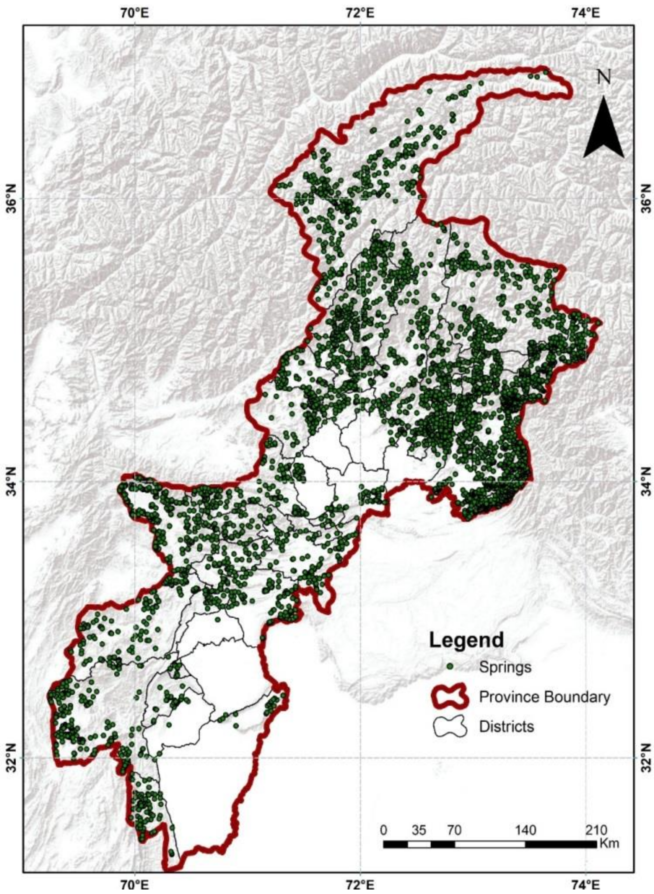

Fig. 4: Spatial distribution of springs in Khyber Pakhtunkhwa province

3.2.2 Punjab

Northern Punjab has larger spring presence (Figure 5), while the arid southern districts show sparse distribution. Springs in Rawalpindi and Chakwal are denser where seasonal monsoons rains are more and altitudes are moderate.

3.2.3 Sindh

The Sindh province show limited spring presence. The few springs found in Sindh are mostly seasonal, occurring in districts like Jamshoro, where occasional monsoon rains temporarily recharge local aquifers, as illustrated in Figure 6.

3.2.4 Baluchistan

The highest number of springs is found in Baluchistan, particularly in districts like Khuzdar and Kalat. Despite the province’s arid climate, the geology favors the presence of springs, which are vital for local communities. The spatial distribution of springs in Baluchistan is presented in Figure 7.

3.2.5 Azad Jammu and Kashmir

The distribution of springs in AJ&K is vital for sustaining local communities and ecosystems. Continued research and effective management strategies are essential to ensure their availability and quality for future generations. The distribution of springs in AJ&K is presented in Figure 8.

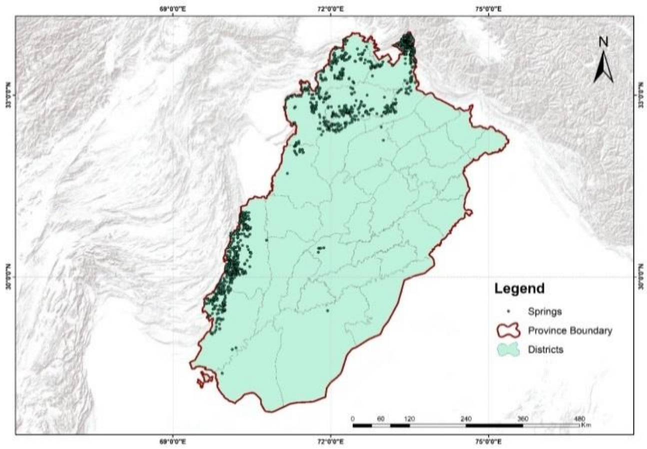

Fig. 5: Spatial distribution of springs across Punjab province

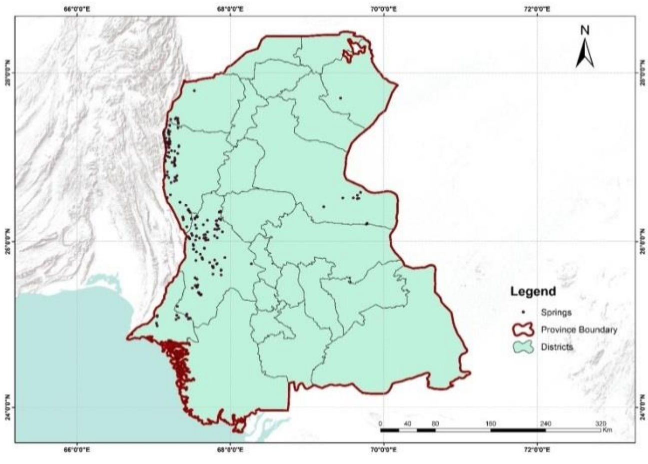

Fig. 6: Spatial distribution of springs across Sindh province

3.2.6 Gilgit Baltistan

The mountainous terrain and higher elevations of GB hosts numerous springs. These springs are critical for agriculture and domestic use, with Skardu and Astore being key districts with a high density of springs. The spatial distribution of springs in GB is given in Figure 9.

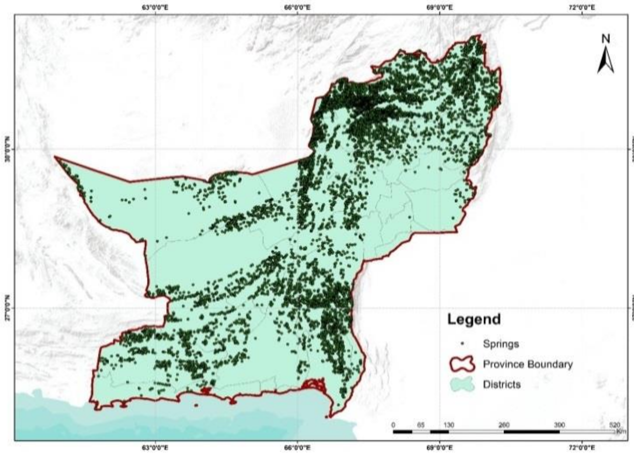

Fig. 7: Spatial distribution of springs in Baluchistan province

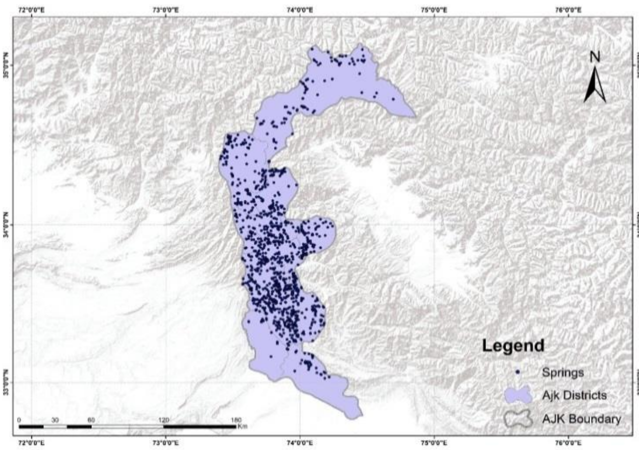

Fig. 8: Distribution of springs in Azad Jammu and Kashmir in Pakistan

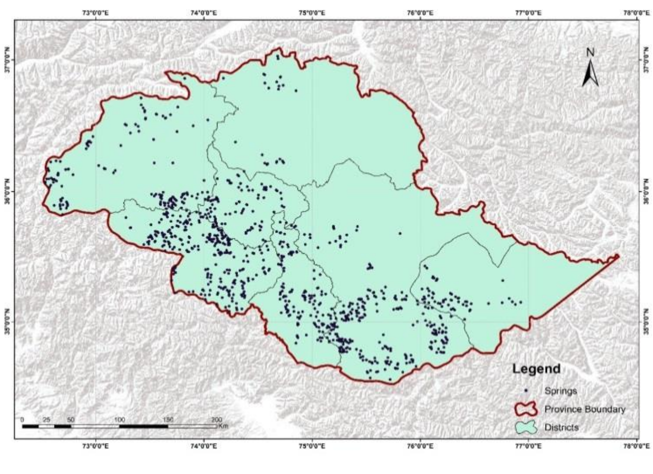

Fig. 9: Spatial distribution of springs in Gilgit Baltistan province

3.2.7 Hindu-Kush Himalaya

The spatial distribution of springs in the HKH region is presented in Figure 10. The north western part of HKH is home to majority of the springs. The HKH region host 5051 springs with majority of springs concentrated in the Himalaya and Hindukush regions while the Karakoram region host a smaller number of springs. The total population of HKH region that falls in Pakistan are around 24 million, while persons per spring are around 4739 and spring density is around 4 springs/ha.

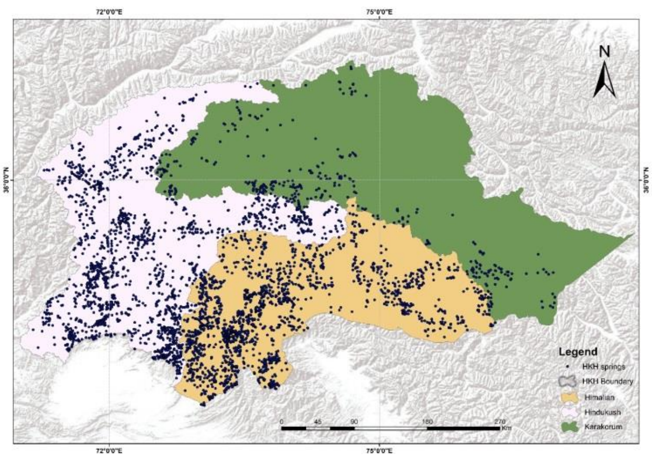

Fig. 10: Spatial distribution of springs in the Hindukush Himalaya region of Pakistan

3.3 Correlation and Regression Analysis

The correlation and regression analysis indicated a generally weak relationship between the number of springs and the climatic or topographical parameters across districts in each province, as summarized in Table 2. However, a more distinct pattern emerged in KP, Punjab, AJ&K, and the HKH region, where the number of springs exhibited a positive correlation with rainfall and elevation and a negative correlation with temperature.

These findings suggest that higher altitudes and increased precipitation Favor Spring formation, likely due to enhanced groundwater recharge and lower evaporation rates. Conversely, warmer temperatures appear to reduce spring viability, potentially due to increased evapotranspiration and reduced groundwater retention. The observed trends underscore the critical role of climatic and topographic factors in governing spring distribution, with implications for regional water management and climate resilience strategies.

In summary, the rainfall is the most significant factor influencing spring distribution, particularly in Punjab, KP, and AJ&K. Higher temperatures negatively impact spring occurrence, but the effect varies by region. Elevation moderately influences spring distribution, particularly in mountainous regions, but is less significant in arid zones such as Sindh and Baluchistan. The HKH region demonstrates a moderate dependence on rainfall, with weaker relationships to temperature and elevation.

4. Discussion

The findings indicate that the existence of springs is likely influenced by the hydro-geological characteristics of the host region, although the study presents only weak evidence regarding the contribution of environmental and topographical factors to the distribution of springs. The results suggest that regions with higher elevations and substantial rainfall, such as KP, AJ&K, and GB, tend to exhibit a higher density of springs, compared to the more arid regions of Sindh and southern Punjab. The negative correlation with temperature aligns with global findings indicating similar impacts of weather and climate change on spring systems in other parts of the HKH region [17-19].

Glacier retreat, unpredictable and extreme rainfall events in northern Pakistan have shortened the spring recharge period, resulting in reduced spring flows, particularly in regions highly dependent on springs, such as Malakand, Hazara, GB, and AJ&K. These findings are consistent with those of other studies [20, 21], which attribute reduced groundwater recharge to rising temperatures and altered rainfall patterns, further diminishing spring flows [22-24]. Land degradation due to deforestation in KP and AJ&K, coupled with the over-extraction of groundwater through deep tubewells, especially in Punjab, are key drivers of spring depletion. Similar patterns of spring depletion have been reported in other countries as well [25-29]. Based on these findings, there is a clear need to develop and implement integrated land use, land cover, forest, rainwater harvesting, artificial recharge systems and groundwater conservation policies, particularly in regions with high spring dependency

Table 2: Relationship Between Spring Distribution and Environmental Variables

Region/Province	Rainfall (r, R^2, p)*	Temperature (r, R^2, p)	Elevation (r, R^2, p)
Khyber Pakhtunkhwa	0.52, 0.27, $p<0.05$	-0.37, 0.13, $p<0.05$	0.36, 0.13, $p<0.05$
Punjab	0.61, 0.37, $p<0.05$	-0.22, 0.05, $p>0.05$	0.39, 0.15, $p>0.05$
Sindh	0.05, 0.002, $p>0.05$	0.32, 0.12, $p>0.05$	0.04, 0.001, $p>0.05$
Balouchistan	0.13, 0.02, $p>0.05$	-0.04, 0.001, $p>0.05$	0.02, 0.0002, $p>0.05$
Azad Jammu & Kashmir	0.58, 0.33, $p>0.05$	0.21, 0.04, $p>0.05$	0.39, 0.15, $p>0.05$
Gilgit-Baltistan	0.03, 0.001, $p>0.05$	-0.18, 0.03, $p>0.05$	0.37, 0.14, $p>0.05$
Hindu Kush-Himalaya	0.43, 0.18, $p<0.05$	-0.15, 0.02, $p>0.05$	0.15, 0.02, $p>0.05$

*(Correlation Coefficient (r), Coefficient of Determination (R^2), and Statistical Significance (p-value))

such as KP and Baluchistan. Reforestation, sustainable land-use practices, and artificial recharge systems of groundwater with rainwater may serve as effective strategies to mitigate spring depletion.

This study reinforces the significance of topographic and climatic factors in determining spring distribution across Pakistan, a pattern observed globally [30-33]. Specifically, regions with higher elevations and greater rainfall, notably KP, AJ&K, and GB, are correlated with a higher number of springs. Conversely, temperature negatively correlates with spring occurrence in arid regions such as Sindh and Baluchistan. Springs in these arid zones are often seasonal and do not provide perennial water flow. Consequently, spring conservation in regions like KP, GB, and AJ&K requires more attention and government investment to ensure sustainable water availability and water security [10]. Comprehensive awareness, policy frameworks, and effective monitoring systems for springs are urgently needed to secure sustainable spring management in Pakistan.

The strong correlation between elevation and spring distribution suggests that mountainous regions have a greater potential for spring formation due to higher rainfall and cooler temperatures, both of which are conducive to spring recharge, as noted by [32]. Furthermore, the moderate to steep slopes, along with relatively more ground cover and forest in these areas, facilitate water percolation into underground aquifers, which is crucial for sustaining spring flows. The negative correlation between temperature and spring distribution, particularly in Sindh and Baluchistan, highlights the vulnerability of springs to rising temperatures. As climate change exacerbates temperature extremes and alters precipitation patterns, the recharge of springs in arid and semi-arid regions is expected to decline further. These findings are consistent with global studies documenting similar climate change impacts on water resources, particularly in the HKH region [32, 34, 35].

In northern Pakistan, particularly in KP, GB, and AJ&K, the increasing frequency of extreme climate events [36] and the shortening of the snowmelt season have reduced the water available for spring recharge, contributing to declining spring flows. This reduction in water availability for domestic and agricultural use has adversely affected the livelihoods of communities that rely on springs [37]. Anthropogenic activities, such as deforestation, land-use changes, direct disposal of sewage water and the over-extraction of groundwater through deep pumping to meet the demands of a growing population are significant contributors to spring depletion and the deterioration of water quality [21]. The accelerating deforestation in KP and AJ&K has diminished the land’s capacity to absorb and retain water, further hindering spring recharge.

The results of this study emphasize the importance of promoting site-specific interventions and an integrated approach to resource management, as advocated by [38], which could be vital for the conservation and sustainable management of springs across Pakistan. Focusing on isolated resource management solutions may not be effective. Instead, a holistic, multidisciplinary approach involving various departments working collaboratively is essential. Managing water resources from the point of rainfall to river basins in an integrated manner is critical. Projects should prioritize interventions based on scientific evidence and in-depth knowledge of local vulnerabilities, taking into account the characteristics of catchments, sub-watersheds, and watersheds to ensure sustainable development and targeted actions for each locality.

5. Conclusion

This study represents a pioneering effort in mapping and analyzing the distribution of springs across Pakistan. Springs are vital water sources for rural and mountainous regions of Pakistan, particularly in areas with limited access to alternative water resources. However, their sustainability is increasingly threatened by climate change, including rising temperatures, altered rainfall patterns, glacier retreat, deep boring and land degradation. These challenges have been particularly pronounced in northern Pakistan, where the dependence on springs for agriculture, domestic use, and ecosystem support is high. The degradation of spring water quality, compounded by deforestation, land-use changes, and over-extraction, further exacerbates the vulnerability of these vital resources.

To safeguard springs and ensure sustainable water availability, it is essential to implement targeted conservation strategies, including rainwater harvesting, artificial recharge of groundwater, reforestation, land-use management, and sustainable groundwater practices. Furthermore, addressing the gaps in updated springs data, spring management, governance, policies and integrating climate change adaptation measures will be crucial to preserving these resources for future generations. This study highlights the urgent need for comprehensive research and policy frameworks that consider the unique environmental and socio-economic dynamics of spring-dependent regions in Pakistan.

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