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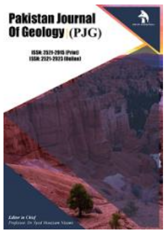

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RESEARCH ARTICLE

ASSESSMENT OF SPRINGS IN DIFFERENT PHYSIOGRAPHIC REGIONS OF PAKISTAN FOR SUSTAINABLE RESOURCE DEVELOPMENT

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ABSTRACT

Mountain regions are highly vulnerable in the context of soaring water demands owing to rapid urbanization, improved living standards, and climate change, which need immediate attention for sustainable development. The current study evaluated spring concentration in various agro-environments of Pakistan to ensure water security and sustainable development in the country. A total of 0.02 million springs were found throughout various physiographic regions of the country, with roughly 33.5% of them located in the low mountains and 21.8% in the middle mountains. The spring densities were observed to be high in the Azad Jammu and Kashmir (i.e., 0.08 springs/km^2) and Khyber Pakhtunkhwa province (i.e., 0.04 springs/km^2), which may be attributed to substantial rainfall recharge and the presence of fractured rock formations here. The gravelly fans and terraces stretching over 9% of the country area contain about 12% springs with a density of over 0.02 springs/km^2. The spring density was observed high in the forest class, i.e., 0.08 springs/km^2, and the rangelands, i.e., about 0.04 springs/km^2, pointing towards the significance of vegetation cover in sustaining the spring ecosystem. The density of springs was maximum about 0.07 springs/km^2 in the >1000 mm rainfall zone, while it ranged within 0.01-0.02 springs/km^2 in other rainfall zones. The spring density exhibited an exponential relationship with the annual rainfall, indicated by an R^2 value of 0.76, underscoring the importance of rainfall in the formation and maintenance of springs in the region. Spring management requires multifaceted actions focusing both on supply and demand-side solutions, improving groundwater recharge and governance, and efficient water use in the country.

KEYWORDS

freshwater aquifer, groundwater recharge, spring density, Indus basin

1. INTRODUCTION

Water demand is increasing rapidly in the wake of growing urbanization, commercial progress, expansion in agricultural land, and climate change during the last several decades (Kaser et al., 2010; Gaddam et al., 2018). Freshwater aquifers continue to supply an increasing amount of water to various sectors of the economy worldwide (Shahid and Hazarika, 2010; Rashid et al., 2017). The groundwater use has increased manifold as a result of growth in urbanization, extension in agricultural activities, and frequent drought conditions in the Indus basin (Siebert et al., 2010; Margat and Van der Gun, 2013; Sadaf et al., 2019). Groundwater is perceived as one of the most significant and reliable freshwater resources globally. The groundwater resources, like tube wells, dug wells, and springs, are the main sources of water supply in major irrigated and hill ecologies of the world. Natural springs are among the most prolific, biologically diverse, and culturally significant water ecosystems on Earth (Junghans et al., 2016; Kreamer et al., 2024).

They vary in size from intermittent seeps to massive pools that flow hundreds of millions of gallons per day (USGS, 2019). Owing to rapid urbanization and changes in climate and land use, Pakistan is facing challenge of reduced water availability for her agriculture sector (World Bank, 2017). Springs are an essential component of the groundwater system and groundwater is typically regarded as safe for human consumption and free of bacteriological pollution (Elizondo and Lofthouse, 2010; Smith et al., 2016). The locals consider springs a safe source of drinking water and preferred this source over surface meltwater because of its better quality for domestic use. The two main types of springs include gravity springs and artesian springs. Gravity springs are found on mountain slopes or hillsides where geology has trapped groundwater flow. One of its forms, called Contact springs, which are formed when the subsurface water in a relatively permeable rock layer is restricted by an underlying impermeable rock layer, forcing the water to emerge on the ground surface under gravity.

Artesian springs form in places where groundwater from the deeper confined aquifer (water-saturated strata/lithology) flows out to the ground surface under pressure via a fractured layer. In a fault zone, groundwater at depth moves up along faults under the hydrostatic pressure of confined aquifers before emerging through ground surface openings to form fault springs. In areas of favorable geological structure, springs are developed in fissured rocks, such as in the mountainous terrain of the Khyber Pakhtunkhwa (KPK), Balochistan, and Gilgit-Baltistan. In several parts in the north and the Kohistan area of Sindh, the carbonate rocks appear to have karstic character with some moderate groundwater discharge (WAPDA and MHW, 1989). In carbonate rocks (i.e., limestone, dolomite), water flowing through the holes and cavities formed by the dissolution of the rock material, emerges through the openings in the form of karst springs.

There is a need to identify spring resource potential to provide scientific evidence and identify strategies to support policy initiatives and sustainable spring management in the country. The current knowledge and data limitations must be addressed to create creative solutions for the sustainable management of the spring resource. The accurate mapping of the water resource using geographic information system (GIS) technologies is the first step in developing a comprehensive plan to

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address these problems. The advanced geospatial technology is gaining a pivotal role in the field of hydrology and water resource management worldwide (Ashraf and Ahmad, 2012; Klemas and Pieterse, 2015; SGL, 2023). It is important to manage the spring resource efficiently for sustainable agriculture and livelihoods in the country. There is no systematic study has been carried out to document the physical setup and characteristics of the springs in the country in the past. In the present study, spring concentration was evaluated in different agro-environments of Pakistan for sustainable resource management in the country.

2. Description of The Study Area

Pakistan stretches over an area of about 0.88 million km^2 within longitudes 60° 19' - 77° 10 E and latitudes 23° 24' - 37° 20' N (Figure 1). The three major mountain ranges, namely the Hindu Kush, Karakoram, and Himalaya, lie in the north; plateaus and plains are in the middle; and coastal areas along the Arabian Sea are in the south of the country. The >500 persons/km^2 density exists mainly in the northeastern and central parts of the Punjab and some parts of the Khyber Pakhtunkhwa (KPK) and Sindh provinces. In Balochistan, a 5-50 persons/km^2 density dominates in most of the districts of the province. Rainfall occurs mainly during the monsoon season from July to September. Winter temperatures reach below zero, especially in the months of January and February, due to western Mediterranean cold winds in the western and northern parts. Most of the snowfall occurs in the northern regions during the winter season. June and July are the hottest months, with an average maximum temperature of about 42ºC in most of the southern region.

Varying sizes of springs form a significant source of drinking water in the mountainous region (Negi and Joshi, 2002; Glazier, 2014; Stevens, 2020). The spring water is channelized for local usage and individuals or communities maintain the system on a self-help basis. The landforms in the Northern region consist of steep mountains and rock outcrops containing shallow and very shallow soils (Figure 2). The southwestern parts of KPK contain patchy soil cover with calcareous, medium-textured, and excessively drained soils. While the central parts of KPK consist of fair to good soil cover, mainly over mountainous terrain. The alluvium deposits occur in the form of old river terraces, sub-recent plains, and active plains in the Indus irrigated plains of Punjab and Sindh provinces. The soils here are mostly calcareous and medium to fine textured. The soils occurring at higher elevations have homogenized to moderate depths; however, major land in the southwestern parts of the country possesses little or no soil cover. At places, crops, such as wheat, maize, fodder, and a variety of vegetables and fruits, are grown using spring water in the mountainous region.

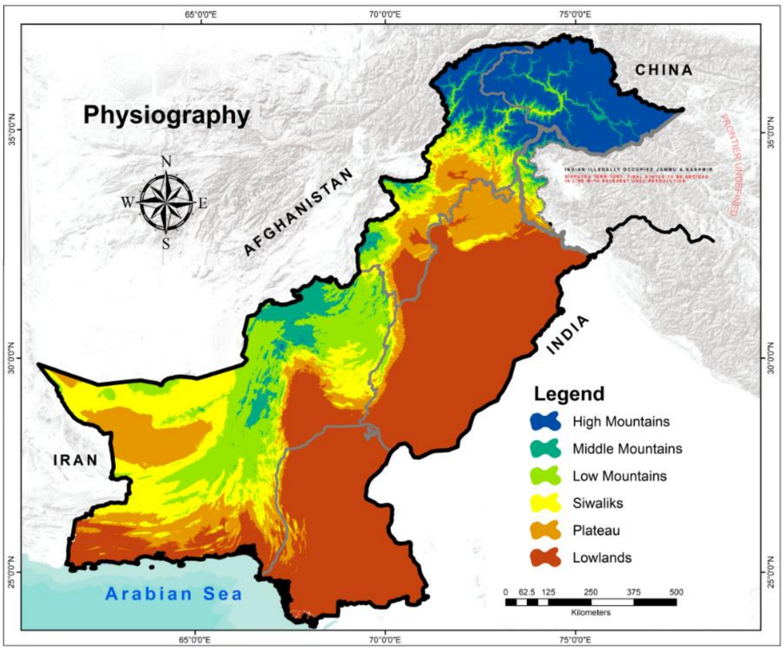

Figure 1: Major physiographic regions in Pakistan

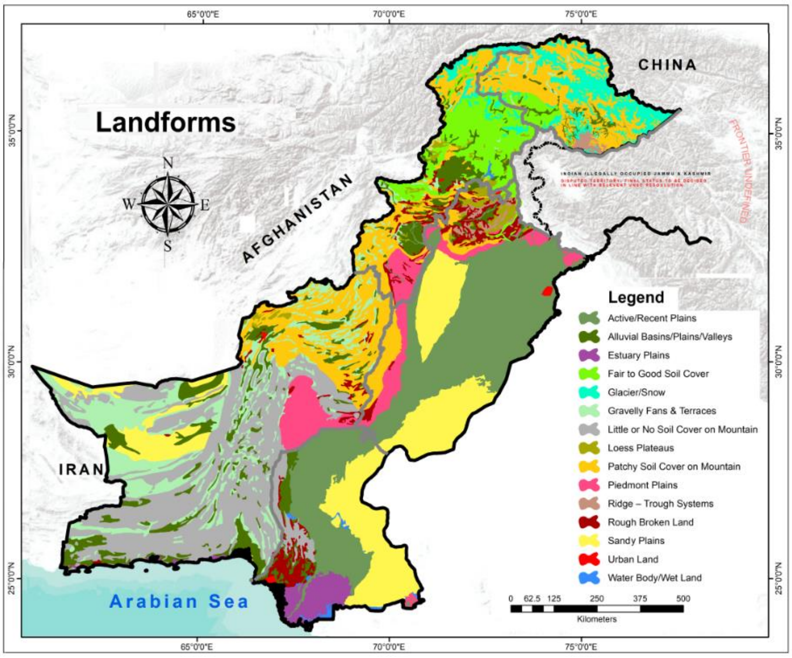

Figure 2: Major landforms distribution in Pakistan

2.1 Geology and hydrogeology

The region has a complicated geological history, which results in the formation of variable types of igneous, metamorphic, and sedimentary rocks and the evolution of diverse landforms (Soil Survey Report, 2006). The mountainous regions in the extreme north, middle, and some southern parts have igneous (i.e., granite, schist, gneiss), and meta-sedimentary rocks. The geology of the central and southern mountains consists of Early Mesozoic rocks (sedimentary, undivided) surrounded by Paleozoic rocks (mostly metamorphic type). In the north of Punjab, the rocks are part of the Mio-Pliocene Siwalik system, where the Main Boundary Thrust (MBT) fault crosses the foothills of the lower Himalayas (Sheikh et al., 2007). The quality and quantity of groundwater vary greatly in different parts of the region due to complex geology, topography, climate, and surface hydrological conditions (Kazmi and Jan, 1997; Rehman et al., 2019).

The groundwater occurs mainly in porous aquifer system in the plains, valleys, and deserts, whereas it exists in fissured aquifer system in the hard rock areas of the mountainous terrain. In most of the area, patchy and discontinuous aquifers exist under the folding and faulting of the underlying hard rock formations (WAPDA 1989, 2001). The groundwater is promising in a fairly thick and extensive aquifer in the Indus plain of the country. Permeability is high in this formation containing layers of gravels, deposits of different grades of sand, and clay lenses (Nazir, 1995). The geological and hydrogeological features of the local area govern the spring flows in the area. The spring discharge typically ranges from less than 0.01 l/s to 10 l/s in the Himalayan region (Pandit et al., 2024). It depends on a number of factors, including precipitation recharge, aquifer water pressure, and springshed size (USGS, 2019).

3. Materials and Methods

3.1 Data used

Time-series climate data of 59 meteorological stations was collected on a monthly time scale (1990-2019 period) from the Pakistan Meteorological Department (PMD). The thematic data of topography, physiography, soils/landforms, hydrogeology, hydrology, and land use were acquired from different departments, i.e., Survey of Pakistan, Soil survey of Pakistan, Water and Power Development Authority (WAPDA) and open sources. The global map of land use/land cover (LULC) derived from the European Space Agency (ESA) Sentinel-2 imagery at 10 m resolution with 13 spectral bands was used for detailed land cover analysis. The geographic data of springs acquired through GPS (Global Positioning System) surveys by Survey of Pakistan were used for spatial analysis and to study association with the influential environmental factors. As it was not possible to gather discharges from the springs due to geographical and accessibility limitations, therefore an analog approach based on estimations from previous research conducted nearby was employed. The DEM of SRTM (Shuttle Radar Topography Mission) was downloaded from the USGS site http://e0srp 01u.ecs.nasa.gov/srtm/ to study the altitudinal behavior of the springs in the region. Field survey was carried out to collect biophysical and socioeconomics data, were acquired through review of the literature, field observations, and discussions with the local communities during the field surveys.

3.2 Spatial database development

The annual rainfall data of 1990-2019 period was interpolated in ArcGIS software for spatial variability analysis at country level. The relationship analysis between spring density and different rainfall zones was performed. The agro-climate zones of the country were developed based on reference evapotranspiration (ETo) and rainfall data of the 30-year period. The ETo was calculated using the Penman-Monteith method following (Allen et al., 1998). As compared with other methods, the Penman-Monteith method indicates better performance in the diverse climatic conditions of Pakistan (Rasul and Mahmood, 2009). The ETo and rainfall data were interpolated following the inverse distance weighting (IDW) interpolation technique in ArcGIS software. In the IDW technique, a weighted average of the values available at the known points is used to determine the values assigned to unknown points. The aridity index (I_a) was estimated using a ratio of 50% probability of rainfall and reference crop evapotranspiration following the relationship and classification (UNESCO, 1964; Roohi et al., 2002) (Equation 1).

$$I_a = R_{0.5} / E_{ta} \tag{1}$$

Where, $R_{0.5}$ is sum of the 50 % probability of monthly rainfall; and E_{ta} - sum of the monthly reference evapotranspiration.

The distribution of springs was examined under various physiographic regions, rainfall zones, slopes, land use/land cover, and administrative units in the study area. The physiographic regions based on elevation ranges include lowlands (<300 m), hilly areas (300-700 m), siwaliks (700-1200 m), low mountains (1200-2000 m), middle mountains (2000-3000 m), and high mountains (>3000 m) (PARC, 2024). Since slope is a crucial component in describing a spring resource, the area's slope was ascertained from the DEM. Different slope classes were defined to find springs' association with the slope in the area (Ashraf and Ahmad, 2024). The <5° and 5°–15° slope classes were found stretching over 72% and 14.3% of the area, respectively. The slope class 15°–30° was identified over 9.4%, and the class 30°–45° over 3.6% of the area, while the slope class >45° was found over 0.7% of the country area. The image processing of Sentinel II image data was performed for land use/land cover analysis. The rangeland and exposed rock outcrops were found collectively over 58% of the country area. The forest cover was assessed over 4.6% area, mainly in the northern half of the country, whereas the cropland was found over 24% of the area, stretching mostly across Indus plains of the Punjab and Sindh provinces.

4. Results and Discussion

4.1 Springs analysis by physiography

The spatial analysis of springs revealed a total of 0.02 million springs in different physiographic regions of the country, among which about 33.5% of springs lie in the low mountains, which stretch over 13.3% of the country area. About 21.8% of springs were observed in the middle mountains and 21.5% in the Siwaliks that stretch over about 5.4% and 14.3% of the land of the country, respectively (Table 1). The concentration of the springs was observed least, i.e., about 2.6% in the lowlands, which mainly contains alluvial plains in the Punjab and Sindh provinces (Figure 3). High density of springs was found in the middle mountains (i.e., 0.08 springs/km^2), low mountains (i.e., 0.05 springs/km^2), and Siwaliks (i.e., 0.03 springs/km^2). About 11.8% of springs were observed in the hilly area and 8.8% in the high mountains, with a density of about 0.02 springs/km^2 each in the western and northern parts of the country (Table 1 and Figure 4).

The springs' concentration was found to be 16.6% in the mountain-valley system of the central KPK province, exhibiting a maximum density (about 0.08 springs/km^2), owing to presence of fair to good soil cover in the mountainous region. About 27.6% of springs were identified in the mountain-valley system consisting of patchy soil cover lying mostly in the upper Balochistan, lower and upper KPK, and parts of the GB area. The springs' density was assessed 0.04 springs/km^2 in this landform. The mountain-valley system with little or no soil cover in the central and southwestern parts of Balochistan exhibited 19.5% springs with a density of about 0.02 springs/km^2. The sedimentary rocks and hard rock formations in mountainous terrain here bear water due to fissures or faults (WAPDA and MHW, 1989). The gravelly fans and terraces stretching over 9% of the area and containing 11.5% springs exhibited a density of about 0.02 springs/km^2, mainly in parts of the Balochistan and KPK provinces.

About 41.2% of the springs were observed over the <5° slope class and 36.3% over the 5°–15° slope class in the country (Figure 4). The 15°–30° slope class contains about 18.5% springs, and the 30°–45° class holds 3.8% springs, while about 0.3% of springs only were observed in the >45° slope class of the country. The spring density was found to be maximum in the 5°–15° slope class, i.e., approximately 0.05 springs/km^2, followed by the 15°–30° class with a density of about 0.04 springs/km^2. The forest exhibited a maximum spring density of about 0.08 springs/km^2, followed by rangeland and cropland, about 0.04 springs/km^2 density each, pointing towards a major contribution of the vegetation cover in sustaining spring resources in the region. The Balochistan province exhibited a maximum of over 56.3% springs, followed by the KPK province (24.2%). High spring densities were observed in Azad Jammu and Kashmir (AJK), i.e., 0.08 springs/km^2, and KPK province, i.e., 0.04 springs/km^2 (Table 2 and Figure 4) due to the presence of fairly thick soil cover and favorable climate in parts of these mountainous regions. Relatively low densities of springs observed in GB and Balochistan province are likely because of the presence of extensive unfractured rock formations in the mountainous terrain. The low densities of springs found in the Sindh and Punjab are because of the existence of vast lowlands and alluvial Indus plains in those provinces.

Table 1: Summary of spring resource in various physiographic regions

Region	Coverage		Springs		Density (Sp/km²)
	Km²	%	Number	%	
High Mount	81791	9.3	1585	8.8	0.02
Middle Mount	47200	5.4	3949	21.8	0.08
Low Mount	117523	13.3	6060	33.5	0.05
Siwaliks	126000	14.3	3890	21.5	0.03
Hilly area	124430	14.1	2136	11.8	0.02
Lowlands	384955	43.7	477	2.6	0.00
Total	881900	100.0	18097	100.0	0.02

Table 2. Summary of spring resource in various provinces/regions of the country

Province	Coverage		Springs		Density (Sp/km²)
	Km²	%	Number	%	
KPK	101741	11.5	4372	24.2	0.04
Punjab	205345	23.3	1249	6.9	0.01
Sindh	140914	16.0	215	1.2	0.00
Balochistan	347190	39.4	10185	56.3	0.03
AJK	13739	1.6	1101	6.1	0.08
GB	72971	8.3	975	5.4	0.01
Total	881900	100.0	18097	100	0.02

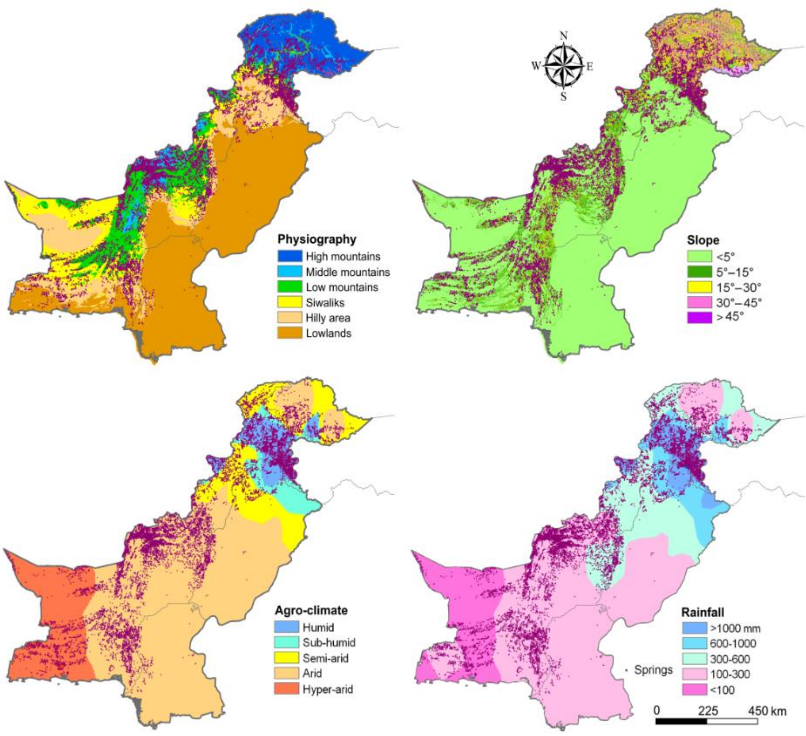

Figure 3: Springs distribution in various physiographic regions, slope classes, agro-climate and rainfall zones in the country

4.2 Spring analysis by agro-climate

The humid class was observed over 5.6%, and the sub-humid over 4.7% area comprising mountainous parts of the upper KPK, AJK and Punjab provinces (Figure 3). The semi-arid class was identified over 12.9% of the area, including parts of KPK and Punjab provinces. Arid class was observed over 63.8% and hyper-arid over 15.5% of the area (Table 3), mainly in the southern and southwestern parts of the country. As a result of receiving low and erratic rainfall, this region contains scanty vegetation of drought-resistant trees and a few shrubs of forage value. A high concentration of springs was found in the arid climatic zone, i.e., about 55.8%, followed by in the humid zone, i.e., 21.7%, with densities of over 0.02 springs/km² and 0.08 springs/km², respectively (Table 3 and Figure 4). The later zone mainly comprises parts of the Himalayan and Hindu Kush mountain ranges, which receive monsoons in the summers and westerly during winter seasons. Some of the intermittent springs here run during the rainy and snowy seasons, as long as the precipitation replenishes them, while the permanent springs run year-round. In one of the watersheds in western Nepal in the Central Himalaya, a group researcher found a spring density of about 1.63 springs/km², which is probably due to the large monsoonal effect and the spatial dimension of the watershed area (Pandit et al., 2024). The density of springs was least pronounced in the hyper-arid zone owing to limited rainfall recharge in the southwest of the country.

During 1990-2019, the rainfall range >1000 mm was observed over 5.6% of the area (Table 4), mainly in the northern parts of the KPK and Punjab provinces. Annual rainfall within the 600-1000 mm range occurs mainly over 6.9% of the area in the upper Indus plain, while less than 100 mm of rainfall occurs over 12.8% of the area in the southwestern parts of the country (Figure 3). The rainfall ranges from 300 to 600 mm and 100 to 300 mm cover about 19.2% and 55.5% of the areas of the country, respectively. The >1000 mm rainfall zone indicated a maximum density of about 0.07 springs/km², while the densities in other zones ranged within 0.01-0.02 springs/km² (Table 4 and Figure 4).

Table 3: Summary of spring resource in various agro-climate zones

Zone	Coverage		Springs		Density (Sp/km²)
	Km²	%	Number	%	
Humid	49012	5.6	3928	21.7	0.08
Sub-humid	41715	4.7	815	4.5	0.02
Semi-arid	113416	12.9	1618	8.9	0.01
Arid	544740	61.8	10104	55.8	0.02
Hyper-arid	133016	15.1	1632	9.0	0.01
Total	881900	100.0	18097	100.0	0.02

Table 4: Summary of spring resource in various rainfall regimes

Rainfall (mm)	Coverage		Springs		Density (Sp/km²)
	Km²	%	Number	%	
>1000	49443	5.6	3694	20.4	0.07
600-1000	61169	6.9	1179	6.5	0.02
300-600	168886	19.2	2686	14.8	0.02
100-300	489309	55.5	9320	51.5	0.02
<100	113094	12.8	1218	6.7	0.01
Total	881900	100.0	18097	100.0	0.02

The spring density exhibited an exponential relationship with the annual rainfall, indicated by R^2 value of 0.76 in the region. The relationship points towards the high influence of rainfall in creating and nurturing the springs in the study area. Such influence of rainfall on spring resource was also studied in some previous studies close to this region (e.g., Negi and Joshi, 2004; Chang et al., 2021).

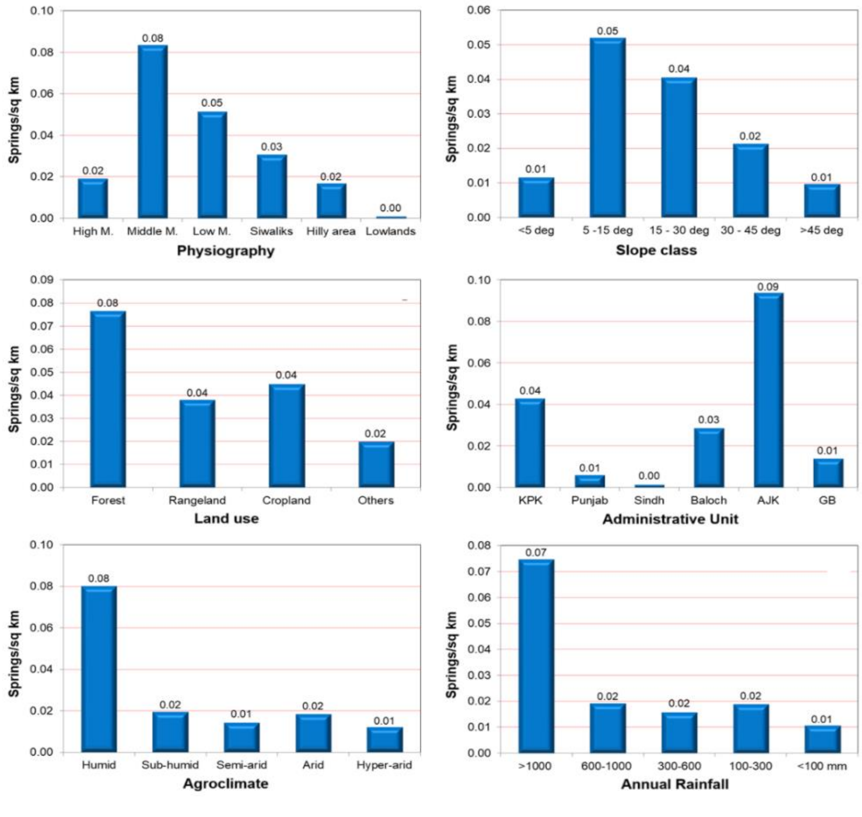

Figure 4: Spring density in different physiographic regions, slope classes, land use, administrative units, agro-climate and rainfall zones of Pakistan

4.3 Sustainable spring management

The springs are vulnerable to unplanned urban development, deforestation, and industrial growth, which affects not only the amount but also the quality of the spring water over time. Deforestation and urbanization change the water cycle by increasing runoff, decreasing natural land cover, and lowering groundwater recharge (Ashraf et al., 2014; Virk et al., 2020; Balaian et al., 2024). The springs and groundwater resources urgently need to be managed sustainably to achieve Sustainable Development Goals (SDGs), such as No Hunger (SDG 2), access to water and sanitation for all (SDG 6), and promoting sustainable use of terrestrial ecosystems (SDG 15). The spring ecosystem is typically affected by factors like flow diversion, groundwater exploitation, land use practices, the introduction of non-native species, pollution, and climate change (Stevens et al., 2022). Afforestation/reforestation offers resilience against topographic and climate effects, potentially halting the degradation of soils and landslide risk, and can improve ecosystem health in mountainous areas on sustainable basis (Hussain, 2010; AbdelRahman, 2023). The spring water may be preserved through farm ponds and storage tanks for use during later dry spells.

Appropriate water policy, governance, and capacity building of the local communities are required to maintain water supplies from the spring resource. It is important to identify options for enhancing spring water recharge and measures against water losses. A series of check dams may be built, and plant cover preserved in the upstream catchment areas, to increase recharge of the springs (Gupta and Kulkarni, 2017). There is a need to maintain centrally located data on groundwater users, uses, aquifer conditions, depth of the water table, and groundwater quality for safe use and sustainable management of the spring resource. As it is challenging to obtain spring discharges owing to geographical constraints in the mountainous region, an analog approach can be adopted based on hydrological modeling and approximations from the site-specific work done in the area. In-depth hydrogeological investigations and impact assessment of climate and land use changes on the springs are necessary for sustainable resource management in the future (Ashley, 2017; Chang et al., 2021).

5. Conclusion

The present study evaluated spring resource potential in various agro-environments of Pakistan to support water security and sustainable development in the country. The findings of the study revealed a total of 0.02 million springs in different physiographic regions of the country, among which about 33.5% of springs lie in the low mountains and 21.8% in the middle mountains. The spring densities were observed to be high in the AJK (i.e., 0.08 springs/km^2) and Khyber Pakhtunkhwa province (i.e., 0.04 springs/km^2) because of the relatively deep soil cover present in these mountainous regions. A high influence of topography, rainfall, and natural vegetation is observed on the spring resource in the region. The density of springs was maximum about 0.07 springs/km^2 in the >1000 mm rainfall zone, while it ranged within 0.01-0.02 springs/km^2 in other rainfall zones. The gravelly fans and terraces containing 11.5% springs exhibited a density of about 0.02 springs/km^2, mainly in parts of the Balochistan and KPK provinces. The forest exhibited a maximum spring density of about 0.08 springs/km^2, followed by rangeland and cropland, about 0.04 springs/km^2 density each, pointing towards a major contribution of the vegetation cover in sustaining spring resource in the region. Springs' concentration indicated a close relationship with the rainfall, highlighting the significant influence of rainfall in creating and nurturing springs in the region. A repository system may be developed to document broad data of spring resource, such as spring discharges, water budget, quality, associated biophysical conditions and microclimate for effective water resource management at various levels. . in the country. Adoption of an integrated water resource management approach coupled with effective water usage is essential for sustaining the spring resource in the region.

Novelty Statement

The study, for the first time, revealed overall spring resource potential and its relation with various agro-environments of Pakistan to support future water security and achieve clean water, food, and health-related sustainable development goals in the country.

Declarations

Conflicts of interest: There is no conflict of interest among authors

Data availability statement: The data will be made available on reasonable request

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Authors' contributions: AA contributed in conceptualization, design and write-up & NM contributed in field data collection, data processing and analysis.

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