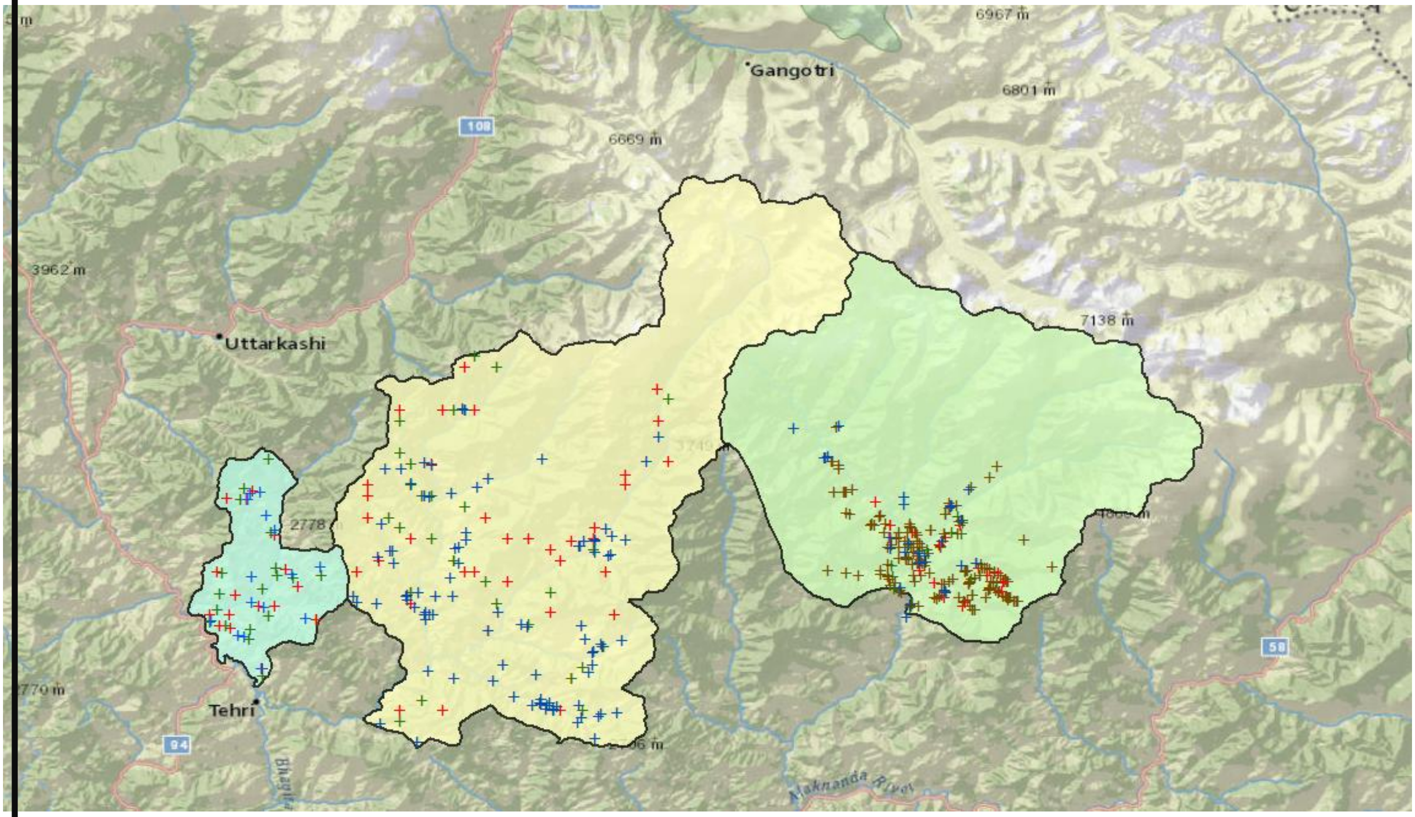
DRAFT FINAL REPORT

Internal Research Study

on

Ascertaining the Efficacy of Use of State-of-the-Art Technologies for Spring Mapping and Sustainability of Springs Through Suitable Interventions



आपो हिष्ठा मयोभुवः

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TABLE OF CONTENTS

Table of Figures

Table of Tables

1. INTRODUCTION

1.1 General

Springs constitute the primary and most dependable source of drinking water for more than 40 million inhabitants of the Indian Himalayan Region (IHR) (NITI Aayog, 2018). In mountains rural settlements are often clustered around natural water springs due to the inaccessibility of perennial surface water sources like rivers and streams, which typically flow through the narrow gorge. These springs commonly referred to as *naula* or *dhara*, not only serve critical roles in drinking and domestic water supply but also act as feeder systems for several River originated from the Himalayas. The hydrological functioning of these springs is intricately linked to the region's geological structures, slope characteristics, land use, vegetation cover, and seasonal precipitation, all of which collectively govern recharge dynamics. However, anthropogenic pressures such as deforestation, unregulated construction, and road expansion have disrupted natural infiltration and recharge zones, while climate-induced changes including reduced winter precipitation, rising temperatures, and erratic monsoon patterns have further constrained groundwater recharge potential (Tambe et al., 2012). It is estimated that in the IHR, less than 15% of total rainfall percolates to replenish subsurface aquifers, with the majority lost to rapid runoff, frequently resulting in flash floods and soil erosion (NITI Aayog, 2018). Studies across the region report that nearly 50% of perennial springs have either dried up or transitioned into seasonal flows, leading to acute water shortages during the dry summer months. This scarcity disproportionately impacts women and children, who bear the physical burden of water collection across remote, steep terrains, reducing their time for education, income-generating work, and other well-being activities (Tambe et al., 2012).

Globally, similar patterns are evident across other mountain regions. In the Hindu Kush-Himalayas, Andes, Alps, and Appalachian regions, springs are critical for both ecological and human systems, acting as key water sources in rural landscapes where piped infrastructure is either absent or unreliable. Research from the European Alps highlights how karst springs are sensitive to changes in snowmelt and precipitation, and how these hydrogeological systems are increasingly vulnerable to climate change (Jeannin et al., 2013; Viviroli et al., 2007). In the Andes, springs are not only critical for agriculture and domestic water use but also form the basis of community-based water rights and traditional management systems (Browder, 2000). In East Africa and the Western United States, declining spring flow has been attributed to land degradation and changing rainfall patterns, prompting both governmental and nongovernmental responses focused on recharge zone protection (Clark et al., 2015; Stevanović, 2015). Methodologies for spring-shed management (SSM) have evolved internationally to integrate hydrogeological assessment, community participation, and nature-based recharge interventions. Notably, the Dhara Vikas programme in Sikkim, India, and similar initiatives in Nepal and Bhutan have demonstrated the efficacy of delineating spring, followed by the implementation of infiltration structures like trenches, percolation pits, and vegetative buffers, which have led to 30–50% increases in spring discharge (Sharma et al., 2016; ICIMOD, 2015; Dorji & Gilmour, 2020). These approaches emphasize participatory planning and the blending of scientific and traditional knowledge, creating scalable and low-cost frameworks for water resource sustainability. In Rwanda, WaterAid has piloted mobile-based spring monitoring applications to improve data collection and facilitate timely protection efforts (WaterAid, 2021). Despite these successes, a lack of standardized spring inventories and limited long-term monitoring still constrain broader replication across diverse hydro-climatic contexts.

Beyond quantity, spring water quality is an increasing concern, particularly in densely populated or tourist-impacted mountain regions. In the Rocky Mountains (USA) and the Swiss Alps, microbial contamination from livestock and recreation has been documented, with seasonal peaks in coliform and *E. coli* levels, often exceeding safe limits (Burns et al., 2014; Dechesne et al., 2021). In Nepal, coliform and nitrate pollution have been linked to open defecation and unregulated agriculture in spring recharge zones (Pant et al., 2020). Internationally, spring water quality is assessed using parameters such as pH, EC, TDS, and major ions, along with trace elements and microbial indicators. Tools such as the Water Quality Index (WQI) provide integrative assessments for potability and spatial prioritization, and have been widely used in studies from Turkey, South Africa, and Latin America (Avvannavar & Shrihari, 2008; Yisa & Jimoh, 2010). These studies reaffirm that spring degradation is not just a local or national issue but a transboundary challenge with implications for health, gender equity, and sustainable development.

In view of the importance of springs, there is urgent need for conducting spring mapping and it was stressed by the NITI Aayog Working group-I report on “Inventory and Revival of Springs in the Himalayas for Water Security” released in 2018. Report took the stock of magnitude of drying of springs in Indian Himalayan Region (IHR) and found that half of the perennial springs have already dried up or have become seasonal resulting in acute water shortages across hundreds of Himalayan villages. The report revealed that the available secondary data on springs underestimate the actual count of spring and hence the report emphasized on the urgent need of spring mapping and creation of Web-enabled database/web portal on which springs can be mapped/tagged by all states, Govt. Depts., R&D Institutions and NGOs working on springs. NITI Aayog estimated a gross estimate of 3 million springs across the Indian Himalayan Region.

Inventorization of huge number of spring through physical investigation is not possible. The springshed project was taken up at the instance of a decision taken in the meeting of Secretary, MoWR on 20.03.2019 that CGWB & Survey of India (SoI) may prepare a proposal for pilot project in some districts of Uttarakhand through which Ganga is flowing. CGWB, Uttarakhand region (UR) recommended that the pilot project can be taken up in one of the three districts Uttarkashi, Tehri Garhwal & Almora. Survey of India has submitted the timeline & cost estimate for drone based systematic mapping of spring, 100% inventory of all springs & their ground-truthing, delineating springsheds, creation of 3-D model of springsheds and preparation of Atlas for Tehri Garhwal District under the guidance of CGWB. As NMCG was already carrying out project with SoI, another project was also taken up for drone study in Tehri Garhwal District & CGWB was advised to take up a pilot study in one area in the district. Accordingly, Pratapnagar Block (about 439 sq km), Tehri Garhwal District was identified for pilot study. Due to various procurement related issues, there has been a delay in the drone survey of Tehri Garhwal district by SoI. Consequently, Ministry has accorded approval for taking up management & restorative initiatives for spring rejuvenation activity in Bhilangana C.D block of Tehri Garhwal (about 1093 sq km.) & Ukhimath C.D. block (about 1081 sq. km.) of Rudraprayag district for which the LiDAR DEM is already available with SoI. By using DEM, point cloud and ORI of Manu Project in Bilangana CD block of Tehri Garhwal District and Ukhimath CD block of Rudraprayag District & drone mounted LiDAR data of Pratpnagar Block, Tehri Garhwal District, spring identification and demarcation of spring shed will be carried out by SoI and shared with CGWB. District Administrations will be approached for carrying out the preparation of DPR for spring rejuvenation structures by MGNREGS & execution of DPR through MGNREGS fund in Bhilangana & Pratapnagar blocks of Tehri Garhwal district & Ukhimath block of Rudraprayag district. In view of the man power constraints, it was decided to take up the study through outsourcing work. As NIH has already completed spring study in parts of Himachal Pradesh & has also prepared a web-based application for spring data storage (ISHVAR - Information System of Himalayan Springs for Vulnerability Assessment and Rejuvenation), it was felt prudent to utilize the expertise of NIH in springshed work. In this regard NIH given a task to physically verify the data collected by State of the technologies (LiDAR DEM, point cloud etc.). In lieu a MoU was inked between CGWB and NIH to jointly carry-out the study titled "Ascertaining the Efficacy of Use of State-of-the-Art Technologies for Spring Mapping and Sustainability of Springs Through Suitable Interventions". As per the MoU the responsibilities of CGWB and NIH in respect of deliverables is as follows (Table.1.1):

Table.1.1 Responsibilities of CGWB and NIH as per the MoU in Relation to Deliverables

S. No.	**Deliverable**	**Responsibility**
1	Validation of spring maps of prepared by SoI using State of the art technologies (drone-based LiDAR, DEM, point cloud & ORI) & updation of spring atlas if necessary	NIH
2	Vulnerable Springs identification	NIH
3	Monitoring of vulnerable springs	CGWB
4	Creation of Spring Database & its regular updation in web based application developed by NIH	NIH
5	Identification of water conservation/artificial recharge structures for sustainability of vulnerable springs	CGWB
6	Liaison with District Administration for preparation of DPR for construction of water conservation/artificial recharge structures & its execution through MGNREGS fund	CGWB
7	Capacity Building	NIH
8	Impact Assessment Report	CGWB
9	Preparation of Final Report	NIH & CGWB

1.2 Objectives of the study

In view of the deliverable and responsibilities given to NIH as per MoU, NIH envisaged an internal study with the following objectives: To physically validate the springs identified by the Survey of India (SOI) using state-of-the-art technologies in the Bilangana and Pratapnagar CD blocks of Tehri Garhwal District and Ukhimath CD block of Rudraprayag District of Uttarakhand state.

1) To create a spring database/spring atlas and establish mechanisms for its regular updating.

2) To conduct water quality analysis of the surveyed springs to evaluate their qualitative status.

3) To identify vulnerable springs that require rejuvenation interventions.

4) To develop the capacity of local stakeholders and implementing agencies for the effective implementation and management of a spring-shed development programme.

2. REVIEW OF LITERATURE

2.1 General

Springs are essential hydrogeological features that support sustainable water supply in mountainous regions worldwide, including parts of Asia, Africa, Europe, and the Americas. They represent naturally emerging groundwater discharge points, often constituting the most accessible and cost-effective sources of potable water in hilly terrains where piped infrastructure is limited or economically unviable (Negi et al., 2020; Rai et al., 2023). In the Indian context, springs provide drinking water to an estimated 15–20% of the rural population, with their importance amplified in ecologically sensitive regions such as the Indian Himalayan Region (IHR), Western and Eastern Ghats, and central uplands like the Satpura and Vindhyan ranges (CGWB, 2021; Sinha et al., 2022). The Indian Himalayan Region, spanning across 12 mountain states and covering an area of approximately 5.4 lakh square kilometers, serves as a vital freshwater reserve, feeding several major rivers including the Ganga, Brahmaputra, and Indus. This region plays a central role in maintaining ecological stability, hydrological connectivity, and climatic balance across the subcontinent (MoEF&CC, 2020). Springs in the IHR not only sustain local biodiversity and forest ecosystems, but also underpin agricultural productivity, rural livelihoods, and drinking water security in thousands of scattered mountain villages (Upadhyay & Das, 2023).

However, with rising pressures from climate change, unregulated development, and land-use alterations, these springs are under increasing stress. The consequences include declining discharge, seasonal drying, and deterioration in water quality, particularly from microbial and nitrate contamination. This has made spring vulnerability assessments and hydrochemical monitoring a national priority under various water resource and climate adaptation programs (NIH, 2022; Rawat et al., 2024). Consequently, integrated, science-driven efforts are needed to map, monitor, and revive spring systems.

2.2. International context

Spring hydrology holds critical importance in mountain regions worldwide, where springs serve as reliable, perennial water sources in steep, inaccessible terrain, often providing the only source of safe drinking water, irrigation, and livestock use for rural and indigenous populations. Globally, mountain springs are essential components of hydrological and ecological systems, ensuring the baseflow of headwater streams, maintaining riparian biodiversity, and securing water for human settlements located away from surface water bodies. In mountainous areas such as the Alps, Andes, Hindu Kush-Himalayas, and Appalachian ranges, springs represent not just physical sources of groundwater emergence but also socio-cultural and economic lifelines. For instance, in the European Alps, springs are tightly linked to karst hydrogeology and snowmelt dynamics, buffering seasonal variability and drought conditions (Jeannin et al., 2013). Similarly, in the Andean highlands, springs support smallholder farming, community water supply, and sacred rituals tied to traditional water governance (Browder, 2000). In regions like Bhutan, Nepal, and Rwanda, the degradation of spring flows has spurred state- and NGO-led interventions aimed at restoring spring recharge through catchment-based approaches (Sharma et al., 2016; Dorji & Gilmour, 2020; WaterAid, 2021). Internationally, springs are generally classified by their hydrogeological and geomorphic characteristics—such as fracture, depression, seepage, or artesian types—and exhibit discharge variability governed by geology, land cover, rainfall intensity, and seasonal snowmelt. Karst springs in the Balkans and southeastern U.S. demonstrate fast and high-volume responses to rainfall due to their conduit-dominated aquifer systems, whereas fractured rock springs, common in the Himalayas and East Africa, show slower recharge responses due to limited permeability and structural controls (Kresic & Stevanović, 2010; Clark et al., 2015). Spring-shed management (SSM), an integrated strategy to protect and enhance spring recharge zones, has emerged as a global best practice in response to widespread spring drying driven by deforestation, land use changes, and climate variability. Notably, the Dhara Vikas program in Sikkim and the springshed revival projects in Nepal and Bhutan have combined hydrogeological surveys and community-led watershed treatments (e.g., trenches, recharge pits, forest conservation) to significantly restore spring discharge and water security (ICIMOD, 2015; Sharma et al., 2016). Rwanda has also implemented mobile GIS-based spring inventories to identify vulnerable sources and prioritize protection through local engagement (WaterAid, 2021). Despite their effectiveness, many mountain regions still lack digitized spring databases, standardized assessment frameworks, and sustained monitoring systems. Another critical dimension is the assessment of spring water quality, which is increasingly threatened by contamination/pollution due to sanitation gaps, agricultural runoff, open defecation, and tourism pressures in ecologically sensitive mountain zones. In the Rocky Mountains and Swiss Alps, coliform outbreaks have been linked to livestock grazing and visitor inflow, while in Nepal and parts of East Africa, nitrate levels exceeding WHO limits have been reported due to agricultural intensification and poor waste management (Burns et al., 2014; Dechesne et al., 2021; Pant et al., 2020).

Consequently, international methodologies emphasize water quality monitoring using both field-based physico-chemical parameters (pH, EC, TDS, temperature) and laboratory analysis for major ions, trace metals, and microbial contaminants through sophisticated machines like IC and ICP-MS (Nkotagu, 1996; Avvannavar & Shrihari, 2008). Many studies also applied Water Quality Index (WQI) frameworks—based on WHO and national drinking water standards—to integrate multiple parameters into a single potability score for easier interpretation by decision-makers. For example, WQI assessments have been applied in the Andes and Turkey to classify spring water quality into categories (excellent, good, poor, etc.), enabling spatial prioritization of interventions (Yisa & Jimoh, 2010; Avvannavar & Shrihari, 2008). Overall, international research highlights the pressing need to safeguard mountain springs through multidisciplinary, climate-resilient, and community-driven approaches. The combination of participatory hydrology, technological innovation (like GIS and mobile-based tools), and long-term hydrochemical monitoring is crucial for reversing the degradation trends and ensuring equitable access to clean and sustainable spring water. However, key knowledge gaps remain in scaling these approaches across diverse geological and cultural contexts, integrating traditional knowledge systems with scientific assessment, and building institutional capacities for spring governance. The international literature makes it clear that springs are not isolated hydrogeological features but dynamic socio-ecological systems requiring holistic management strategies that consider groundwater recharge, ecological function, social dependency, and climate risks. As climate change continues to alter precipitation patterns and increase hydro-meteorological variability, protecting mountain springs through evidence-based planning and inclusive governance becomes more urgent than ever for ensuring water security and resilience in vulnerable upland regions across the globe.

2.3. National context

Over the past two decades, a significant number of Himalayan springs have either dried up or become seasonal, largely due to land-use changes, deforestation, and unregulated development, which have disrupted natural recharge processes (ICIMOD, 2015; Agarwal et al., 2012). This degradation is further compounded by climatic stressors, including rising temperatures, delayed monsoons, and increasingly erratic rainfall patterns, which reduce infiltration and groundwater recharge (Rawat et al., 2016). Empirical studies across the Indian Himalayas reveal alarming trends. In Kumaon, a 40% reduction in spring discharge was reported between 1951 and 1986 due to vegetation and land-use shifts (Valdiya & Bartarya, 1989). Similarly, in the Kosi basin, nearly 28% of perennial springs became seasonal by 2010

(Rawat et al., 2016). In Sikkim, Tambe et al. (2012) observed a 50% decline in discharge within a decade, prompting the launch of the Dhara Vikas programme—India's pioneering spring-shed initiative—which improved spring flow by up to 230% through catchment-based recharge interventions. Spring drying is not limited to the Eastern Himalayas; in Himachal Pradesh, only 30% of traditional sources were found functional, while 70% faced imminent failure (Bharadwaj, 2014) in a survey conducted in *grampanchyat* of seven districts of the state. Studies also link topography, geology, rainfall patterns, and anthropogenic disturbances with spring vulnerability (Negi & Joshi, 2004; Jeelani et al., 2010).These findings underscore the urgent need for localized recharge planning and integrated watershed management to restore spring sustainability in the Western Himalayas.

The Bhilangana, Pratapnagar, and Ukhimath blocks, located in the Western Himalayan region of Uttarakhand, exemplify this vulnerability. These areas are characterized by rugged topography, steep slopes, and scattered rural settlements, where natural springs remain the primary source of drinking water. Field studies and local knowledge suggest a notable decline in spring discharge, especially during lean seasons. The Bhilangana block falls within the Bhilangana river catchment, while Pratapnagar lies across tributaries draining into the Bhagirathi, and Ukhimath is located within the Mandakini river catchment. These river systems are sustained in their upper reaches by the glacier melts and spring flows, which are now increasingly become intermittent (Malik et al., 2023; Bisht et al., 2024).

In addition to decreasing discharge, spring water quality is a growing concern. Recent hydrochemical investigations have indicated rising concentrations of nitrate, coliform bacteria, and other contaminants due to land-use changes, open defecation, and agrochemical runoff, posing significant health risks to dependent populations (Pant et al., 2021). As spring ecosystems are deeply interlinked with forest health, soil properties, and subsurface hydrology, their degradation threatens not only human water security but also regional biodiversity and ecological integrity.

Recognizing the socio-ecological importance of springs, and the urgent need for evidence-based planning, there is urgent need for identification, assessment, and sustainable management of springs in the Indian Himalayan region. A combination of field surveys, hydrochemical analysis, spatial data integration, and community engagement need to be employed to assess both the vulnerability and quality of spring resources.

3. STUDY AREA

The present study was carried-out in three water scare blocks of Uttarakhand i.e., Bhilangana and Pratapnagar blocks of Tehri Garhwal district and Ukhimath block of Rudraprayag district.

3.1 Bhilanagna block

The Bhilangana Block is situated in the Tehri Garhwal district of Uttarakhand, India, and largely falls in the Bhilangana River catchment, between 30°22′–30°55′ N latitude and 78°32′–79°04′ E longitude, covering an area of approximately 1,343.5 km² (Fig. 1). The region is traversed by the Bhilangana River and its two major tributaries Balganga and Dharmganga which are originated from the Khatling Glacier (30°49′ N, 78°54′ E) at an elevation of around 3,700 m amsl. These tributaries meet at Budhakedar, after which Balganga flows southward for about 25 km to join the Bhilangana River at Ghansali. Bhilangana River flow continues toward the Tehri Dam, one of the highest dams in India, where it ultimately merges with the Bhagirathi River (Banerjee et al., 2020). The region is physiographically diverse, with elevations ranging from 620 m to 6,700 m amsl, encompassing rugged middle Himalayan zones, glacial landscapes, and deep valleys. Geologically, the area is divided into the Lesser Himalayan Zone and the Central Himalayan Zone, separated by the prominent Main Central Thrust (MCT) (Rai et al., 2024). Topographically, the area consists of steep ridges, fluvio-glacial valleys, and a dense drainage network shaped by active erosion and downcutting. Soils in the region varies from brown forest soils at higher altitudes to alluvial soils in the valley regions. The climate of the region ranges from cold temperate in the north to subtropical in the southern valleys. Winter temperatures can drop to around 0°C, and summer temperatures range between 17°C and 36°C. Annual precipitation varies with elevation, and relative humidity ranges from 35% to 76%, with snowfall common in higher altitudes and rainfall prevailing in the lower zones.

3.2 Pratapnagar Block

The Pratapnagar block, situated in the western part of Tehri Garhwal district in Uttarakhand, India, lies between 30°22′–30°36′ N latitude and 78°23′–78°43′ E longitude, covering an area of approximately 755.4 km² (Malik et al., 2023). The block is predominantly hilly, featuring terraced slopes, moderately elevated ridges, and deeply incised valleys, with elevations ranging from 800 meters to 2,400 meters above mean sea level (amsl). Pratapnagar Block comprises several minor tributaries that ultimately drain into the Bhagirathi and Bhilangana

Rivers, forming an integral part of the upper Ganga River system. The region experiences a humid subtropical to temperate climate, characterized by warm summers and cold winters. Summer temperatures typically range from 15°C to 32°C, while winter lows can drop to around 3–4°C. The average annual rainfall is between 1,100 mm and 1,300 mm, most of which is received during the southwest monsoon from June to September. Occasional winter precipitation also contributes to the hydrological regime. This monsoonal rainfall pattern plays a crucial role in recharging the groundwater that sustains the numerous natural springs in the region. However, increasing deforestation, agricultural expansion, and slope instability have placed mounting pressure on the region's spring resources, affecting both spring discharge and water quality. These stressors render the Pratapnagar block a critical area for spring vulnerability assessments and hydrochemical evaluations, especially in the context of climate variability and sustainable water resource management in the Himalayas.

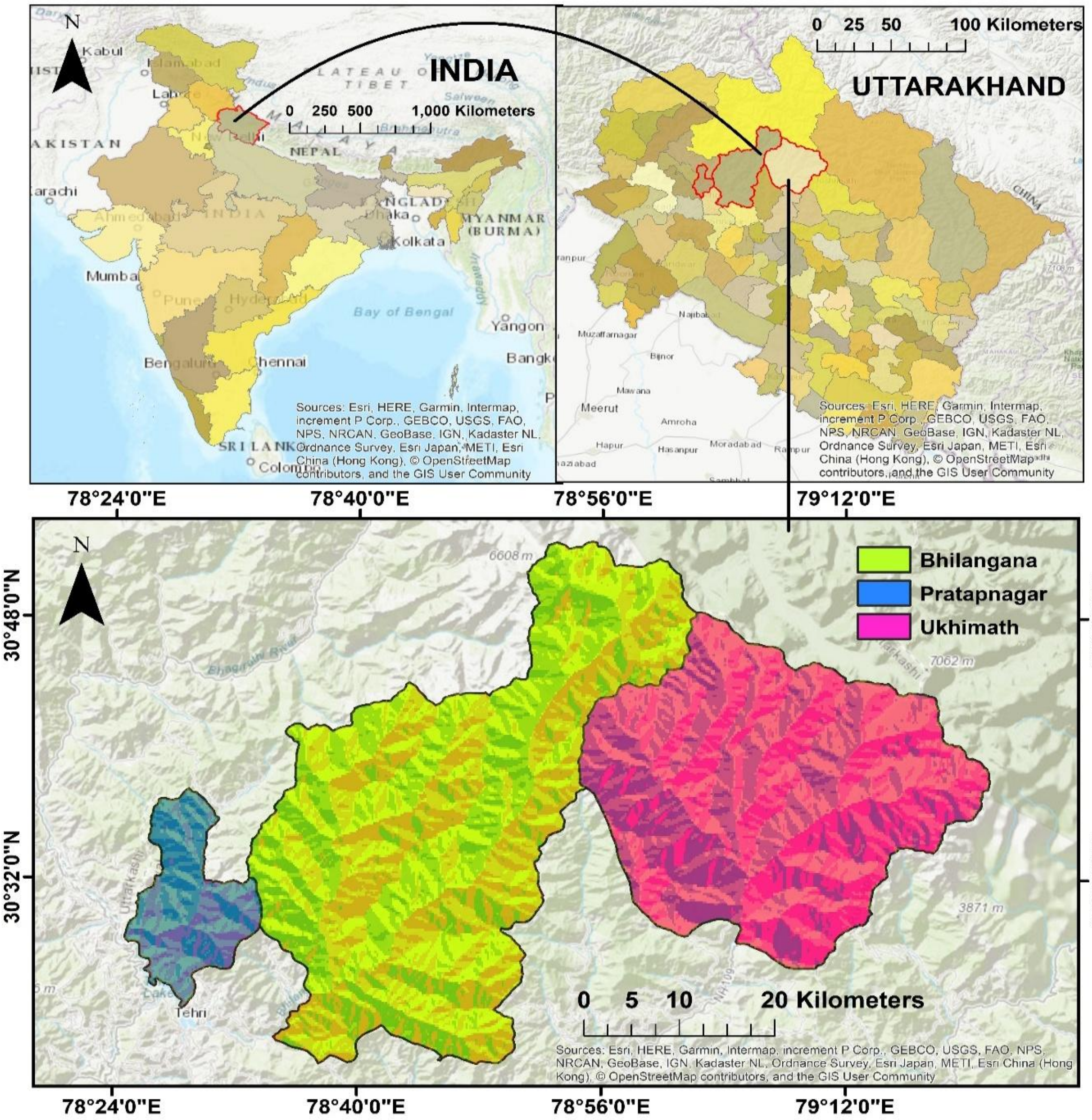

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Fig. 3.1 Study area map

3.3 Ukhimath Block

The Ukhimath Block, situated in Rudraprayag district, lies between 30°28′–30°42′ N latitude and 79°03′–79°25′ E longitude, covering approximately 703.2 km². Elevations range from 1,300 m to 3,900 m amsl, placing the block in a transitional zone between mid-Himalayan valleys and high-altitude terrain. It falls within the Mandakini River catchment, with the river sourced from the Chorabari Glacier near Kedarnath (~3,895 m). Numerous smaller streams and glacial melt-fed channels traverse the area. The climate is humid temperate to subalpine, governed by elevation. Summer temperatures range from 10°C to 25°C, while winter temperatures frequently fall below 0°C, with snowfall common in upper regions. The block receives average 1,300 mm of rainfall annually, mostly during the monsoon, with significant snowfall during December to February months. These climatic dynamics influence spring recharge patterns, especially in higher altitudes where snowmelt plays a critical role. Topographically, Ukhimath is characterized by steep ridges, glacial valleys, and fragile slopes. Springs are essential for high-altitude settlements that lack perennial surface water. However, climate variability, glacial retreat, and increased tourism have stressed spring systems, leading to seasonal drying, reduced discharge, and rising contamination risks.

The region is covered by dense forests of deodar (*Cedrus deodara*), oak (*Quercus leucotrichophora*), and fir (*Abies spectabilis*), which are vital for aquifer recharge. However, land-use changes and slope degradation have exacerbated spring vulnerability, particularly during heavy monsoon rainfall.

3.4. Geological Setting and Structural Lineaments of the Study Area

3.4.1 Geology

The study area, encompassing the Bhilangana, Pratapnagar, and Ukhimath blocks in the western part of Uttarakhand, is geologically diverse and structurally complex, lying within the active Himalayan orogeny. The region primarily features six major geological units: Bhilangana Group, Central Crystalline, Garhwal Group, Jaunsar Group, Newer Alluvium, and Undifferentiated Quaternary deposits, as represented in the legend. The Central Crystalline rocks dominate the central and northeastern sectors. These are chiefly composed of high-grade metamorphic rocks such as gneisses, schists, and migmatites, indicative of deep crustal processes (Valdiya, 1980). These formations are often highly jointed and fractured, significantly influencing groundwater percolation. The Garhwal Group occupies the transitional belt and comprises low- to medium-grade metamorphic rocks, including phyllites and quartzites. These lithologies serve as moderate aquifers in structurally controlled zones (Fig. 3.2). The Jaunsar Group, found in the southwestern margins, is made up of metasedimentary rocks like slates and sandstones. The Bhilangana Group represents a significant litho-tectonic unit with intercalated volcanic and sedimentary sequences, associated with tectonically sheared zones. This unit is particularly prone to landslides and slope instability (Nautiyal et al., 2014). The Newer Alluvium and Undifferentiated Quaternary deposits along the river valleys and lower elevations consist of unconsolidated sediments sand, gravel, and silt acting as important shallow aquifers with high recharge potential (Rawat & Pant, 2021). Lineament analysis, often aligned with thrusts and faults (like MCT and MBT), reveals that the study area is structurally dissected, facilitating preferential groundwater flow paths. The presence of numerous lineaments, especially in the Central Crystalline and Bhilangana formations, suggests tectonic control over spring emergence zones (Singh et al., 2020).

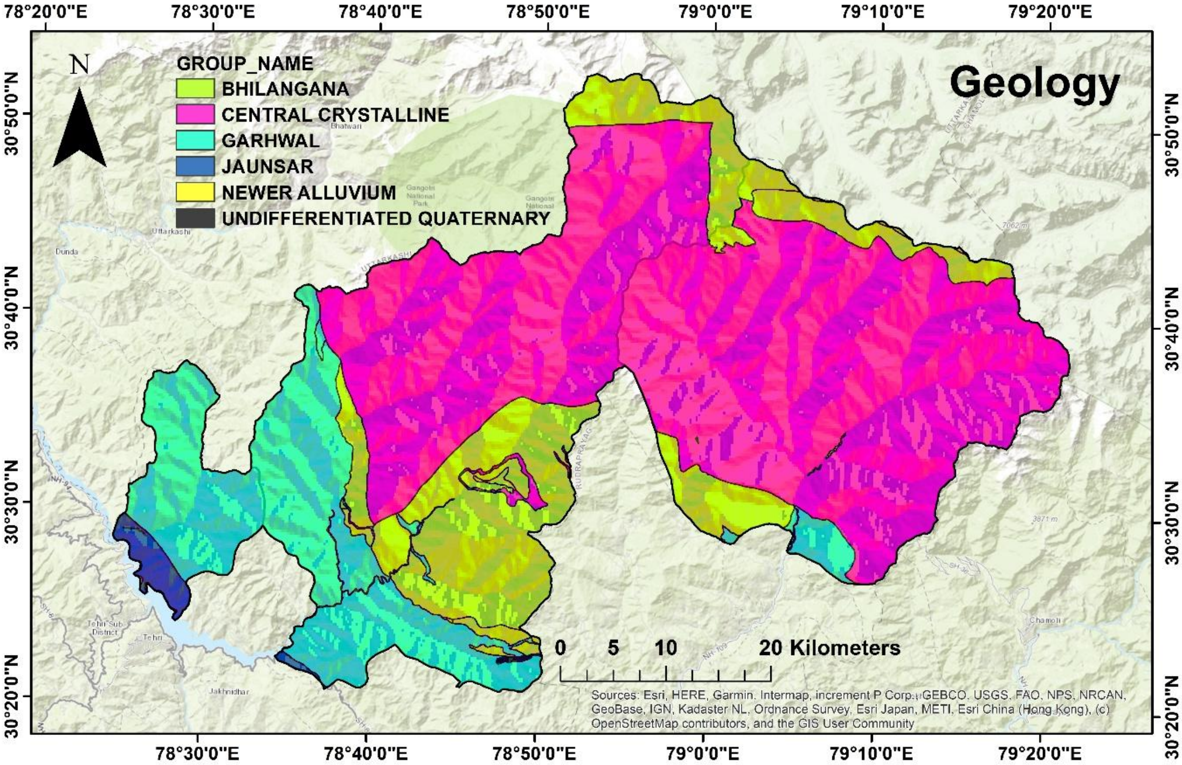


Fig. 3.2 Geology of the Study area

3.4.2. Lineament

The study area, comprising the Bhilangana, Pratapnagar, and Ukhimath blocks, is traversed by a well-defined network of structural and geomorphic lineaments, interpreted from remote sensing data and topographic analysis (Fig. 3.3). The structural lineaments, represented by red dashed lines, predominantly follow NE–SW and NW–SE orientations, indicating strong tectonic control and suggesting zones of crustal weakness that influence local deformation, slope breaks, and subsurface permeability. Geomorphic lineaments, shown in green dashed lines, are primarily concentrated in the Bhilangana block, with limited presence in Ukhimath. These lineaments follow linear valley systems and drainage alignments, highlighting the influence of erosional processes and structural controls on landscape evolution.

Among the three blocks, Bhilangana shows the highest density of both structural and geomorphic lineaments, indicating a more tectonically active setting with potentially greater subsurface water movement through fractures. In contrast, Ukhimath exhibits a moderate distribution of structural lineaments, particularly trending ENE–WSW, which may play a role in linking deeper aquifers to surface discharge points. Pratapnagar displays fewer and more dispersed structural lineaments, with no geomorphic lineaments identified in the mapped extent, suggesting limited structural influence or subdued topographic relief. The intersection zones of structural and geomorphic lineaments are particularly significant, as they are favorable sites for groundwater recharge and spring emergence, making them valuable targets for spring rejuvenation and watershed management efforts in the region.

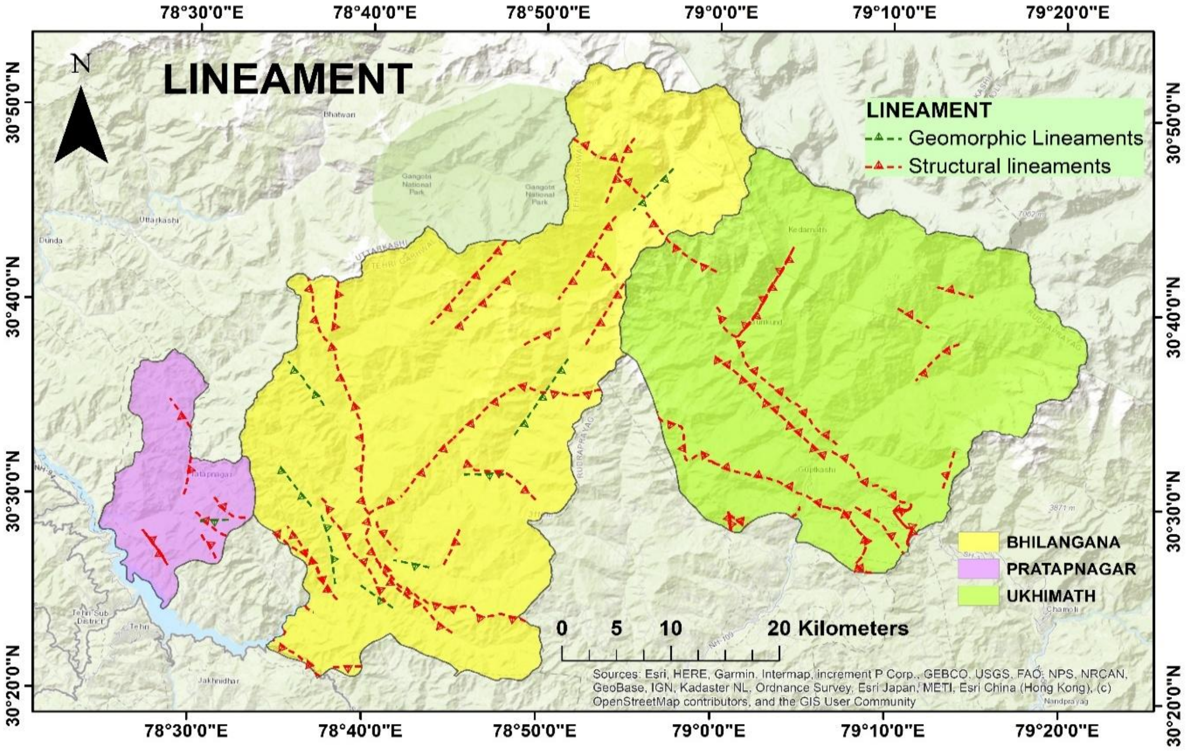


Fig.3.3 Lineament Structures of the Study area

3.5. Land Use/Land Cover and Soil Characteristics of the Study Area

3.5.1 Land Use/Land Cover

The LULC map of the Bhilangana, Pratapnagar, and Ukhimath blocks (Fig. 3.4) illustrates a predominantly forested landscape, typical of the mid- to high-altitude Himalayan regions. According to the legend, the area is classified into six major LULC categories: Forest, Built-up Area, Barren Land, Water Bodies, Snow, and Rangeland. Forest cover is the most dominant category, accounting for over 70% of the total area. These forests play a vital role in maintaining the ecological and hydrological balance, particularly in recharging springs and regulating streamflow (Rawat & Pant, 2021). Built-up areas are scattered, concentrated mainly around Tehri, Ghansali, and Ukhimath towns, indicating low-density rural settlements. Expansion in these zones is primarily linear, following road networks and valleys (Singh et al., 2020). Barren lands are observed in the higher elevations, often above the treeline. These areas include rocky outcrops and degraded slopes with little to no vegetation, prone to erosion and landslides (Nautiyal et al., 2014). Water bodies, marked in blue, are sparse but include rivers like the Bhilangana and Bhagirathi, which play a key role in downstream irrigation and hydropower generation. Snow cover is evident in the northern parts of Ukhimath, particularly along the ridges of Kedarnath Wildlife Sanctuary and Gangotri National Park. These zones contribute significantly to seasonal snowmelt recharge to springs and rivers (Negi et al., 2015). Rangelands are prevalent in transition zones between forested and barren areas, often used for seasonal grazing. These areas are important for local livelihoods but are also susceptible to overgrazing and soil compaction.

Land use is significantly influenced by elevation, slope, and accessibility, with anthropogenic activities increasing near accessible lower slopes. The pattern observed reflects the fragile mountain socio-ecology where land cover changes directly affect spring discharge and watershed health.

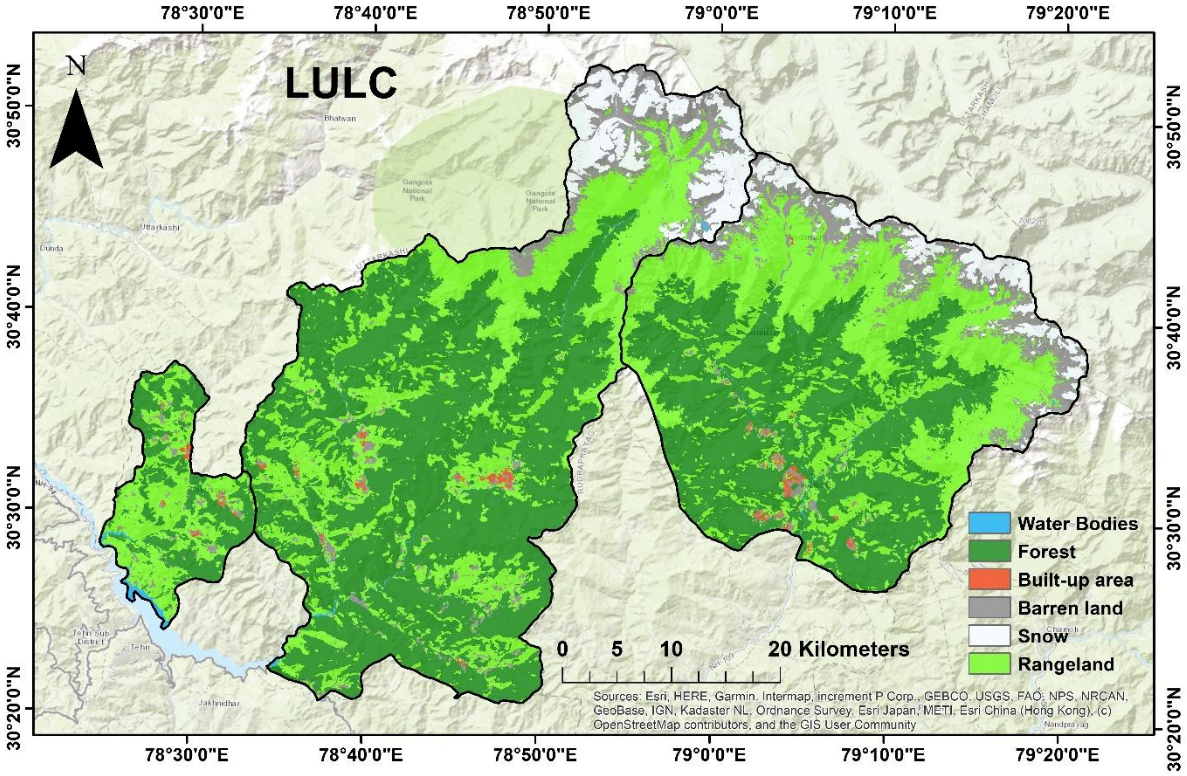
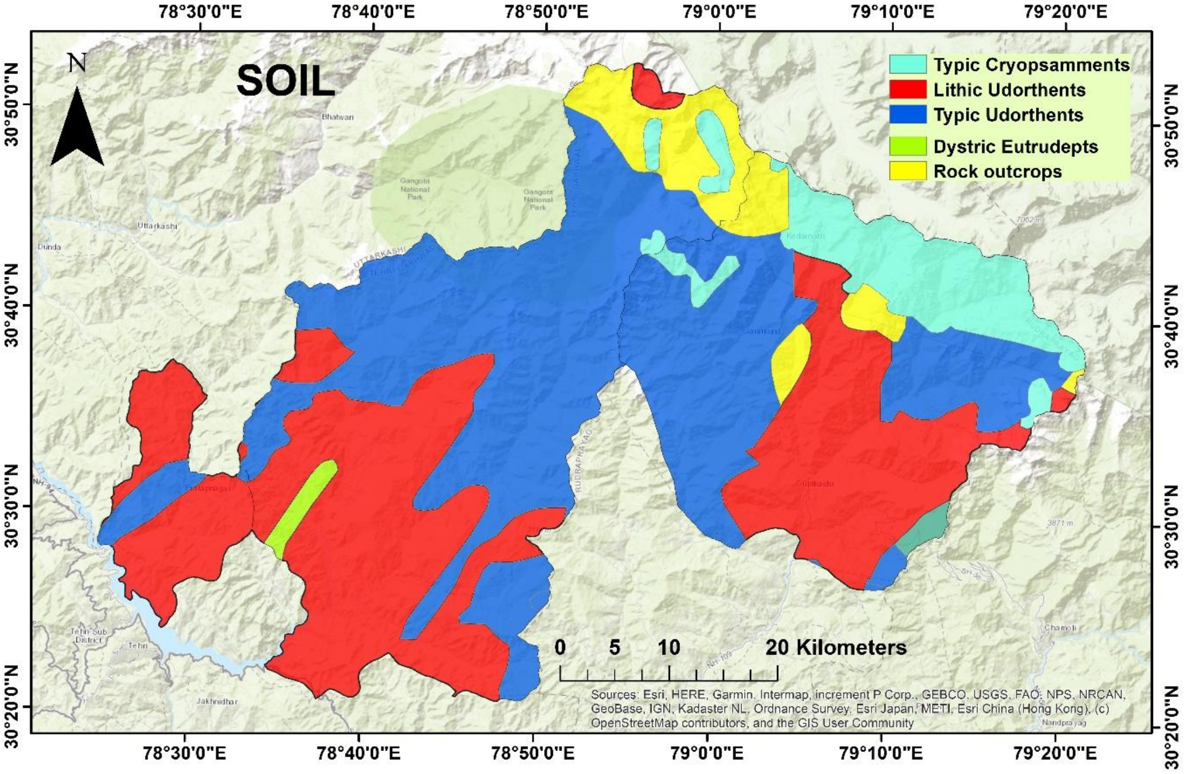


Fig.3.4 LULC of the Study area

3.5.2. Soil Characteristics

The study area spans a geologically and topographically complex terrain that hosts a variety of soil subgroups as depicted in the soil map. The identified soil types include Typic Udorthents, Lithic Udorthents, Typic Cryopsamments, Dystric Eutrudepts, and Rock Outcrops, each distributed across different physiographic units (Fig. 3.5). Typic Udorthents dominate the central and southern parts of the study area, particularly in the Bhilangana and Ukhimath regions. These are shallow to moderately deep, well-drained, and formed from colluvial or residual materials on hill slopes. They are typically skeletal, erosion-prone soils associated with steep slopes (Rawat & Pant, 2021). Lithic Udorthents are distributed in the western and southeastern margins, especially in Pratapnagar. These are shallow soils with lithic contact within 50 cm, indicating proximity to bedrock. Their limited depth and stoniness reduce their agricultural and recharge potential (Nautiyal et al., 2014). Typic Cryopsamments found in the high-altitude northern regions of Ukhimath, are coarse-textured, sandy soils formed under cold climate conditions. These soils are typically associated with periglacial environments and have poor nutrient retention (Negi et al., 2015). Dystric Eutrudepts occurring in isolated patches in Bhilangana and Pratapnagar, are moderately developed, acidic soils with moderate fertility. These are derived from schist and gneissic parent material and are moderately suitable for agriculture in gently sloping areas (Singh et al., 2020). Rock outcrops are found along the high relief zones, particularly in the north and northeast. These areas are non-arable and represent zones of minimal soil formation, usually exposed or thinly covered by soil. The variation in soil distribution reflects the underlying geology, slope gradient, and erosion processes, which in turn directly influence the hydrological response of the catchment, including spring discharge and recharge areas.

Understanding these soil characteristics is vital for spring-shed development, erosion control, and sustainable land use planning in the fragile Himalayan ecosystem.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Fig.3.5: Soil Characteristics of the Study area

4. MATERIALS AND METHODS

4.1 Spring Mapping Methodology

The present study adopted a systematic methodology to assess spring water resources in the Himalayan region. The process included site selection, spring inventory, and sampling for hydrochemical and quality analysis. Laboratory analysis was conducted to evaluate key water quality parameters. The Water Quality Index (WQI) and vulnerability assessment frameworks were applied to determine potability and risk levels. Climatic and topographic data were integrated to understand spring recharge dynamics; Fig.1 illustrates the complete methodology in a schematic flowchart.

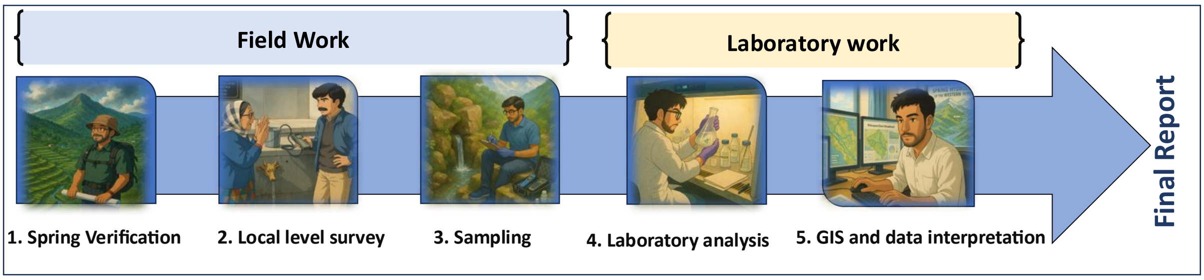


Fig.4.1: Flowchart of methodology

(a) Verification and Geotagging of Springs

To verify the spring locations provided by the Survey of India (SOI), a systematic geospatial and field-based approach was adopted. The spring location data received from SOI included latitude and longitude coordinates, which were initially compiled and organized into a structured dataset. This geospatial data was then converted into CSV and KML file formats using GIS software tools to facilitate visualization and navigation in Google Earth Pro. The KML files were imported into GPS-enabled mobile devices, enabling field teams to access and track spring coordinates on-site. During field visits, a positional filter of ≤50 meters was applied to identify and validate the presence of springs near their mapped coordinates. This buffer was chosen based on acceptable GPS accuracy under standard field conditions. Each site was assessed for the presence of an actual spring, and its condition was recorded. In certain locations, network connectivity issues posed challenges in real-time GPS positioning using mobile devices. To overcome this, a Garmin handheld GPS device was also used to capture precise coordinates and cross-check the location accuracy. This dual verification method ensured a higher level of confidence in spatial accuracy, especially in remote and topographically challenging terrains.

(b) Onsite parameters and Collection of Water Samples for Laboratory Analysis.

Onsite measurements of basic physico-chemical parameters such as pH, temperature, and electrical conductivity (EC) were carried out at each spring using portable field meters. These real-time observations provided immediate insights into the water's physical condition and potential contamination. The Fig.2 illustrates field photographs taken during activities conducted in the study area. Water samples were then collected in pre-cleaned, sterilized polyethylene bottles following standard procedures (APHA, 2017). Each sample was labelled with the spring name, location coordinates, date, and time of collection. The samples were promptly transported to the laboratory under cooled conditions for detailed analysis of major ions and other water quality parameters.

Fig. 4.2 Field and laboratory activities for spring water assessment: (a) community interaction during site visit, (b) on-site measurement and sampling, (c) sterile water sample collection, (d) field testing at a natural spring, and (e) laboratory analysis of samples.

4.2 Laboratory analysis

(a) Carbonate and Bicarbonates

The measurement of carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and alkalinity was carried out using unfiltered water samples on an automatic titrator, following the APHA Standard Methods for the Examination of Water and Wastewater (2017), Method 2320 B.

For the analysis, 25 ml of each sample was titrated with 0.02N sulfuric acid (H_2SO_4). The titration endpoints corresponding to carbonate and bicarbonate were determined using the automated detection system. To ensure analytical accuracy, a subset of randomly selected samples was re-analysed. The concentrations of CO_3^{2-}, HCO_3^{-}, and total alkalinity were calculated and expressed in mg/L as $CaCO_3$.

(b) Major Ions

The samples collected in 250 ml narrow mouth bottles for the analysis of major ions were filtered through 0.45μ nylon filters. The major ions i.e. Fluoride (F^-), Chloride (Cl^-), Sulphate (SO_4^{2-}), Phosphate (PO_4^{2-}), Nitrate (NO_3^-), Sodium (Na^+), Potassium (K^+), Ammonium (NH_4^+), Magnesium (Mg^{2+}) and Calcium (Ca^{2+}) were analysed on Ion Chromatograph (IC). Prior to analysis the instrument was calibrated with Merck standards and the results were reported with an analytical precision of ±5%. 5ml of each sample were diluted 10 times with Milli-Q water (De-ionized water with a resistance of 18.2 MΩ-cm) to bring the ionic concentration in the sample within the sensitivity of the instrument.

(c) Trace metals

One aliquot of samples was also collected in 60 ml bottles to carry out the analysis of trace metals. Total 10 trace metals including lead (Pb), zinc (Zn), arsenic (As), cadmium (Cd), nickel (Ni), boron (B), aluminium (Al), chromium (Cr), manganese (Mn) and iron (Fe) were analysed on Inductively Coupled Plasma Mass Spectrometry (ICP-MS). During the sampling 0.3 ml concentrated HNO_3/60ml of the samples were added to lower down the pH to 2.0. Prior to analysis, the instrument was calibrated with Merck (multi-element) standards to maintain the accuracy of the results. The results are reported with an analytical precision of ±5%.

4.4 Water Quality Index (WQI) Computation

To evaluate the suitability of spring water for drinking purposes, the Water Quality Index (WQI) method was employed. This index provides a comprehensive representation of overall water quality by aggregating multiple physico-chemical parameters into a single score. The methodology adopted in this study adheres to the standards and permissible limits outlined by the Bureau of Indian Standards (BIS) IS: 10500 (1991, revised 2012) and the World Health Organization (WHO, 2006).

(a) Selection of Water Quality Parameters

A total of 11 physico-chemical parameters relevant to human health and water potability were selected for the analysis. These include pH, Fluoride (F^-), Chloride (Cl^-), Sulphate (SO_4^{2-}), Nitrate (NO_3^-), Sodium (Na^+), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), Total Dissolved Solids (TDS), Total Hardness, and Ammonium (NH_4^+). The concentration of each parameter was determined using standard laboratory techniques.

(b) Assignment of Weights (w_i)

Each parameter was assigned a weight (w_i) based on its relative importance and potential health impact, with a scale ranging from 1 (least significant) to 5 (most significant). Parameters with greater health significance, such as nitrate (NO_3^-), were assigned the highest weight ($w_i = 5$), considering their potential toxicity and widespread occurrence in groundwater pollution. These weight assignments were guided by previous studies (e.g., Ramakrishnaih et al., 2009) and regulatory guidelines.

(c) Calculation of Relative Weights (W_i)

The relative weight (W_i) for each parameter was computed using the following formula:

$$W_i = wi/\sum_{i=1}^{n} \mathrm{wi}$$

where Wi is the relative weight, wi is the weight of each parameter, n is the number of parameters.

Subsequently, a quality rating scale (qi) has been computed for each parameter by using the following formula;

$$q_i = (C_i * S_i) *100$$

where q_i is quality rating, C_i is concentration of parameters in mg/l, S_i is standard

concentration as per BIS 10500 (1991) norms.

This was followed by calculating the sub-index (SI) and WQI using the following formula:

$SI_i = W_i \times q_i$

$$W_i = \sum_{i=1}^{n} SI_i$$

where SI_i is sub-index of the i^{th} parameter; q_i is rating based on the concentration of i^{th} parameter; n is the number of parameters.

(d) Classification of Water Quality

To interpret the Water Quality Index (WQI) results for spring water, the computed WQI values were categorized into five classes based on established national and international guidelines (Brown et al., 1970; BIS, 2012). These categories Excellent (<50), Good (50–100), Poor (100–200), Very Poor (200–300), and Unsuitable for Drinking (>300) provide a standardized framework for assessing the potability of water (Table 4.1). This classification helps in translating complex water quality data into a simple, communicable format, aiding decision-makers and local stakeholders in identifying critical water quality issues. The categorization also facilitates spatial comparison across springs and highlights areas needing urgent intervention (Tyagi et al., 2013). In this study, most springs were classified under the 'Excellent' category (WQI < 50), indicating high suitability for drinking purposes.

Table 4.1: Range of Water Quality Index values and the respective quality of water

WQI values	Type of water
< 50	Excellent water
50–100	Good water
100–200	Poor water
200–300	Very poor water
> 300	Water unsuitable for drinking purposes

4.5 Vulnerability Analysis

The vulnerability assessment of spring water sources is a vital in the context of the Himalayan region, as springs are the source of water for majority of people. In reality, these regions are characterized by rugged terrain, variable climatic conditions, and limited surface water availability, making springs a critical and often sole source of freshwater for communities. Springs in these areas serve multiple essential functions including drinking water supply, small-scale irrigation, and domestic usage particularly in remote and high-altitude villages where piped supply infrastructure is sparse or absent. Given the increasing anthropogenic pressures, climate variability, and geological fragility of the region, it becomes imperative to understand the vulnerability of these spring systems both in terms of water quality and quantity, and socio-economic dependence. The objective of this assessment is to identify springs at risk of drying, degradation, or contamination and to propose priority areas for *conservation and rejuvenation efforts.*

(a) Database and Indicators for Spring Water Vulnerability Assessment

The vulnerability assessment of spring sources in the Tehri and Rudraprayag blocks was conducted using a multi-criteria evaluation approach that incorporated both hydro-physical and socio-economic indicators. This methodology aimed to capture the complexity of spring dynamics in a mountainous environment, where natural and human-induced factors interact to influence water availability and quality. Eight key parameters were identified based on an extensive review of literature, expert consultation, and contextual relevance to the Himalayan region setting (Table 4.3). The first parameter, spring discharge (measured in litres per minute, lpm), provides a direct measure of the hydrological health of springs. Springs exhibiting low discharge, especially during the pre-monsoon period, were classified as highly vulnerable due to their greater likelihood of drying. The second parameter, nature of the spring (perennial or seasonal), was used to evaluate flow consistency across the year. Perennial springs offer more stability, while seasonal springs common in the mid-altitude regions of Tehri and Rudraprayag are highly susceptible to climatic variations and anthropogenic disruptions such as deforestation or unregulated land-use change. The third indicator, number of dependent households, captured the socio-economic implications of spring vulnerability. Springs serving a larger population were considered more critical due to their role in providing community water security. Fourth parameter i.e., level of dependency, which indicates whether spring water serves as a primary or secondary source for the dependent village. In villages where villagers are using spring water for all/most of the purposes such as drinking, domestic, small-scale irrigation, cattle feeding, etc., spring will pose high vulnerability. The fifth parameter, availability of alternative sources, considered the presence of alternate water sources such as rivers, tanks, or piped networks.

Table 4.3: Spring vulnerability parameters and ranks

S. No.	Parameters	Weight	Classes	Rank
1	Spring discharge magnitude (LPM)	**0.17**	≤5 LPM	**3**
			5 LPM < to ≤20 LPM	**2**
			> 20 LPM	**1**
2	Spring water availability across the year	**0.19**	Seasonal	**3**
			Perennial Spring	**1**
3	Total dependent population on spring (n)	**0.16**	> 300	**3**
			50 < to ≤ 300	**2**

			≤ 50	1
4	Level of dependence	**0.14**	Low	1
			Medium	2
			High	3
5	Availability of alternative water sources	**0.11**	Only Spring	3
			Spring + Pipeline	2
			Spring + Pipeline + Stream	1
6	Variability of spring water flow	**0.13**	Highly Decreased	3
			Decreased	2
			No Change	1
7	Totally Dissolved Solids (mg/L)	**0.16**	TDS > 300	3
			250 < TDS ≤ 300	2
			TDS ≤ 250	1
8	pH	**0.05**	6.5 ≤ pH ≤ 8.5	1
			pH < 6.5 or pH > 8.5	3

Areas with no or limited alternatives were marked as highly vulnerable. The sixth indicator, local observations about whether spring flow was increasing, stable, or declining. These qualitative insights added depth to the quantitative measurements and highlighted the socio-ecological awareness of affected populations. Lastly, water quality, assessed through the measurement of pH and Total Dissolved Solids (TDS) as seventh and eights parameters, provided a critical view of potability and contamination risk. Deviation from Bureau of Indian Standards (BIS, 2012) thresholds for these parameters indicated geogenic or anthropogenic contamination. Overall, this integrated framework provided a comprehensive basis for identifying vulnerable springs in the region, aiding in prioritization of springs for conservation and spring-shed management interventions.

5. RESULT AND DISCUSSION

5.1. Verification of spring location

As part of the spring-shed management initiative, a detailed field verification of spring locations identified by the Survey of India (SOI) was conducted across the Bhilangana, Pratapnagar, and Ukhimath blocks. The SOI had initially mapped 76 spring locations in Bhilangana, 37 in Pratapnagar, and 270 in Ukhimath. Upon ground verification by the National Institute of Hydrology (NIH), only 66 (86.8%) in Bhilangana, 35 (94.6%) in Pratapnagar, and 245 (90.7%) in Ukhimath could be verified, indicating a moderate level of spatial agreement, rather than a high degree of accuracy. Notably, 10 springs in Bhilangana, 2 in Pratapnagar, and 25 in Ukhimath were inaccessible and thus excluded from final validation. Furthermore, the number of springs actually found at or near their mapped locations (within a 50 m buffer) was limited: only 30 in Bhilangana, 19 in Pratapnagar, and 16 in Ukhimath, accounting for less than half of the verified springs in each block. A substantial proportion of the remaining springs were found to be deviated within >50 m, reflecting potential geolocation inaccuracies in the SOI dataset. This is particularly evident in Bhilangana (36 springs deviated), Pratapnagar (16), and Ukhimath (19), suggesting that the SOI data lacks the precision required for reliable hydrogeological mapping and field planning.

Additionally, a significant number of new springs were discovered during the fieldwork 94 in Bhilangana, 15 in Pratapnagar, and 27 in Ukhimath further reinforcing the limitations of the SOI dataset in capturing the actual distribution of spring sources. In the case of Ukhimath, it is also noted that 185 of the identified SOI locations were later determined to represent seasonal streams rather than perennial springs, highlighting a major misclassification issue. Overall, the analysis suggests that while SOI data provides a preliminary framework, it is not sufficiently reliable for detailed spring-shed management planning without thorough field verification.

Table. 5.1 Verification of Springs

Survey Status	**Bhilangana**	**Pratapnagar**	**Ukhimath**
Total Spring locations given by SOI	**76**	**37**	**270**
Total Spring locations verified by NIH	**66**	**35**	**245**
Spring found as per the SoI location	**30**	**19**	**16**
Springs not found (at SoI location)	**36**	**16**	**19**

Number of inaccessible springs	**10**	**2**	**25**
Additional Springs (not listed in the SoI ocation)	**94**	**15**	**27**

Furthermore, 94 in Bhilangana, 15 in Pratapnagar, and 27 springs in Ukhimath have been found in addition to SOI springs. Notably, 185 springs identified as spring by SOI were found to be seasonal streams, highlighting the importance of ground-truthing for accurate spring documentation and planning.

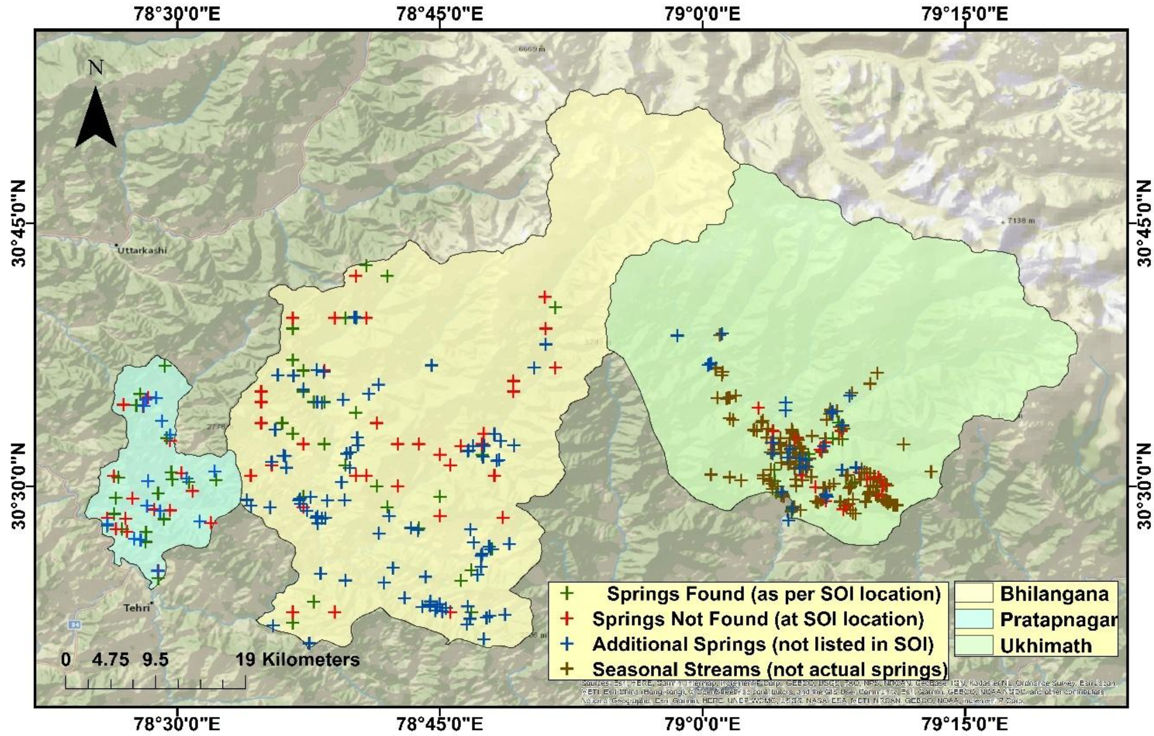


Fig. 5.1: verification of spring locations

5.2 Vulnerability Assessment

The vulnerability assessment of spring water sources in the Garhwal Himalayan region is a crucial to understand the interplay between hydrochemical characteristics, discharge behavior, and socio-economic dependencies. In the rugged terrains of the Himalayas, where surface water access is often limited, springs act as natural outflows of groundwater and serve as lifelines for rural and remote communities (Valdiya & Bartarya, 1991). These springs provide essential water for domestic use, agriculture, and small-scale industries, and their sustainability is directly influenced the well-being and livelihood resilience of dependent populations.

Given the environmental sensitivity of the Garhwal Himalayas, it is vital to evaluate how vulnerable these spring sources are to changing climatic, hydrological, and anthropogenic pressures. A multi-criteria framework was employed to assess this vulnerability, combining both quantitative hydrogeological parameters and qualitative socio-economic indicators. Each parameter was evaluated and weighted based on its relative importance in determining spring vulnerability, informed by expert judgment gathered through a structured survey instrument administered to domain specialists (n=27).

The parameters considered in this assessment include:

(a) EC (Electrical Conductivity)

The comparative assessment of Electrical Conductivity (EC) across the three Himalayan blocks Ukhimath, Pratapnagar, and Bhilangana demonstrates marked spatial variability in groundwater quality, reflecting underlying hydrogeological and anthropogenic influences. Bhilangana block exhibits the highest proportion of low-EC springs, with approximately 55% of its springs measuring below 100 µS/cm (Fig. 5.2). This dominance of low conductivity values suggests minimal mineralization, indicative of pristine recharge conditions, potentially through direct precipitation, shallow subsurface flow paths and low residence time. Such characteristics are typically associated with limited anthropogenic activity and geochemically immature groundwater systems. In contrast, Pratapnagar block presents a broader distribution of EC values. Only 16% of springs fall in the <100 µS/cm category, while a notable 10% exceed 400 µS/cm the highest among the three blocks (Fig. 5.4). This distribution suggests a combination of factors, including geological mineral dissolution, relatively longer groundwater residence time, and possible anthropogenic inputs such as agricultural runoff or domestic wastewater infiltration, as supported by previous studies (Nautiyal et al., 2018). Ukhimath block, located at higher elevation, shows a profile similar to Bhilangana, with 47.4% of springs exhibiting EC below 100 µS/cm (Fig. 5.2). However, 40.4% fall within the 100-200 µS/cm range (Fig. 5.4), suggesting slightly mineralized conditions possibly driven by natural rock-water interactions and seasonal snowmelt contributions. Overall, Bhilangana's EC profile reflects relatively unimpacted water quality, while Pratapnagar appears more susceptible to either natural enrichment or early anthropogenic degradation. Ukhimath represents a transitional setting, both in topography and water chemistry, likely influenced by mixed recharge sources and moderate weathering processes.

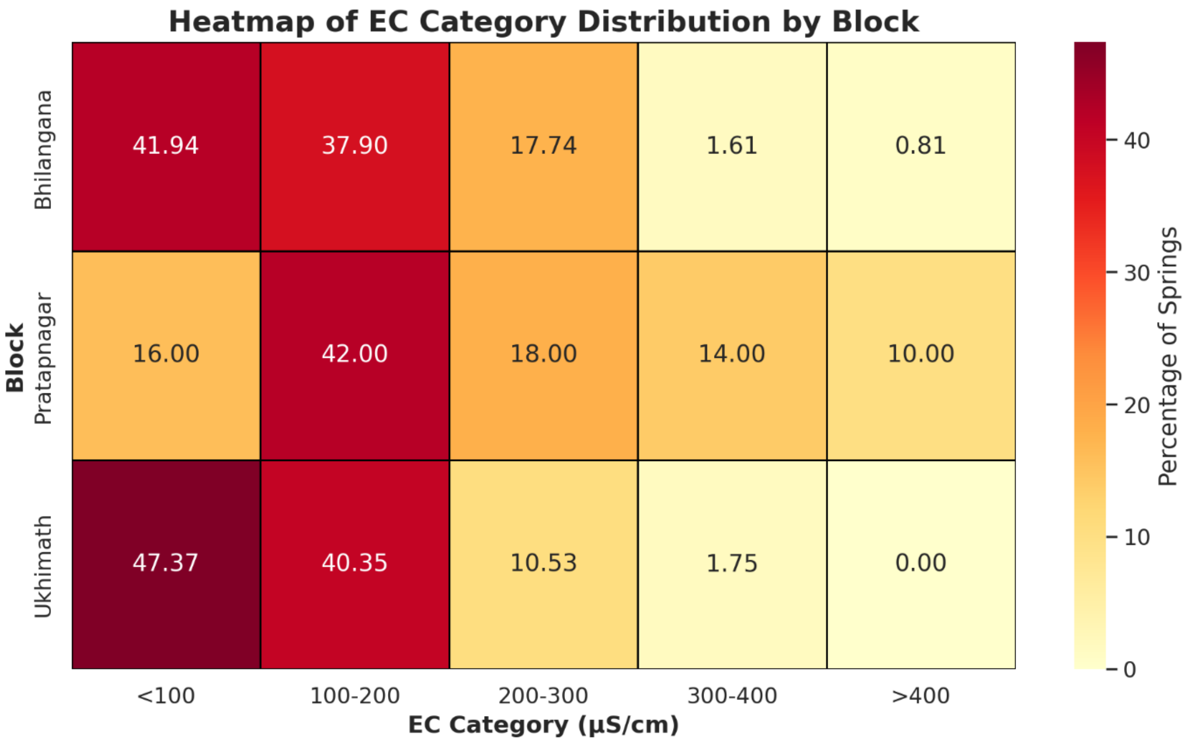


Fig. 5.2 EC heat map of the Study area

(b) Discharge

The violin plot provides a detailed visualization of the distribution and density of spring discharge (LPM) across the three blocks Ukhimath, Pratapnagar, and Bhilangana. The shape and width of each violin reflect the frequency and spread of discharge values within each block. In Ukhimath, the plot shows a wide spread and significant bulging at both lower and higher discharge levels, indicating the presence of both low- and high-yielding springs. This variability suggests complex hydrogeological conditions, likely influenced by diverse geological formations, steep terrain, and possible snowmelt recharge. Pratapnagar's violin is narrow and sharply peaked near the lower discharge values, reflecting a high concentration of springs below 5 LPM. The absence of wider spread or higher discharge outliers points indicate limited recharge potential and generally low-yielding spring systems. This makes it a critical block for spring-shed management and recharge interventions. Bhilangana, by contrast, exhibits a balanced and moderately wide violin, indicating a more uniform discharge distribution with moderate peaks in the 5–20 LPM range (Fig.5.3). This pattern is typical of well-recharged mid-altitude springs and reflects relatively stable hydrogeological conditions. Overall, the violin plot highlights Ukhimath's discharge diversity, Pratapnagar's yield stress, and Bhilangana's moderate consistency, offering valuable insight for targeted spring rejuvenation and water security planning.

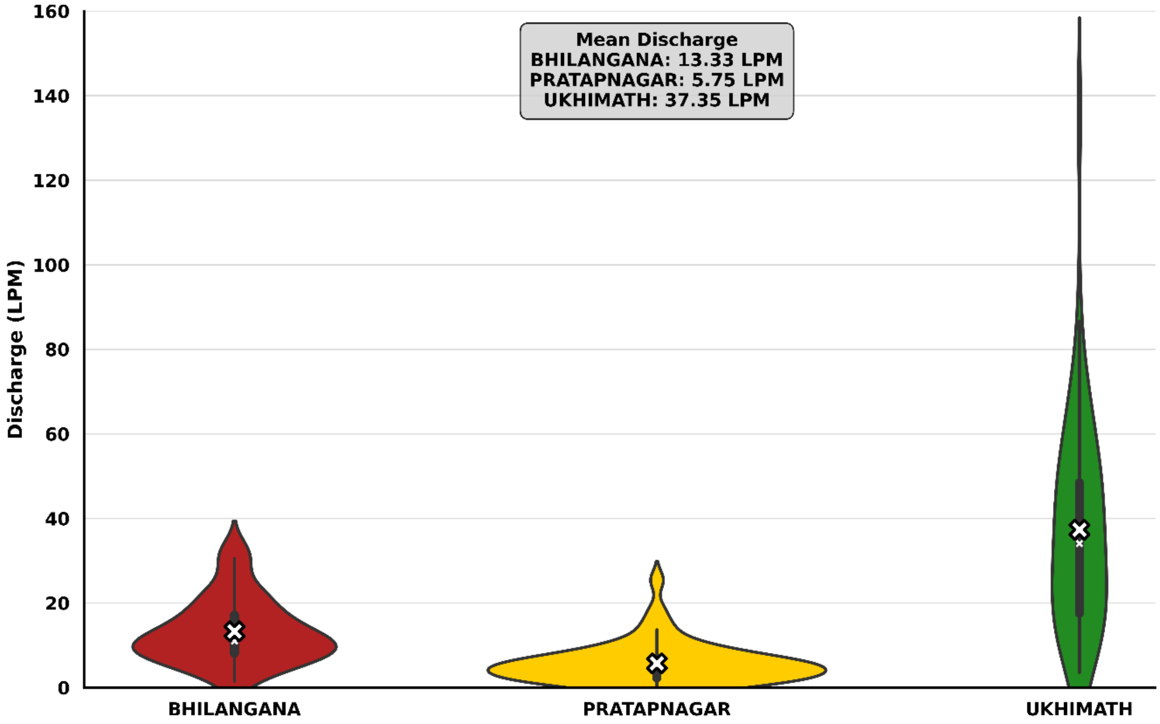


Fig. 5.3 Spring Discharge of the Study area

(c) Meinzer classification

The Meinzer classification of springs, developed by Oscar E. Meinzer in 1923, is a widely recognized system that categorizes springs based on their discharge rates, measured in liters per second (LPS). This classification serves as a valuable tool for hydrogeologists and water resource planners, particularly in mountainous regions where springs are a major source of freshwater. The Meinzer classification of spring discharge across Bhilangana, Pratapnagar, and Ukhimath blocks (Fig. 5.4) reveals a predominance of Sixth class springs (3.78-37.8 LPM), accounting for 62.10%, 63.27%, and 70.77% respectively, indicating that moderately discharging springs form the backbone of rural water supply in these regions. Seventh class springs (0.48-3.78 LPM), which are low-yielding are notably higher in Bhilangana (33.87%) and Pratapnagar (36.73%), but relatively lower in Ukhimath (15.38%). Fifth class springs (high discharge) are minimal in Bhilangana (3.23%) and present in Ukhimath (12.31%) but absent in Pratapnagar, while Eighth class springs (very low discharge) are recorded in Bhilangana (0.81%) and Ukhimath (1.54%).

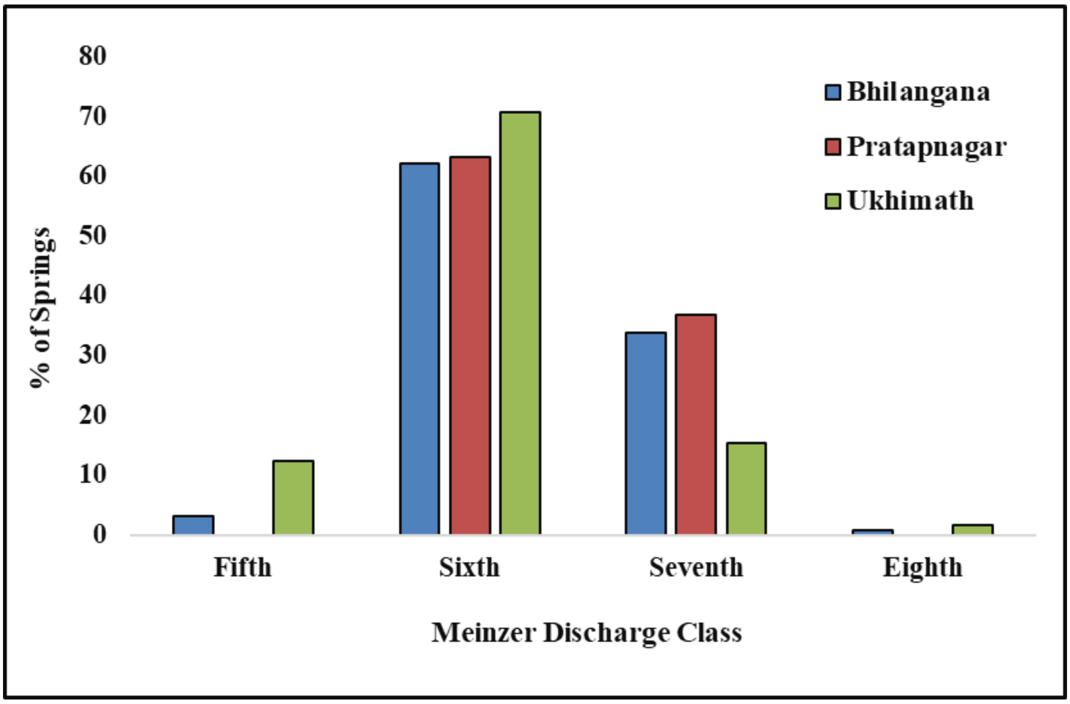
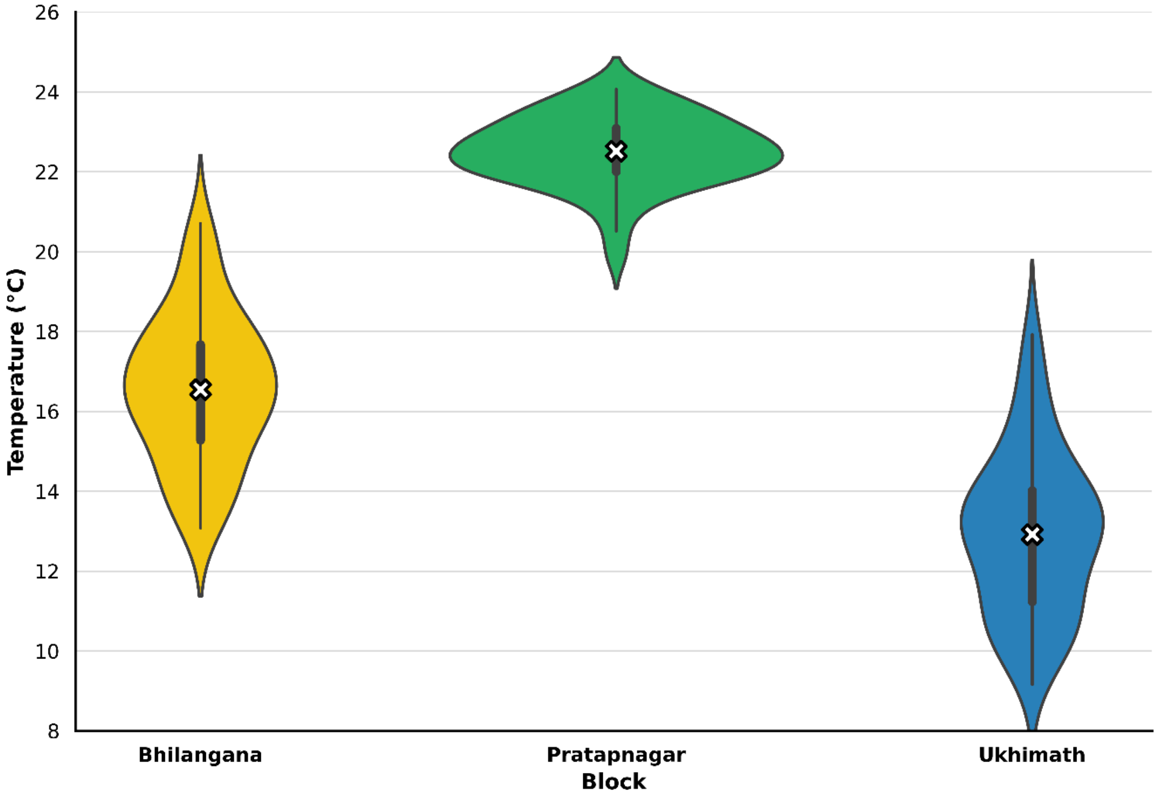


Fig. 5.4 Blockwise Meinzer classification of the Springs

(d) Temperature

The spring water temperature across Ukhimath, Pratapnagar, and Bhilangana blocks reveals notable spatial variability, as depicted in the violin plot (Fig. 5.5). Ukhimath block exhibits relatively lower spring temperatures, typically clustering between 8°C and 17°C, with a median near 13°C. This trend aligns with the higher elevation and colder microclimatic conditions prevalent in the upper Himalayan terrain. These findings are consistent with studies by Negi and Joshi (2012), which associate lower spring temperatures in higher altitudes with snowmelt and shallow aquifer recharge processes dominated by recent precipitation. Pratapnagar block shows a narrow, elevated temperature band between 18°C and 24°C, with a median near 22.5°C, reflecting moderate altitude, low vegetation with anthropogenic heating influences. The narrow distribution suggests stable thermal regimes and deeper aquifer sources. Similar patterns were reported by Rawat et al. (2021), who observed relatively higher and stable spring temperatures in mid-altitude villages due to deeper flow paths and limited seasonal variability. In contrast, Bhilangana block demonstrates a broader distribution of temperatures, ranging from 15°C to over 28°C, with a median near 17°C . This heterogeneity could be attributed to mixed recharge sources, varied geological formations, and local land-use impacts. Prior research by Nautiyal et al. (2015) noted that diverse lithologies and land use, including agricultural return flows, could cause localized warming of spring water. The temperature analysis does not only aids in identifying the hydrothermal regime of spring-sheds but also provides indirect evidence about the recharge depth, aquifer insulation, and potential climate sensitivity.

Fig.5.5 Temperature of the Spring of the Study area.



(e) Elevation

Spring elevation plays a pivotal role in determining the hydrogeological behavior and recharge potential of mountainous aquifers. In the present study, comparative analysis across Bhilangana, Pratapnagar, and Ukhimath blocks in Uttarakhand reveals notable variation in spring altitudes, reflecting distinct geomorphological and tectonic settings. Ukhimath block, located in the higher reaches of the Garhwal Himalayas, exhibits the highest median spring elevation (~1774 m), indicating its dominance of orographic recharge and snowmelt-fed systems. Conversely, Pratapnagar block displays the lowest median elevation (~1330 m), representing mid-altitude zones where springs are more likely to be influenced by seasonal rainfall recharge. Bhilangana block demonstrates a wider altitudinal spread with springs ranging from ~789 m to >2600 m. suggesting the coexistence of both shallow and deep fractured aquifer systems. The presence of springs at elevations above 2400 m (Fig.5.6).

Bhilangana indicates high-altitude recharge zones that are less impacted by anthropogenic interference, while lower elevation springs may be more vulnerable to surface contamination and over-extraction. Previous studies (Negi & Joshi, 2021; Tambe et al., 2012) have emphasized that higher elevation springs often yield more consistent discharge during lean seasons due to sustained recharge from snow and glacial melt, as well as slower percolation through fractured rock systems. Moreover, low-elevation springs, though more accessible, are highly sensitive to climatic variability and human-induced land-use changes (Valdiya & Bartarya, 1991).

Understanding elevation gradients of springs is essential for designing altitude-specific rejuvenation strategies, this analysis supports the prioritization of high-altitude springs for long-term conservation and mid-to-low elevation springs for community-scale recharge interventions.

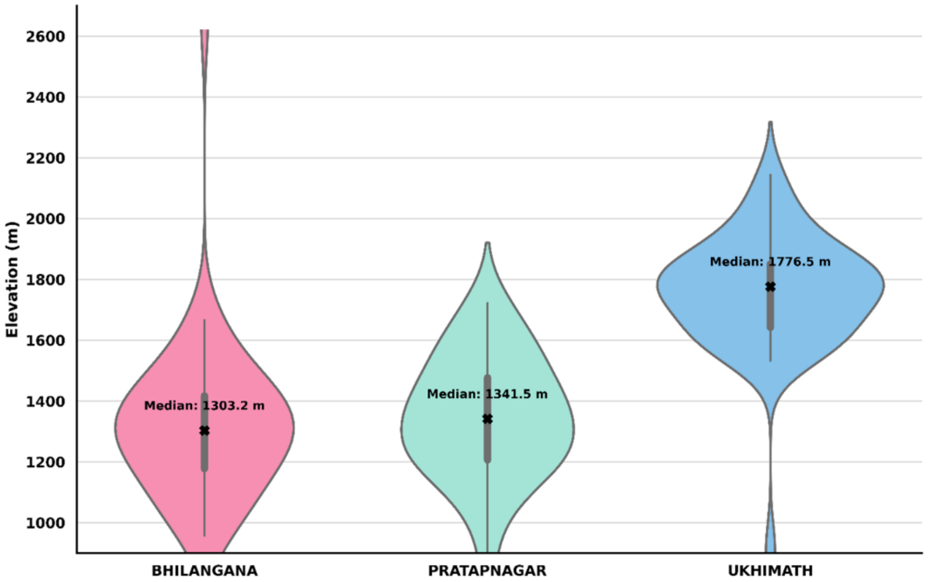


Fig. 5.6 Elevation ranges of the Spring of the Study area

(f) pH

The analysis of spring water pH across Bhilangana, Pratapnagar, and Ukhimath blocks reveals notable spatial variation in the hydrochemical environment of the Garhwal Himalaya. The median pH values for Bhilangana (6.98), Pratapnagar (7.05), and Ukhimath (7.70) indicate that all three blocks exhibit slightly acidic to moderately alkaline water (Fig. 5.9), which falls within the BIS and WHO permissible limits for drinking water (6.5–8.5). Ukhimath block, located at a higher altitude with minimal anthropogenic pressure, shows the highest median pH, suggesting the influence of carbonate-rich lithology and prolonged water–rock interaction, leading to natural alkalinity. This aligns with the findings of Negi and Joshi

(2012), who noted that high-elevation springs often reflect neutral to basic pH due to geological buffering and reduced contamination. Pratapnagar block, characterized by mid-altitude settlements and agricultural activity, demonstrates a lower pH (close to neutral) with moderate spread. The relatively slightly acidic to neutral pH may be influenced by organic matter decomposition, agrochemical leaching or intensive land use, corroborating past assessments by Rawat et al. (2021) in mid-Himalayan catchments. Bhilangana block shows greater variability in pH, possibly due to its diverse topography and mixed recharge sources, including shallow fractured aquifers and surface connectivity (Fig.5.7). The wider interquartile range suggests variable recharge conditions and local geochemical influences, as reported by Sharma et al. (2016). These pH patterns are crucial for understanding aquifer health, microbial habitat suitability, and long-term water quality trends. Monitoring deviations in pH can also serve as an early indicator of chemical weathering, pollution, or spring ecosystem stress in the fragile Himalayan waterscape.

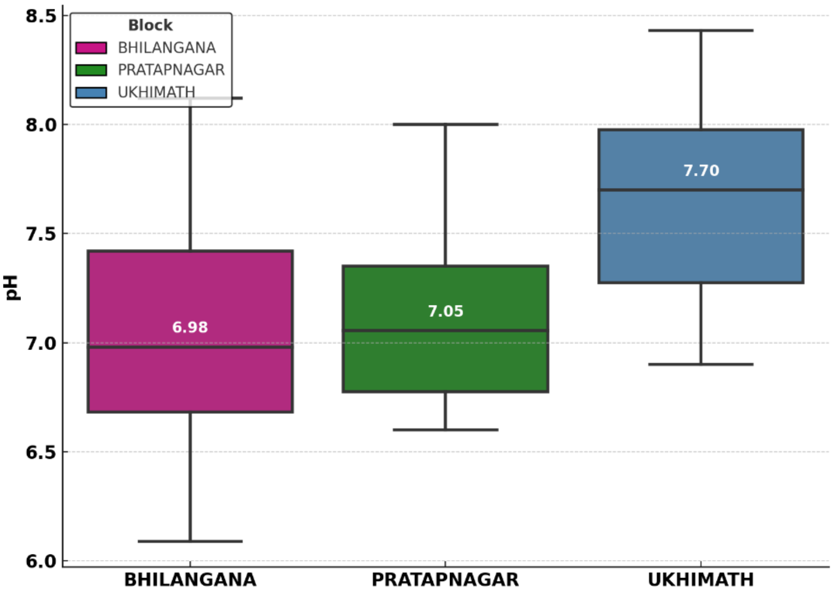


Fig. 5.7 pH variability of the Spring of the study area

(g) Primary Landuse landcover

The presented graphs illustrate (Fig 5.8) the distribution of primary Land Use/Land Cover (LULC) associated with spring locations in three Himalayan catchments: Bhilangana, Pratapnagar, and Ukhimath.The top bar chart displays the percentage of springs falling under each LULC category, a percentage-wise stacked bar representation, facilitating relative comparison across the catchments. In Bhilangana, 47 springs (37%) are situated in settlement areas, followed by 35 springs (28%) in agricultural land, and 33 springs (26%) in forests (Fig.

5.10). Other land types like scrubland (9 springs), pasture (1), and barren land (1) account for minimal shares. This suggests Bhilangana has significant human settlement and cultivated land influence. Pratapnagar is primarily dominated by agriculture (24 springs, 44%), followed by shrubs (13 springs, 24%), and settlement (10 springs, 18%), with a small portion under forest (3 springs, 5%). Ukhimath reflects a more ecologically resilient setting with 27 springs (42%) in Agricultural land and 25 springs (39%) under forest cover. The remaining springs are distributed across scrubland (5 springs, 8%) and Settlement (8 springs, 12%), suggesting a balance between cultivated and natural landscapes. It can be concluded from the analysis that Bhilangana is dominated by the springs in urbanized areas, Pratapnagar springs are mostly emerged in agricultural with high shrub presence areas, and Ukhimath dominant by the springs emerged in a forest-agriculture mix, potentially supporting better natural recharge and spring sustainability.

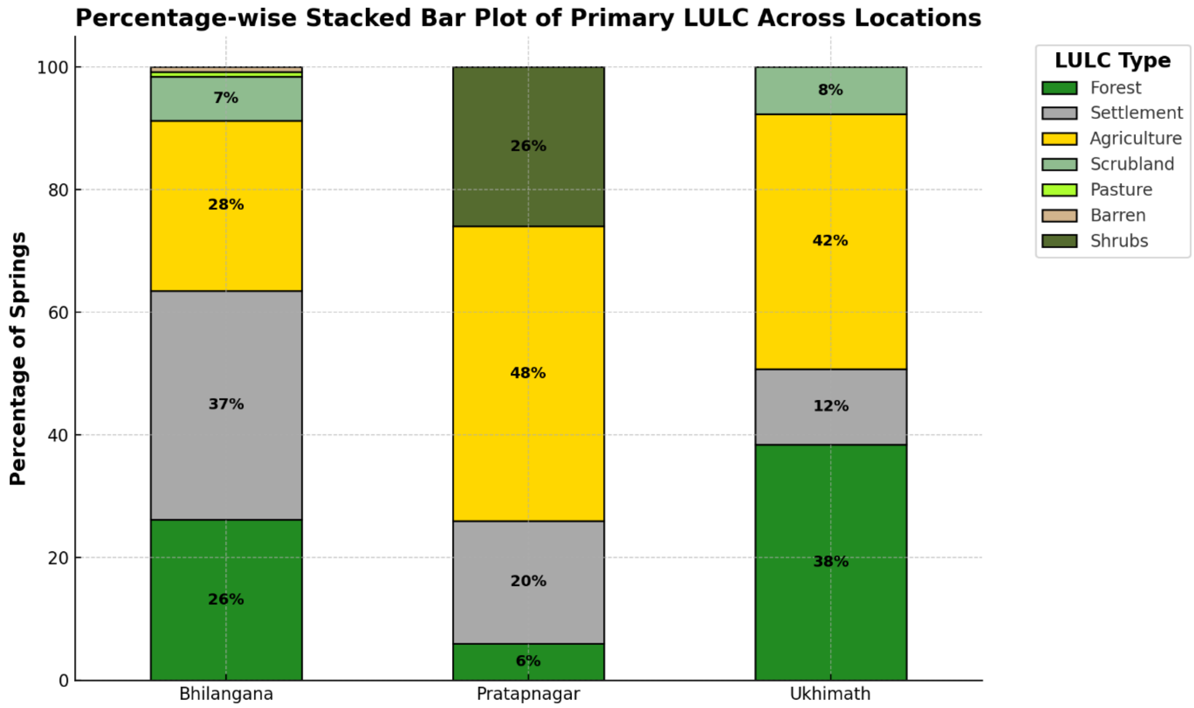


Fig. 5.8 LULC of the Spring of the study area.

(h) Springs Discharge

The stacked bar chart as depicted in Fig. 5.9 provides a comparative overview of spring discharge behavior across the three study blocks i.e., Bhilangana, Pratapnagar, and Ukhimath based on the categorization of 124, 50, and 65 springs, respectively. In Ukhimath, out of 65 springs, 43 springs (66.15%) exhibit seasonal variability, while 21 springs (32.3%) demonstrate constant discharge with no variation, and only 1 spring (1.5%) falls under the no information available category. Pratapnagar displays a relatively balanced distribution, with 18 springs (36%) showing seasonal variability, 20 springs (40%) classified as constant discharge with no variation, and 12 springs (24%) having no information available status. In Bhilangana, of the 124 springs, 58 springs (46.8%) show constant discharge with no variation, followed by 51 springs (41.1%) under seasonal variability, and 15 springs (12.1%) with no information available. This block-level analysis highlights the dominance of seasonal springs in Ukhimath, potentially due to shallow aquifer systems and higher sensitivity to rainfall patterns. In contrast, Pratapnagar and Bhilangana have a greater proportion of springs with constant discharge, suggesting more stable aquifer conditions.

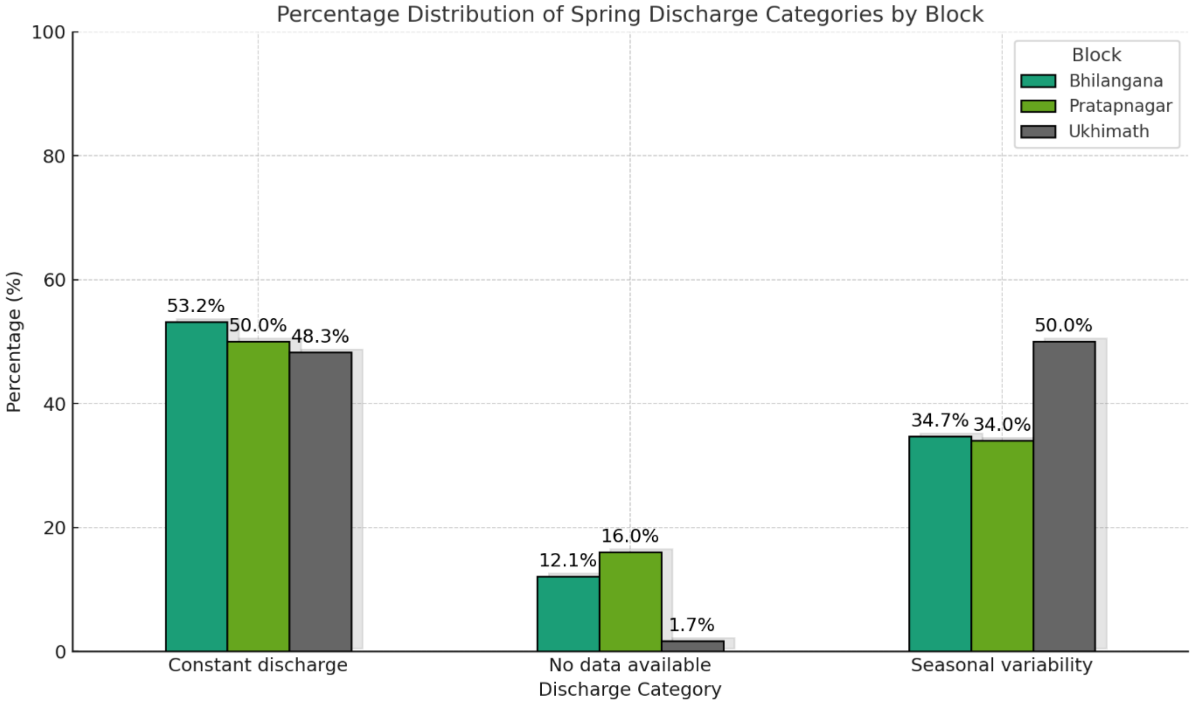


Fig. 5.9 Spring discharge

(i) Dependency of villages (Hamlets)

The analysis of spring dependency across Bhilangana, Pratapnagar, and Ukhimath blocks in the Garhwal Himalayas reveals significant spatial variation in Hamlet dependent on spring water sources. Survey-based data highlight that over 70%, 66% to 74% of springs in Bhilangana, Pratapnagar, and Ukhimath blocks, respectively are exclusively depended by a single hamlet (Fig. 5.10), indicating localized dependency and limited water-sharing networks. Howevere, there are the springs (16-28%) where two hamlets are dependent. Few Springs (6-17%) have the dependency more than 3 hamlets. These findings advocate for targeted spring-shed management interventions, prioritizing springs having high no. of dependent hamlets. The vulnerability of spring-fed systems in this mountainous terrain is not only hydrogeological but also socio-economically embedded, necessitating integrated, data-driven governance frameworks.

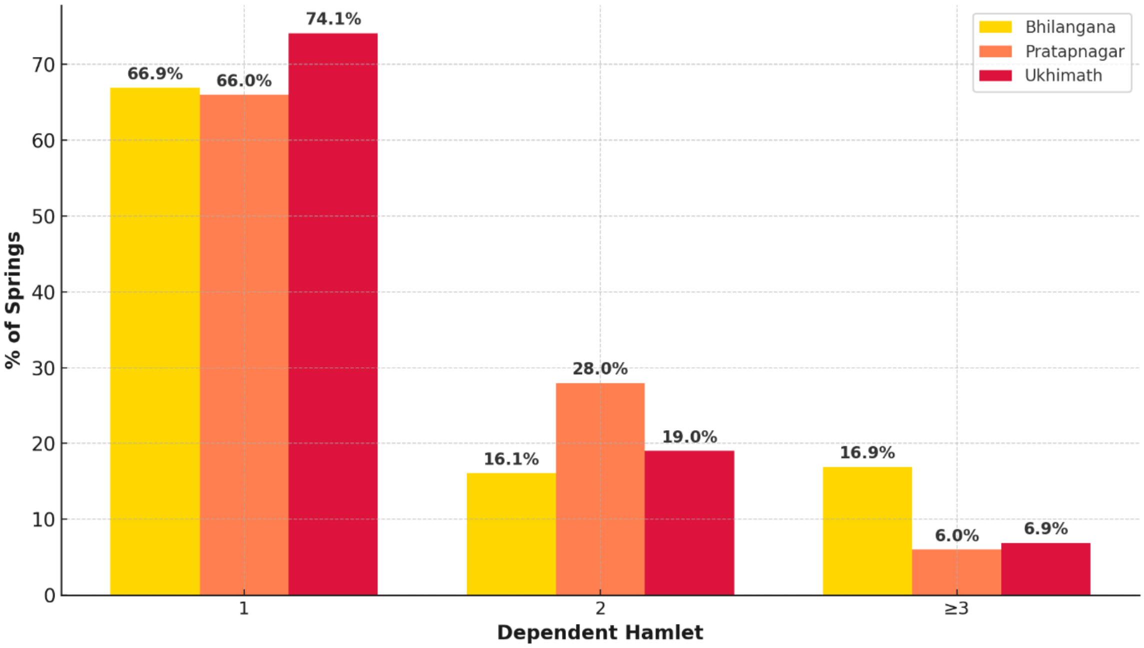


Fig. 5.10 No. of dependent hamlets on the springs of three blocks.

(j) Resource Threats on Springs

The analysis of spring resource threats across three blocks of the Garhwal Himalayan region Bhilangana, Pratapnagar, and Ukhimath reveals significant spatial variation in threats. Ukhimath exhibits the highest no. of spring (70.69%) having resource threats (Fig. 5.11). In contrast, 44% of springs in Pratapnagar having threat (Fig. 5.13), due to localized land-use changes and seasonal water stress. Bhilangana, with only 13.71% of springs under threat, demonstrates relatively better ecological stability, possibly due to preserved forest cover and minimal anthropogenic disruption. These findings highlight the importance of implementing springshed-based management strategies tailored to each region's specific potential threats.

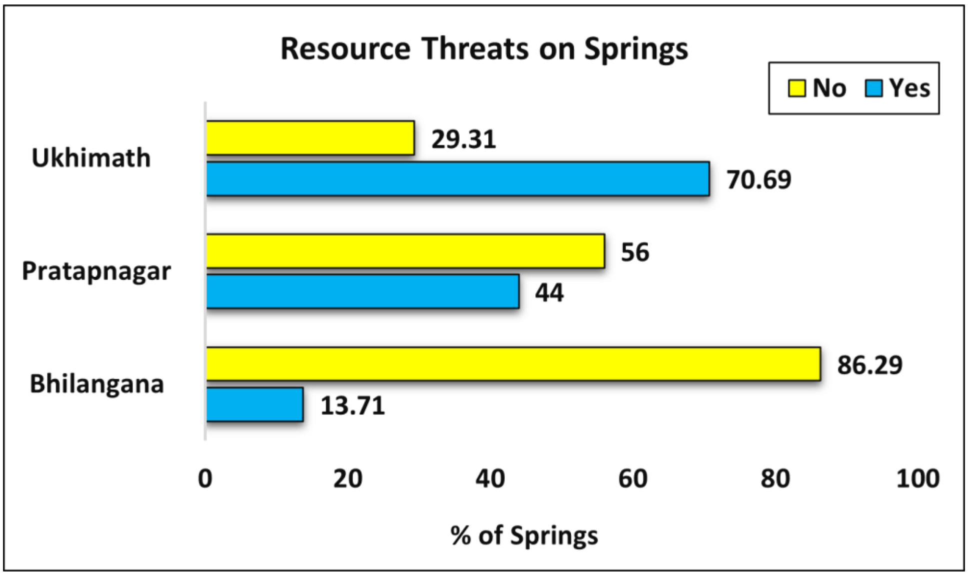


Fig. 5.11 Springs having resource threats in three blocks.

(k) Numbers of Springs outlets

The distribution of spring outlets in the three blocks of the Garhwal Himalayan region Ukhimath, Pratapnagar, and Bhilangana indicates a dominant prevalence of single-outlet springs. In Ukhimath, 86.2% of springs have a single outlet, with 6.9% having two and another 6.9% possessing three outlets (Fig. 5.12). Pratapnagar demonstrates the highest proportion of single-outlet springs at 94%, and the lowest percentage of springs with multiple outlets. Bhilangana shows a relatively more diversified outlet pattern, with 86.3% of springs having one outlet, 12.1% with two, and 1.6% with three outlets. The presence of multiple outlets can indicate high discharge, high dependency and multiple uses of the spring, whereas a predominance of single-outlet springs may reflect single use of spring's water probably for drinking.

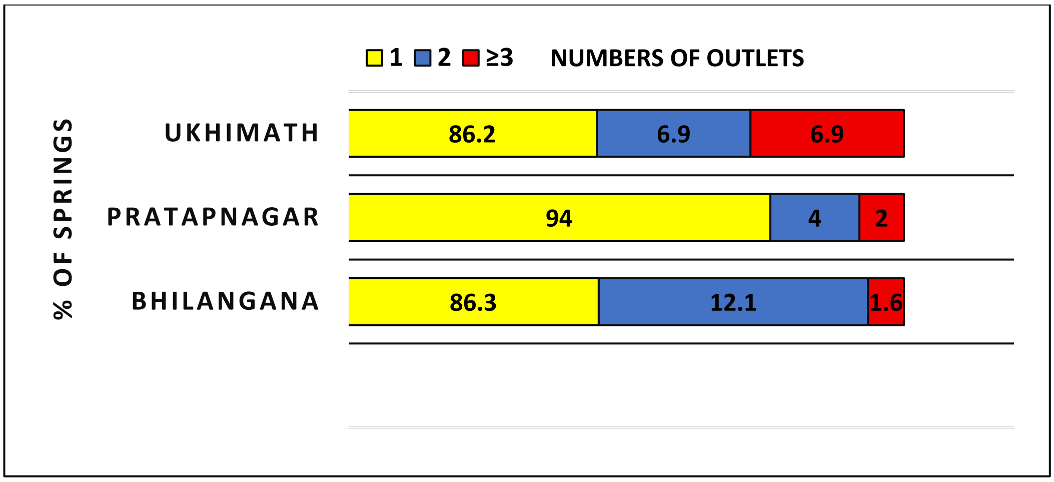


Fig. 5.12 Numbers of outlets on the Spring.

(l) Scouring and gully erosion

The survey on the status of scouring and gully erosion in the Garhwal Himalayan region reveals most of the springs are vulnerable to the erosion. It can be evident from the Fig. 5.13 that in all three blocks most of the springs are prone to moderate erosion. Such information is very important to protect the springs against the possible erosion threats.

The identified threats from the potential erosion underscore the critical necessity for targeted vulnerability assessments and mitigation measures tailored to the specific geological and anthropogenic contexts of each block. Prior studies (e.g., Agarwal et al., 2018; ICIMOD, 2020) have emphasized the role of erosion and gully formation as significant indicators of ecological vulnerability, with direct implications for water quality, spring recharge capacity, and overall watershed health. Consequently, this survey's results offer a crucial scientific foundation for planning integrated springshed management strategies, informed by localized erosion dynamics and supported by community engagement and sustainable land-use policies.

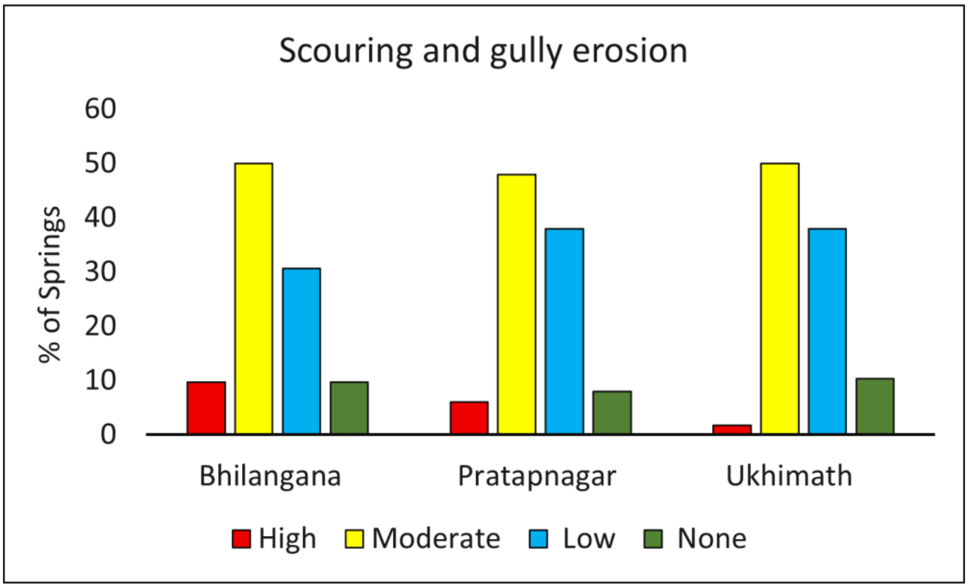


Fig. 5.13 Scouring and gully erosion on the Spring

(m) Major Stressor

Based on the graphical data (Fig. 5.14), the major stressors affecting springs across Ukhimath, Pratapnagar, and Bhilangana blocks in the Garhwal Himalayan are anthrpogenic as well as natural. The anthropogenic stressors are particularly pronounced, with Ukhimath exhibiting the highest proportion of springs (41.38%) impacted by human activities, closely followed by Pratapnagar (36%). Bhilangana shows significant resilience, with 40.32% of springs experiencing no evident of stressor, although anthropogenic stressors still impaceted about 29.84% of its springs. Furthermore, springs influenced by both natural and anthropogenic factors range notably between 18.97% (Ukhimath) and 24% (Pratapnagar), suggesting integrated pressures demanding holistic management approaches. This spatial differentiation highlights the critical need for targeted and management practices at micro scale focusing particularly on controlling human-induced impacts in Ukhimath and Pratapnagar. The prevalence of anthropogenic threats underscores the urgent requirement for regulatory frameworks to mitigate environmental degradation, coupled with community awareness initiatives to sustainably manage these crucial water resources. Effective springshed management will significantly depend on understanding localized threats and implementing adaptive strategies as documented in the literature (ICIMOD, 2020; Agarwal et al., 2018).

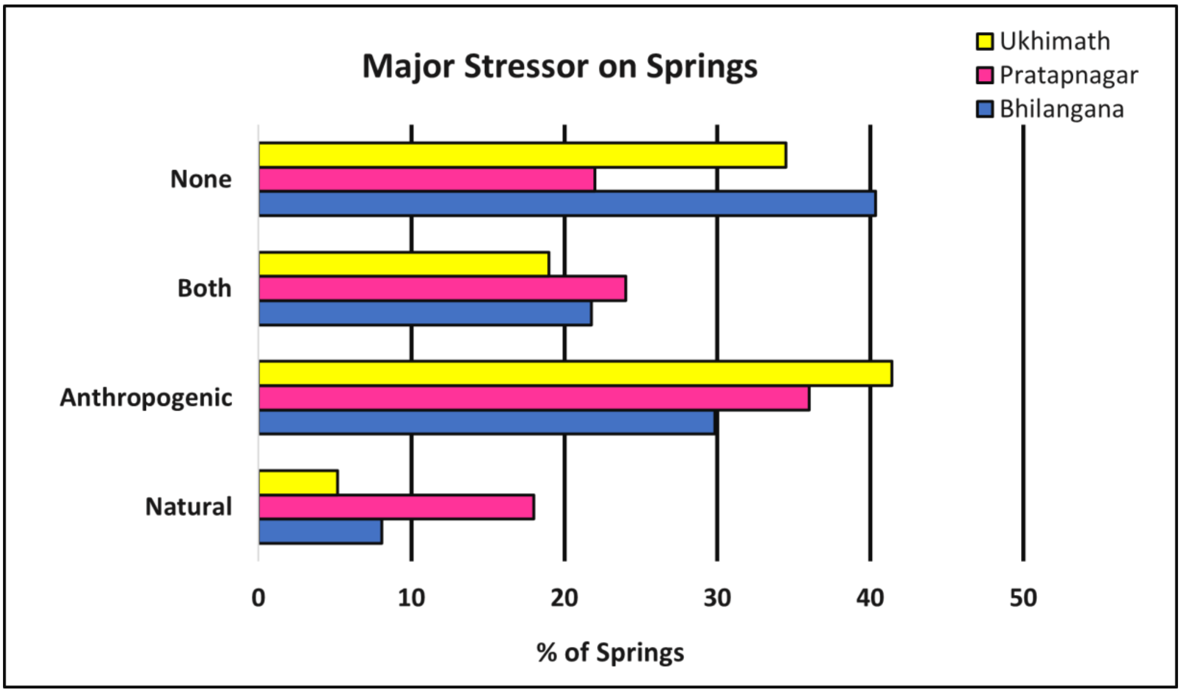


Fig. 5.14 Major stressor on the spring

(o) Primary use of Springs

The assessment of primary spring water usage across Bhilangana, Pratapnagar, and Ukhimath blocks in the Garhwal Himalayan region reveals a dominant reliance on springs for drinking and cooking purposes, with usage rates exceeding 85% in all three blocks (Fig. 5.15). It is evident that springs are the solely used for drinking/cooking purpose in Bhilangana block (96.8% dependency for drinking/cooking purpose), reflects limited alternative water sources in meeting domestic needs. It is clear from the graph that uses of springs water for secondary uses such as washing/sanitation and agriculture/cattle are very limited, indicating there are water sources, but villagers are still solely dependent on springs for meeting their daily drinking and cooking water demand. These findings are critical for springshed management, emphasizing the need to prioritize water quality protection and sustainable recharge to support drinking water security.

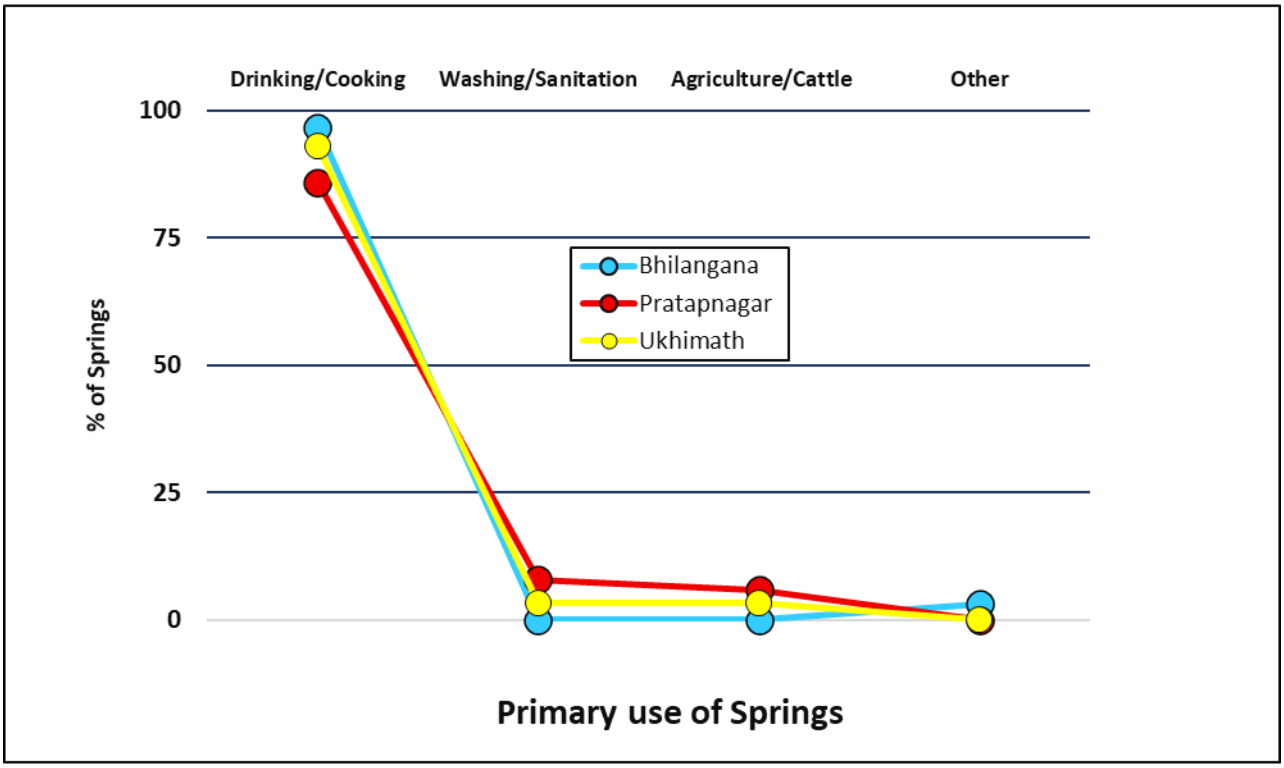


Fig. 5.15 Primary use of Spring

(p) Dependent Household

The vulnerability of spring-dependent communities across Bhilangana, Pratapnagar, and Ukhimath blocks was assessed based on the proportion of households relying on an individual springs. The analysis reveals that Ukhimath and Pratapnagar have a higher concentration of springs serving smaller populations (<50 households), accounting for over 68% and 64%, respectively (Fig. 5.16). This suggests greater dispersion and potentially more localized water stress, especially during lean seasons. In contrast, Bhilangana block shows a substantial proportion (14.52%) of springs supporting over 100 households, indicating a higher dependency stress on few water sources, making them highly vulnerable to both quantitative and qualitative deterioration. Overall, Bhilangana emerges as more structurally vulnerable due to clustered reliance, while Ukhimath and Pratapnagar face scattered vulnerabilities that may be harder to monitor and manage collectively.

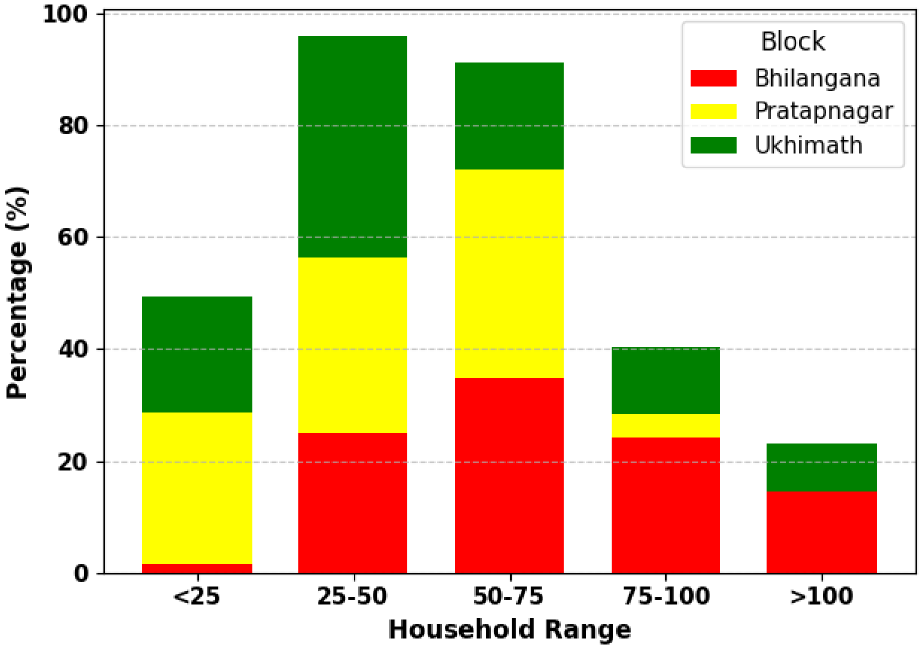


Fig. 5.16 Dependent household of Spring

(q) Dependent population

The vulnerability of spring was assessed by analysing the population dependent on springs through four defined ranges: <50, 50–100, 100–200, and >200 individuals per spring. Bhilangana and Pratapnagar have a high proportion of springs catering to populations exceeding 200, with 48.39% and 52.27%, respectively. This indicates a concentrated pressure on fewer springs, increasing their vulnerability to depletion and degradation. In contrast, Ukhimath shows a more distributed pattern, with only 18.97% of springs serving >200 people. A significant share of Ukhimath's springs (41.38%) serve populations between 50–100, indicating relatively lower per-spring stress (Fig. 5.17). Springs serving less than 50 people are minimal across all blocks, showing a smaller number of people will suffer if such springs will be dried-up. The dominance of high-population dependent springs in Bhilangana and Pratapnagar highlights the urgent need for targeted rejuvenation and protection strategies. Overall, the pattern indicates that the springs in Bhilangana and Pratapnagar are more vulnerable due to high-population dependent springs, whereas Ukhimath's springs, though geographically dispersed, present logistical challenges rather than critical water stress.

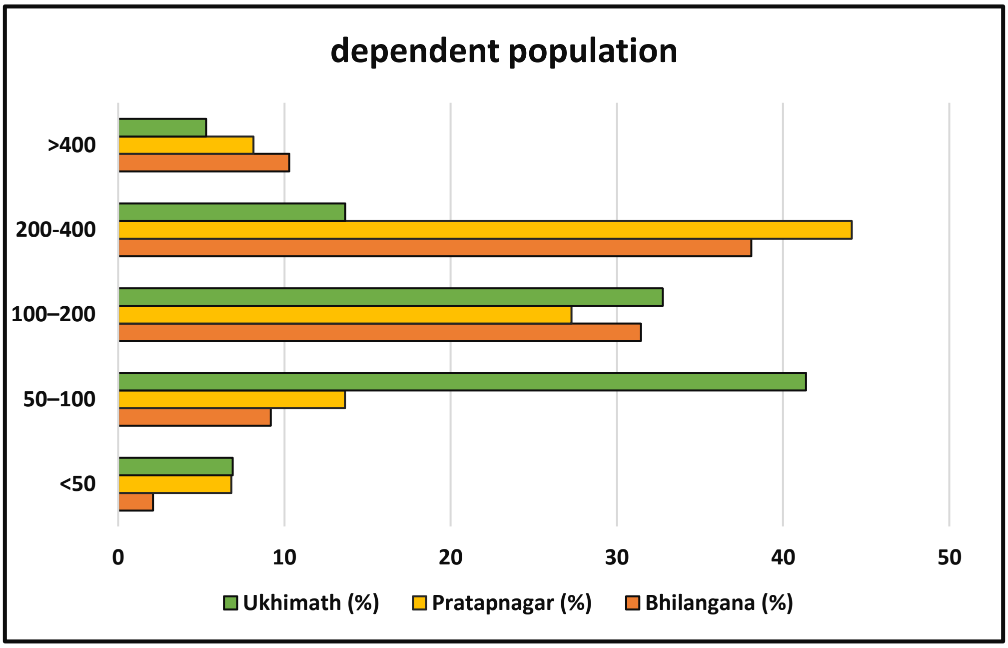


Fig 5.17 Dependent Population of Spring

5.3 Spatial Vulnerability Zonation

The spring vulnerability assessment across the Bhilangana, Pratapnagar, and Ukhimath blocks reveals significant spatial variations in vulnerability levels, which are critical for identifying priority areas for spring rejuvenation and water security planning. Based on the computed vulnerability indices, the springs were categorized into two classes: Moderately Vulnerable and Highly Vulnerable, illustrated in the vulnerability zonation map (Figure 5.18). In the Bhilangana block, approximately 71.77% of springs were found to be moderately vulnerable, indicating relatively stable hydrological and environmental conditions with some seasonal stress. The remaining 28.22% of springs fall under the highly vulnerable category, largely located in zones with steeper terrain, variable recharge conditions, and higher anthropogenic pressure. The Pratapnagar block shows a balanced distribution, with 50% of the springs classified as moderately vulnerable and the other 50% as highly vulnerable. This equal split highlights the coexistence of both resilient and fragile spring systems in this region. Factors contributing to high vulnerability here include intensive land use changes, slope instability, and limited access to alternate water sources.

In contrast, the Ukhimath block displays a higher concentration of highly vulnerable springs, accounting for 75.86%, while only 24.13% fall in the moderately vulnerable category. The high percentage of vulnerability in Ukhimath is primarily due to its sensitive geological setup, steep gradients, seasonal discharge variability, and significant dependency of local populations on springs for domestic use.

These findings emphasize the need for site-specific interventions to enhance spring sustainability, especially in highly vulnerable zones of Ukhimath and southern Pratapnagar. Measures such as catchment protection, artificial recharge structures, and community-led monitoring systems are recommended to reduce vulnerability and ensure long-term water availability.

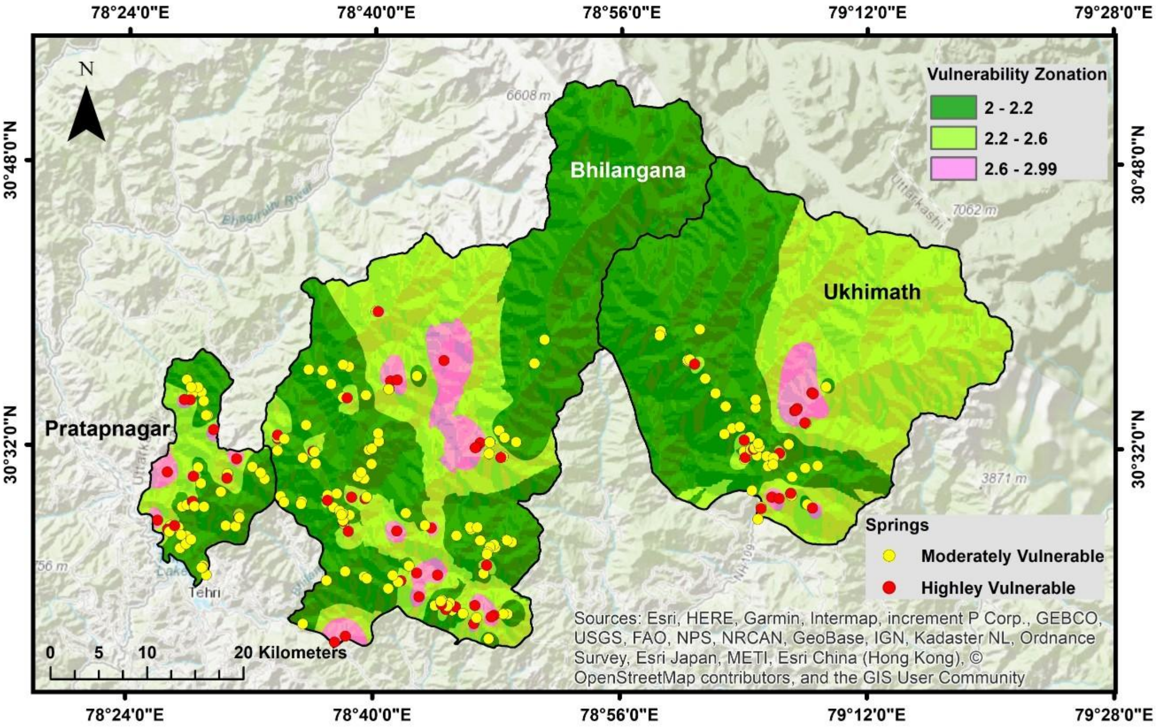


Fig.5.18 Vulnerability zonation map

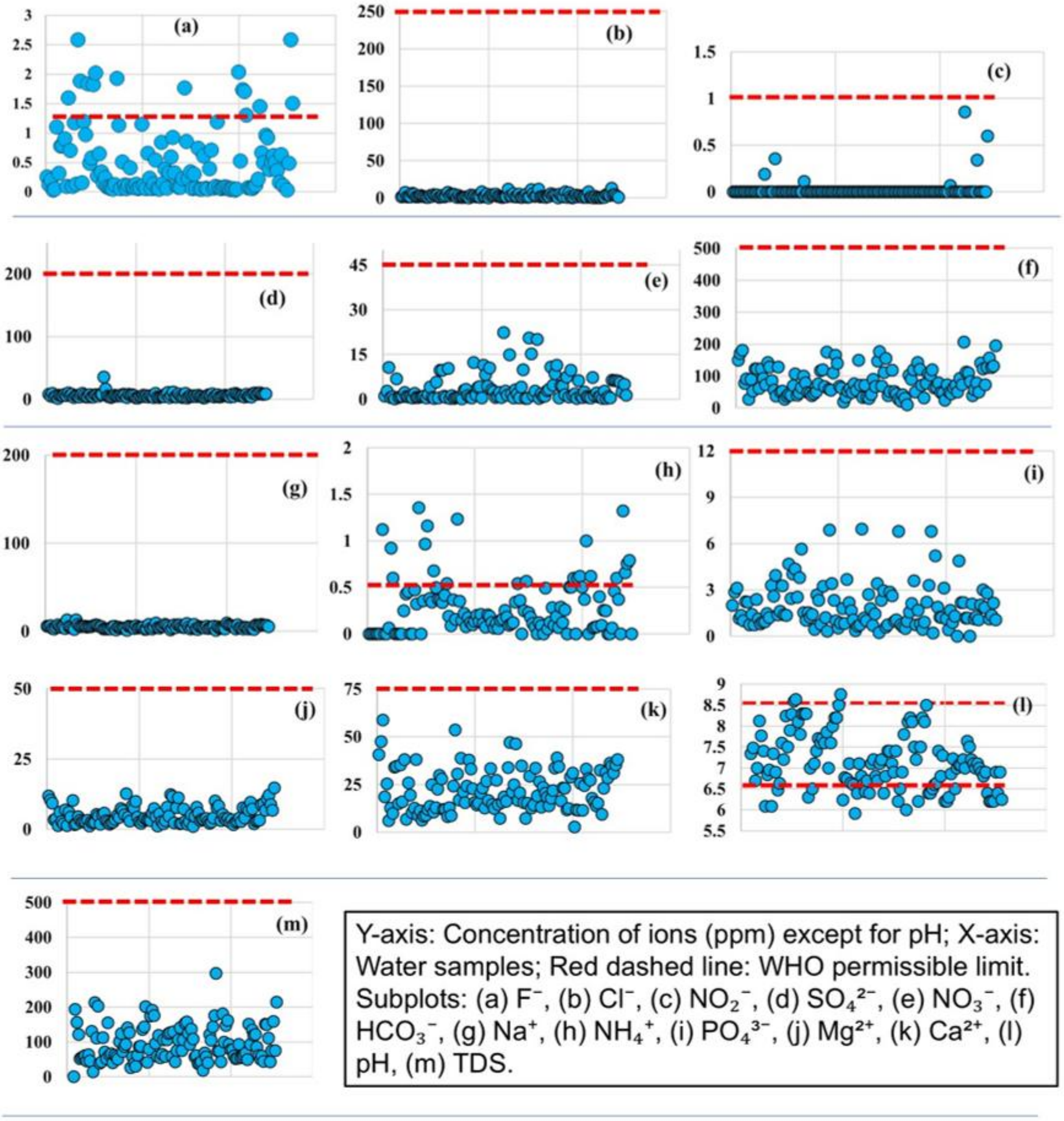
5.4 Water Quality Index and Hydrochemical Analysis

The Water Quality Index (WQI) was used to evaluate the potability of spring water in the Bhilangana and Pratapnagar blocks by integrating multiple physicochemical parameters into a single value. A significant proportion of springs were classified as ‘Excellent’ (WQI < 50), comprising 74.8% in Bhilangana and 64% in Pratapnagar, indicating high-quality water that is safe for direct consumption. Springs falling under the ‘Good’ category (WQI 50–100) accounted for 13.8% and 22%, respectively, and are generally acceptable for drinking. However, some springs fell into the ‘Poor’ (7.3% Bhilangana; 8% Pratapnagar), ‘Very Poor’ (2.4%; 4%), and ‘Unsuitable’ (1.6%; 2%) categories, indicating the need for either basic or extensive treatment before use. Further analysis of ionic composition showed that most parameters such as Chloride (Cl^-), Sulfate (SO_4^{2-}), Bicarbonate (HCO_3^-), Sodium (Na^+), Ammonium (NH_4^+), Phosphate (PO_4^{3-}), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), and Total Dissolved Solids (TDS) were within WHO recommended limits, reflecting good hydrochemical conditions across most springs. However, Fluoride (F^-), Nitrate (NO_3^-), and Nitrite (NO_2^-) exceeded safe limits in several locations, indicating a risk of health issues such as fluorosis and methemoglobinemia, especially for sensitive populations. The trace metal analysis revealed elevated concentrations of Aluminum (Al), Iron (Fe), Manganese (Mn), and Chromium (Cr) in multiple samples. These elements, when present above permissible levels, can pose serious health threats including neurological and carcinogenic effects. Although metals like Cadmium (Cd), Lead (Pb), and Arsenic (As) were generally within acceptable levels, a few samples showed borderline exceedances that may require attention. In summary, while the majority of spring water samples meet drinking water standards, localized exceedances of F^-, NO_3^-, NO_2^-, Al, Fe, Mn, and Cr degrade water quality in specific areas. These findings highlight the need for targeted monitoring, source protection, and community-based water safety interventions to ensure long-term sustainability and safety of spring water resources.Settlements such as Ranidhang, Chamiyala, Mald, Lashiyal Gaon, Bhatgaon, and Gauna showed notably poor WQI values, often exceeding 100. These quality issues were linked to deforestation, unlined drainage, and human and livestock activity near spring recharge zones, indicating a need for urgent water management interventions. In Pratapnagar Critical zones such as the Majaf range and villages like Kangsali and Dinganv faced contamination due to poor sanitation, open defecation, and unprotected catchments, particularly affecting water quality during the monsoon season.While most springs in both blocks are safe for drinking, the presence of even a small proportion of Very Poor and Unsuitable springs highlights the need for targeted interventions such as spring protection, catchment treatment, community awareness, and local treatment solutions like chlorination or filtration. Continued monitoring and integrated springshed management are essential to ensure safe and sustainable spring water access in these Himalayan regions.

(a) Analysis of Major Ions in Spring Water: Compliance with WHO Standards

(i) Bhilangana

Most parameters were found to lie within acceptable ranges across the majority of samples. However, Fluoride (a) showed values exceeding the WHO limit of 1.5 ppm in several instances, indicating a potential health risk related to dental or skeletal fluorosis. Similarly, isolated exceedances of Nitrate (e) and Nitrite (c) were observed, which are critical due to their link with methemoglobinemia and other health concerns. The pH (l) values across samples remained within the optimal range (6.5–8.5), suggesting that the spring water maintains a neutral to slightly alkaline character. TDS (m) levels remained below the maximum recommended threshold of 500 ppm, indicating relatively low mineralization and good palatability. Other anions and cations such as Chloride (b), Sulfate (d), Bicarbonate (f), Sodium (g), Ammonium (h), Phosphate (i), Magnesium (j), and Calcium (k) generally remained within safe limits, though some fluctuation was noted in a few samples (Fig. 5.19). These findings suggest that while the overall ionic composition of spring water is within permissible limits for most constituents, localized exceedances particularly in fluoride, nitrate, and nitrite warrant closer monitoring and possibly intervention measures to ensure long-term drinking water safety.

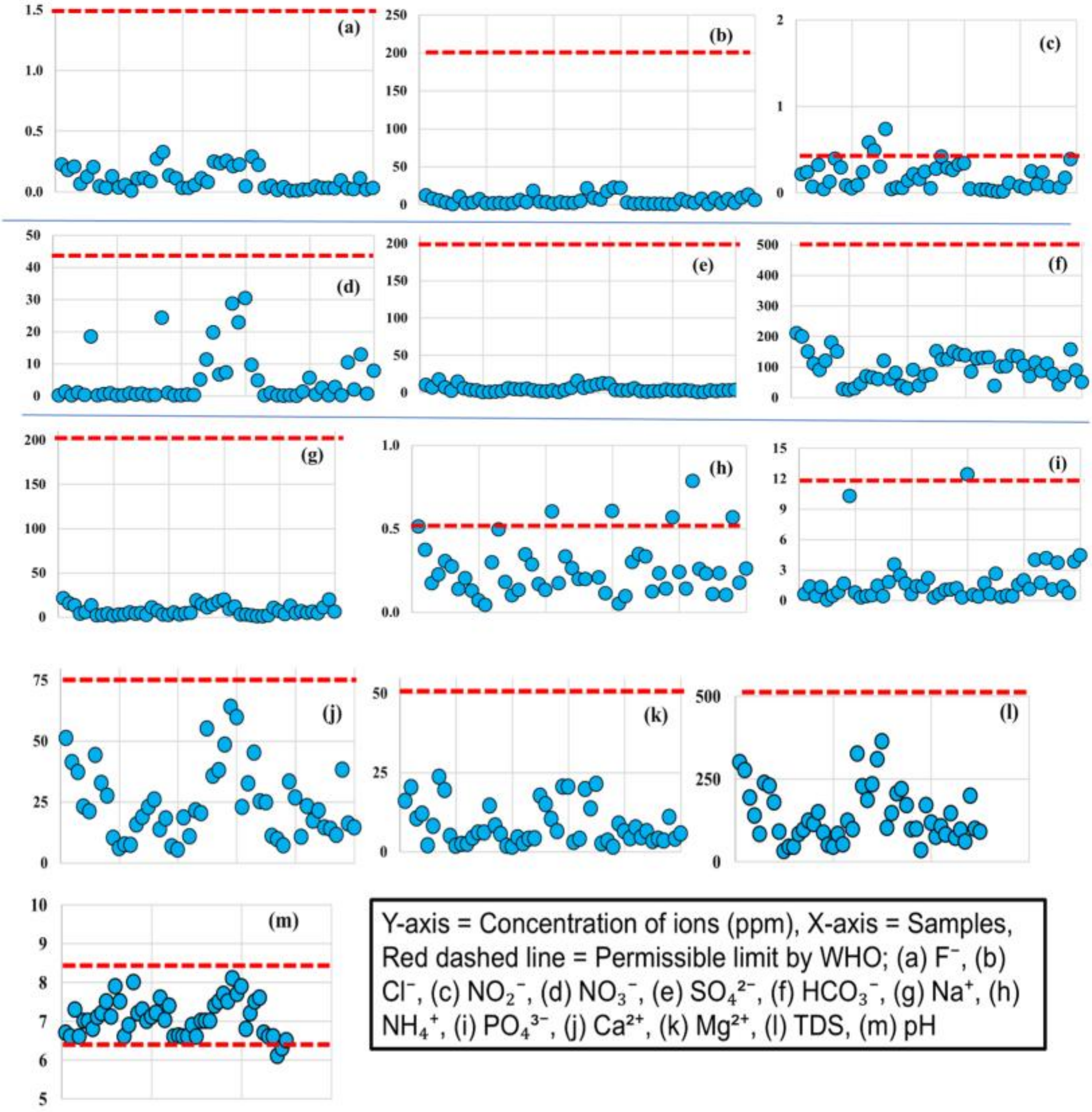


Y-axis: Concentration of ions (ppm) except for pH; X-axis: Water samples; Red dashed line: WHO permissible limit. Subplots: (a) F^-, (b) Cl^-, (c) NO_2^-, (d) SO_4^{2-}, (e) NO_3^-, (f) HCO_3^-, (g) Na^+, (h) NH_4^+, (i) PO_4^{3-}, (j) Mg^{2+}, (k) Ca^{2+}, (l) pH, (m) TDS.

Fig.5.19 Variation of Major ions Compliance with WHO Standards of Bhilangana

(ii) Pratapnagar

The (fig. 5.20) presents a comprehensive analysis of the concentrations of major physicochemical parameters across 50 spring water samples. Each subplot (a–m) corresponds to a specific parameter, plotted against WHO permissible limits indicated by red dashed lines. In subplot (a), Fluoride (F^-) concentrations remain well below the permissible limit of 1.5 mg/L across all samples, indicating no risk of fluorosis. (b) Chloride (Cl^-) levels also show consistently low concentrations compared to the 250 mg/L threshold. (c) and (d) depict Nitrite (NO_2^-) and Nitrate (NO_3^-) respectively; while Nitrite is within safe limits (2 mg/L), a few samples in (d) exceed the 45 mg/L limit for Nitrate, indicating potential agricultural runoff or sewage contamination. In (e), Sulfate (SO_4^{2-}) concentrations remain safely below the 200 mg/L limit. Bicarbonate (HCO_3^-) in (f) shows considerable variation but remains within the general guideline of 500 mg/L, reflecting natural buffering capacity. (g) Sodium (Na^+) levels are well within the acceptable range (200 mg/L), posing no taste or health concerns. Ammonium (NH_4^+), shown in (h), exceeds the 0.5 mg/L permissible limit in several samples, suggesting organic pollution or insufficient filtration. (i) illustrates Phosphate (PO_4^{3-}) levels, which remain below the tentative threshold of 12 mg/L, though regular monitoring is advised due to eutrophication risks. Subplots (j) and (k) represent Calcium (Ca^{2+}) and Magnesium (Mg^{2+}), both of which are within safe levels of 75 mg/L and 50 mg/L respectively, but with some fluctuations indicating spatial variability in mineral content. (l) shows TDS (Total Dissolved Solids), and although values vary, most samples appear under the 500 mg/L limit, confirming overall acceptable water quality. Finally, (m) depicts pH values, which mostly fall within the WHO recommended range of 6.5–8.5, suggesting neutral to slightly alkaline water conditions. Overall, the water quality assessment indicates that the majority of the spring water sources are within WHO guidelines, though periodic exceedances in nitrate and ammonium call for targeted monitoring and spring-shed management strategies to ensure sustainable and safe drinking water for local communities.



Y-axis = Concentration of ions (ppm), X-axis = Samples, Red dashed line = Permissible limit by WHO; (a) F^-, (b) Cl^-, (c) NO_2^-, (d) NO_3^-, (e) SO_4^{2-}, (f) HCO_3^-, (g) Na^+, (h) NH_4^+, (i) PO_4^{3-}, (j) Ca^{2+}, (k) Mg^{2+}, (l) TDS, (m) pH

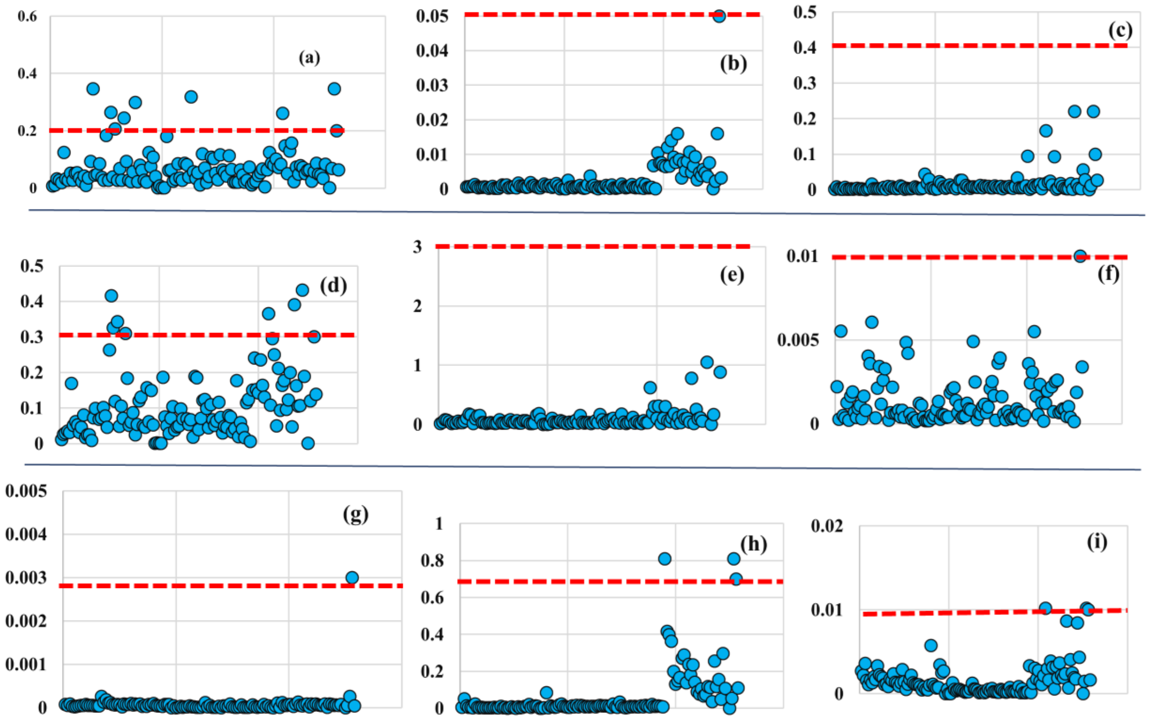
Fig. 5.20 Variation of Major ions Compliance with WHO Standards of Pratpnagar

(b) Trace Metal Concentration in Spring Water: Comparison with WHO Drinking Water Standards

(i) Bhilangana

The concentration of trace metal ions in spring water samples was assessed to evaluate compliance with the World Health Organization (WHO) drinking water standards. Figure (Fig. 5.21) presents the concentration distribution of nine selected metal ions in parts per million (ppm) across all samples, with the red dashed line indicating the WHO permissible limit. The elements analyzed include (a) Al, (b) Cr, (c) Mn, (d) Fe, (e) Zn, (f) As, (g) Cd, (h) Ba, and (i) Pb.Most of the analyzed metals were found within the permissible limits for the majority of samples. However, concentrations of Al (a) and Fe (d) exceeded the WHO limits in several samples, indicating possible geogenic inputs such as weathering of silicate minerals or anthropogenic influence. Mn (c) also exhibited notable spikes above the threshold in a subset of samples, suggesting localized contamination. Conversely, Cr (b), Zn (e), Cd (g), and Ba (h) remained largely within safe limits, with only a few samples approaching the threshold. As (f) and Pb (i) showed marginal exceedances in isolated samples, highlighting the need for periodic monitoring due to their toxicological significance even at low concentrations.

The findings emphasize the importance of continual surveillance of metal concentrations in spring water sources to ensure safe drinking water quality and to identify areas that may require mitigation strategies.



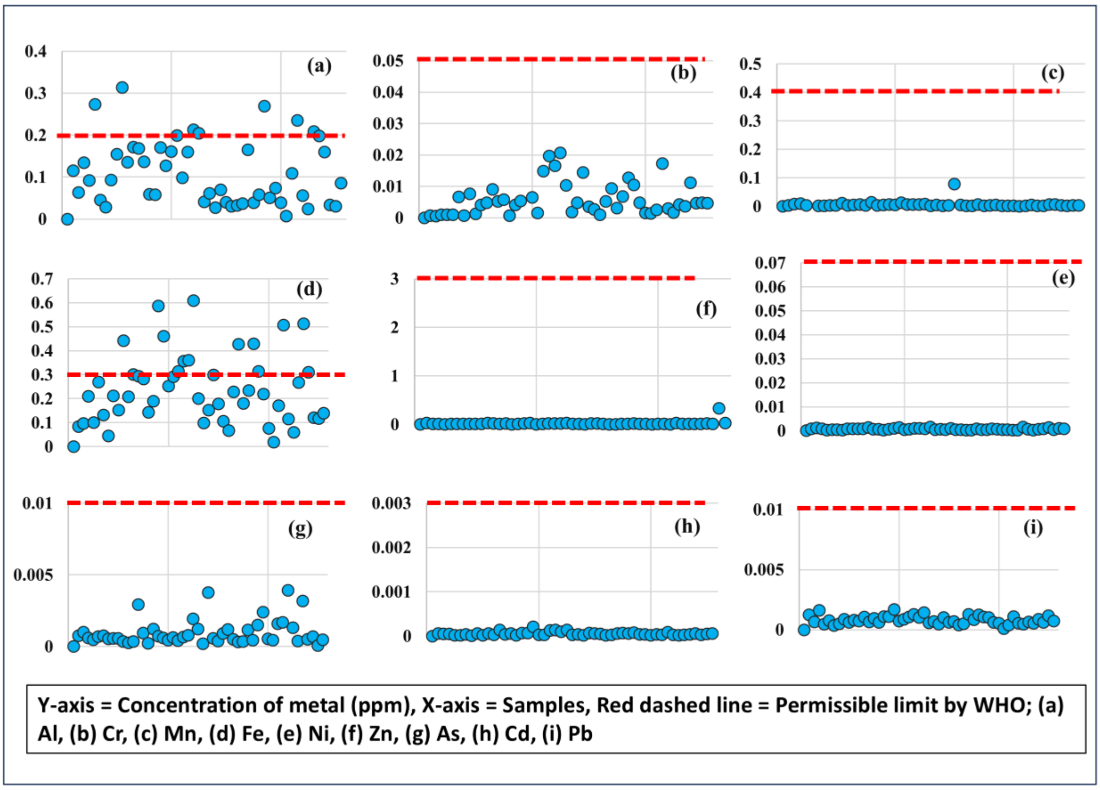
Y-axis = Concentration of ions (ppm), X-axis = Samples, Red dashed line = Permissible limit by WHO; (a) Al, (b)Cr, (c) Mn, (d)Fe, (e) Zn, (f) As, (g) Cd, (h) Ba, (i) Pb.

Fig. 5.21 Variation of Trace metal Compliance with WHO Standards of Bhilangana

(ii) Pratapnagar

The concentration of selected heavy metals in spring water samples was analyzed and compared against the permissible limits set by the World Health Organization (WHO). The graphical representation in Figure [X] shows the distribution of metals in parts per million (ppm) across all collected samples. Among the analyzed metals, Aluminum (a), Chromium (b), Manganese (c), Iron (d), Nickel (e), Zinc (f), Arsenic (g), Cadmium (h), and Lead (i) were considered.Most samples exhibited metal concentrations well below the WHO permissible limits (indicated by the red dashed line), indicating generally safe water quality. However, a few exceptions were observed. Elevated levels of Al (a) and Fe (d) exceeded the permissible thresholds in several samples, suggesting potential geogenic or anthropogenic contributions. Minor exceedances were also noted for Cr (b), though most samples remained within safe limits. All other metals Mn (c), Ni (e), Zn (f), As (g), Cd (h), and Pb (i) were present in trace amounts and remained significantly below the acceptable limits.

These results highlight localized concerns for aluminum and iron contamination, which may warrant further hydrochemical investigation and potential management interventions. Overall, the spring water quality remains within safe limits for most heavy metals assessed.



Y-axis = Concentration of metal (ppm), X-axis = Samples, Red dashed line = Permissible limit by WHO; (a) Al, (b) Cr, (c) Mn, (d) Fe, (e) Ni, (f) Zn, (g) As, (h) Cd, (i) Pb

Fig. 5.22 Variation of Trace metal Compliance with WHO Standards of Pratpnagar

(c) Hydrochemical Facies Analysis

(i) Bhilangana

The Piper diagram as shown in Fig. 5.23 reveals the dominant hydrochemical facies of the spring water samples collected from the Bhilangana region. In the cation's triangle, most samples plot in the lower-left corner, indicating a dominance of Ca^{2+} over Mg^{2+} and Na^{+}+K^{+}, suggesting calcium-rich groundwater (Fig. 5.23). The anion triangle shows a clustering toward the lower-left corner (Fig. 5.23), indicating that HCO_3^{-} is the dominant anion, indicating the recharge zones influenced by carbonate weathering. The central diamond field confirms the water type as Ca^{2+}–HCO_3^{-}, classifying the groundwater under alkaline earth bicarbonate type (Fig. 5.23). Few samples drift slightly toward Mg–HCO_3^{-} and mixed zones, possibly due to localized lithological variability or cation exchange processes. Absence of samples in the Cl^{-} and SO_4^{2-} rich zones indicates minimal anthropogenic contamination or industrial influence. This facies pattern is typical for freshwater sources in mountainous, limestone- and silicate-rich terrains, indicating low mineralization and active recharge conditions. These results align with findings by Singh et al. (2020) and Rawat & Pant (2021), who reported similar water types in Himalayan springs.

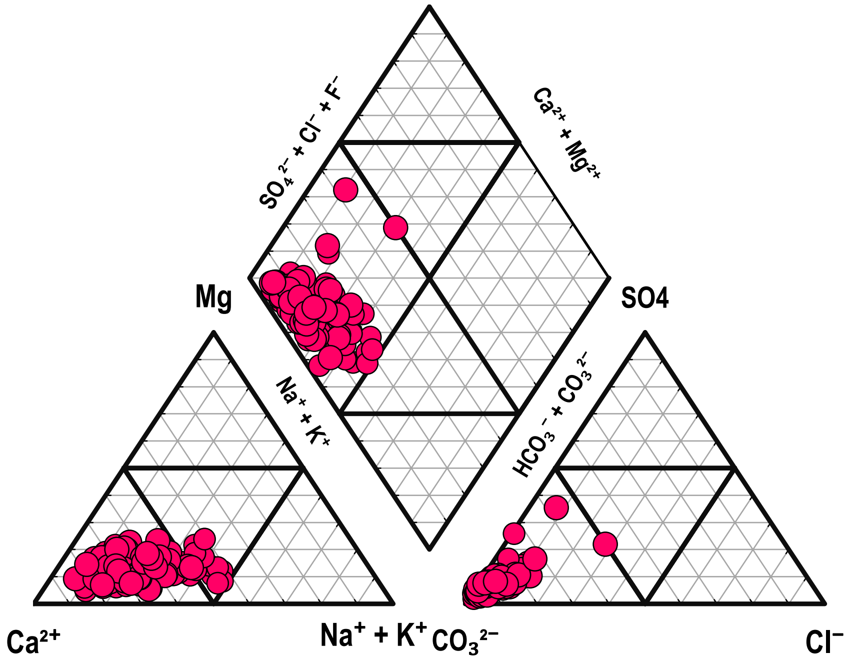


Fig. 5.23 Piper diagram showing the dominant hydrochemical facies in spring water of Bhilangana block, Tehri Garhwal, Uttarakhand.

(ii) Pratapnagar

The Piper diagram for the springs of Pratapnagar block provides clear insight into the hydrochemical facies of the spring waters. The cation triangle reveals a strong dominance of calcium (Ca^{2+}), followed by magnesium (Mg^{2+}), with only minor contributions from sodium (Na^+) and potassium (K^+). This suggests that the water chemistry is primarily governed by carbonate weathering processes rather than silicate weathering or anthropogenic sources. In the anion triangle, bicarbonate (HCO_3^-) overwhelmingly dominates, with negligible presence of chloride (Cl^-) and sulfate (SO_4^{2-}), indicating minimal influence from anthropogenic pollution, salt intrusions, or evaporite dissolution.

When the cation and anion fields are combined in the central diamond, the clustering of samples clearly falls within the Ca^{2+}–Mg^{2+}–HCO_3^- zone (Fig. 5.24). This defines a calcium-bicarbonate water type, which is characteristic of shallow, freshly recharged groundwater in regions underlain by limestone and dolomite. Such facies are typical in mountainous

Himalayan terrains, where the aquifer is composed of carbonate rocks and groundwater experiences limited chemical evolution. The tight grouping of sample points also implies a uniform hydrogeochemical regime across the catchment, with little variation in water type, suggesting similar lithological control and recharge conditions throughout. The dominance of alkaline earth metals ($Ca^{2+} + Mg^{2+}$) over alkali metals ($Na^{+} + K^{+}$) and of weak acids (HCO_3^{-}) over strong acids ($Cl^{-} + SO_4^{2-}$) indicates a geochemically young water system, reflecting limited ion exchange or anthropogenic interference. Overall, the Piper diagram confirms that the spring water in this catchment belongs to a Ca–HCO_3 or Ca–Mg–HCO_3 facies, representing high-quality, geogenically derived water suitable for domestic use, especially in rural and mountainous settings.

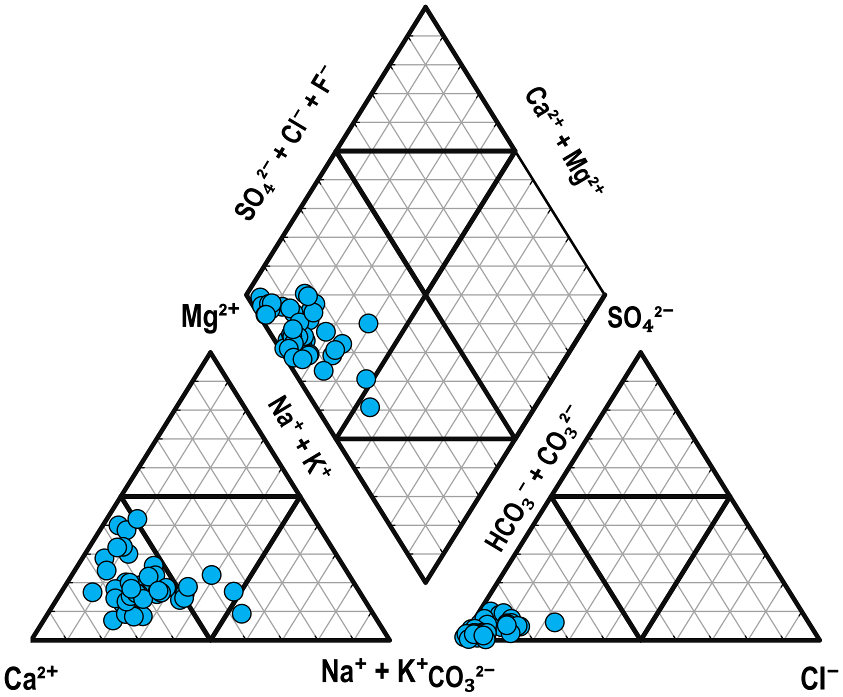


Fig 5.24 Piper diagram showing the dominant hydrochemical facies in spring water of Pratapnagar block, Tehri Garhwal, Uttarakhand.

(d) Spatial hydrochemical Distribution of Bhilangana

The spatial distribution of hydrochemical parameters in the study area reveals significant variability influenced by both natural and anthropogenic factors. The Water Quality Index (WQI) indicates that water quality ranges from ‘excellent’ in scattered southern zones to ‘very poor' in certain northern patches. Bicarbonate (HCO_3^-) concentrations are notably higher in the southwestern part, suggesting lithological control from carbonate-bearing formations. Elevated ammonia (NH_4^+) levels are observed centrally and towards the north, while sulphate (SO_4^{2-}) shows (Fig. 5.25) a distinct north-south central concentration pattern. Nitrate (NO_3^-) hotspots in the north-central region point to possible agricultural or domestic pollution. Sodium (Na^+) exhibits an increasing gradient from west to east, with the southeastern zone showing higher values. Phosphate (PO_4^{3-}) remains low overall but is marginally elevated in south-central pockets. Potassium (K^+) displays patchy enrichment in eastern and southeastern areas. These spatial trends, visualized using GIS, highlight vulnerable zones—particularly in the central, southern, and eastern parts of the study area—necessitating focused water quality monitoring and management strategies.

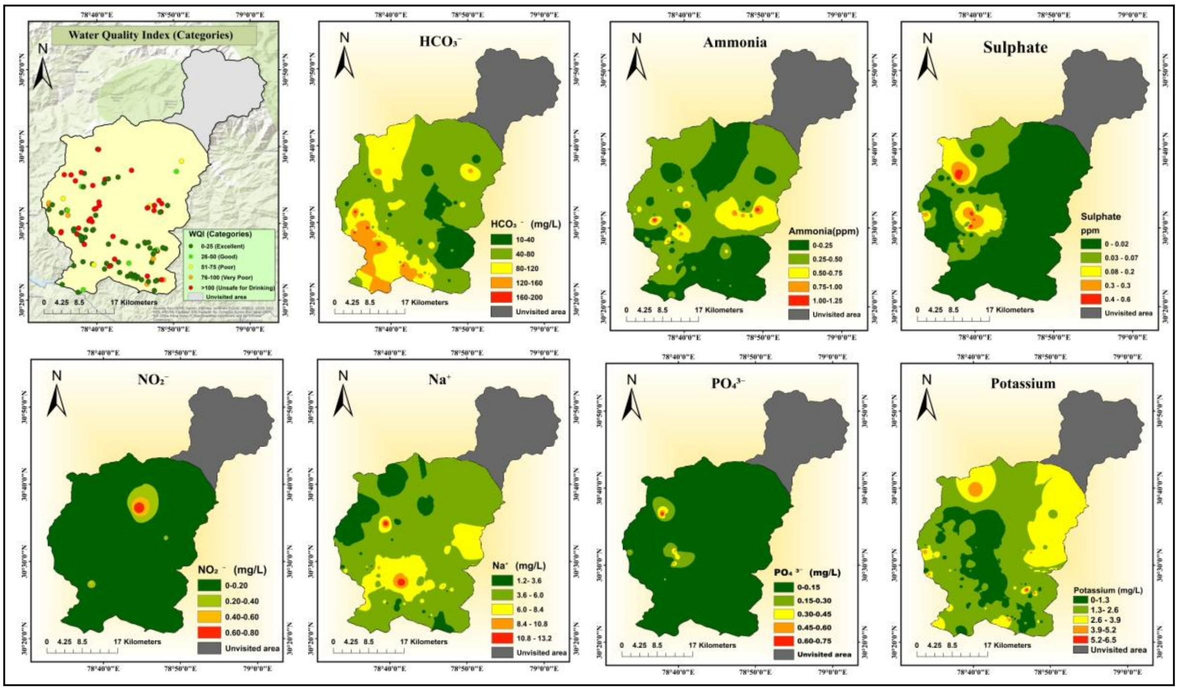


Fig.5.25 Spatial hydrochemical (major ions) Distribution of Bhilangana

(e) Chemical Weathering

Based on the scatter plot of ($Ca^{2+} + Mg^{2+}$) vs ($HCO_3^- + SO_4^{2-}$) in Fig. 5.26, the hydrochemical analysis reveals the dominant weathering processes influencing spring water chemistry in the study area. The data points generally align along the 1:1 line (Fig. 5.26), indicating a strong stoichiometric relationship between alkaline earth metals (Ca^{2+}, Mg^{2+}) and the major anions (HCO_3^-, SO_4^{2-}). A significant cluster of samples lies below the 1:1 line, which is characteristic of carbonate weathering, suggesting that the dissolution of limestone and dolomite is a major contributor to the ionic composition of groundwater. This is typical in regions underlain by carbonate-rich lithology. However, a noticeable number of samples also fall above the 1:1 line (Fig. 5.24), implying a relative excess of Ca^{2+} and Mg^{2+}. These samples indicate the influence of silicate weathering, where cation exchange and slower weathering of silicate minerals (like feldspar and pyroxenes) may be contributing to the groundwater chemistry. The presence of SO_4^{2-} in the anionic composition, along with HCO_3^-, also suggests minor contributions from sulfate-bearing minerals such as gypsum or from anthropogenic sources. Overall, the hydrochemical data confirm that the spring water chemistry is primarily governed by carbonate dissolution, with secondary contributions from silicate weathering, depending on the local geology. This dual signature reflects the heterogeneous lithological setting and possible variations in residence time and flow paths of spring water in the mountainous terrain.

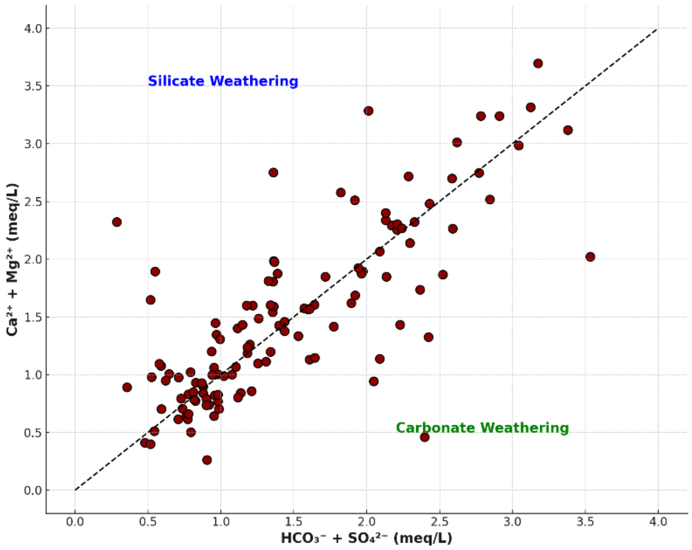


Fig 5.26 Scatter plot of ($Ca^{2+} + Mg^{2+}$) versus ($HCO_3^- + SO_4^{2-}$) in meq/L indicating dominant weathering processes.

(i) Gibbs Plot Analysis of Water Chemistry

The Gibbs diagrams presented in the above plots provide insight into the mechanisms controlling the hydrochemistry of the spring water in the study area. In the Fig.5.27 (a) (Na^+/Na^++Ca^{2+} vs TDS), the majority of the samples fall within the "rock dominance" zone, suggesting that water chemistry is primarily influenced by the weathering of silicate and carbonate minerals in the geological formations. Similarly, the Fig.5.27 (b) ($Cl^-/Cl^-+HCO_3^-$ vs TDS) also indicates a strong clustering of samples within the rock dominance field, further confirming the dominance of geogenic processes such as mineral dissolution over other mechanisms like precipitation or evaporation. The minimal presence of samples in the evaporation or precipitation dominance fields suggests that anthropogenic activities and climatic influences play a lesser role in shaping the ionic composition of spring water in this region. These findings highlight the critical role of lithological control in governing groundwater quality and composition in the mountainous terrains of the Bhilangana.

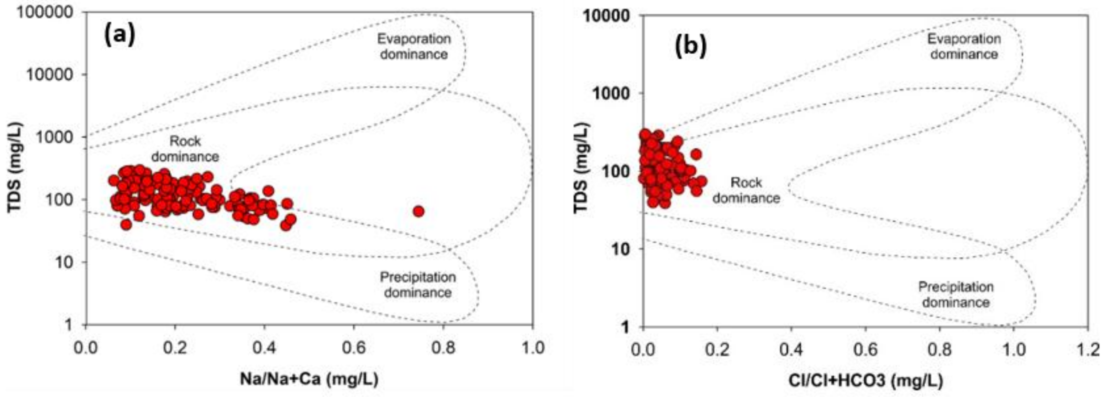


Fig. 5.27 Gibbs plot **(a)** TDS vs. $Na^+/(Na^+ + Ca^{2+})$, **(b)** TDS vs. $Cl^-/(Cl^- + HCO_3^-)$

The plot of Mg^{2+}/Na^+ versus Ca^{2+}/Na^+ (in meq/L) is used to identify the dominant geochemical processes influencing spring water chemistry. The majority of the data points in the graph fall within the region indicative of carbonate dissolution, with a smaller proportion aligning with silicate weathering. This suggests that the groundwater in the study area is primarily controlled by the dissolution of carbonate minerals such as calcite and dolomite, which release Ca^{2+} and Mg^{2+} into the water. The contribution from silicate weathering is secondary, indicating limited interaction with silicate-bearing rocks. Notably, no samples fall within the evaporite dissolution zone, implying negligible influence from evaporite minerals like halite or gypsum. Overall, the diagram emphasizes that carbonate rock interaction is the principal mechanism driving the hydrochemical composition of spring water in the region.

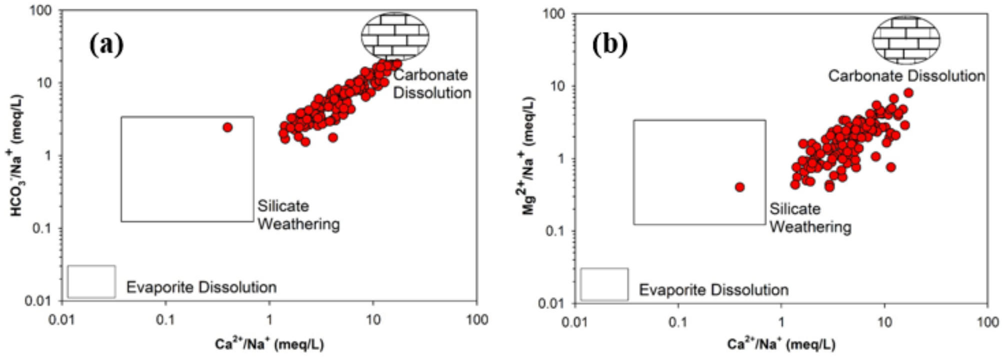


Fig.5.28 Gibbs-type scatter plots **(a)** HCO_3^-/Na^+ vs. Ca^{2+}/Na^+ (meq/L), **(b)** Mg^{2+}/Na^+ vs. Ca^{2+}/Na^+

6. CONCLUSIONS AND SCOPE OF FUTURE WORK

The study titled “Ascertaining the efficacy of use of state-of-the-art technologies for spring mapping and sustainability of springs through suitable interventions, conducted a comprehensive assessment of springs across Bhilangana, Pratapnagar, and Ukhimath blocks in Uttarakhand, supporting DoWR, RD&GR, Ministry of Jal Shakti, GoI’s spring revival agenda and achieving SDG-6 by year 2030. Out of total 383 identified springs by SOI by using art-of-state technologies, NIH verified 346 springs located in accessible areas. Only 65 matched SOI coordinates closely, while 71 showed spatial deviation and 136 new springs were identified during the field verification, which suggests that art-of -state technologies to be needed more evaluation/refinement to achieve the acceptable accuracy for mapping springs. Vulnerability assessment revealed that many springs, especially in Bhilangana and Pratapnagar, are moderately to highly vulnerable due to degraded recharge zones and human pressures. Hydrochemical analysis showed $Ca–HCO_3$ as the dominant water type, with carbonate weathering as the key geogenic process. Elevation trends indicated lower EC and ion levels at higher altitudes, with increased DO and pH. WQI analysis found 70% of springs in ‘Excellent’ to ‘Good’ categories, though 7–10% showed nitrate contamination in mid-altitude areas. These findings highlight the urgent need for monitoring, rejuvenation of vulnerable springs particularly located in the lower altitudes where settlement exist, and participatory management to ensure long-term spring sustainability in the Himalayas.

Chapter 1: Introduction This chapter outlined the importance of spring ecosystems in the Himalayan region and discussed challenges like spring degradation, water insecurity, and lack of long-term monitoring. It set the objectives for verification of springs identified by the SOI using art-of-state technologies, vulnerability assessment, hydrochemical analysis, and integration of spatial tools for sustainable spring management.

Chapter 2: Review of Literature This chapter reviewed international and national-level studies on spring hydrology, vulnerability assessments, and water quality monitoring. It highlighted various methodologies, case studies, and policy frameworks, providing a foundational understanding for the current research. Key findings from Himalayan and non-Himalayan regions helped shape the analytical approach and springs characteristics parameters used in this study.

Chapter 3: Study Area The physiographic, geological, hydrological, and socio-economic characteristics of Bhilangana, Pratapnagar, and Ukhimath blocks were elaborated to establish the regional context. Variations in elevation, rainfall, geology, and land use patterns provided critical background for interpreting spatial heterogeneity in spring water characteristics.

Chapter 4: Methodology The methodology section described the protocols followed for spring inventory, field surveys, water sampling, laboratory analysis, and the use of geospatial techniques. Indicators were selected for vulnerability assessment and Water Quality Index (WQI) calculations, along with plotting techniques (e.g., Piper, scatter, and dissolution diagrams) to interpret hydrochemical processes.

Chapter 5: Results and Discussion This chapter presented key findings on spring location verification, water quality variation, and spatial distribution of hydrochemical parameters.

(i) Verification of SoI springs dataset

The verification of spring locations across Bhilangana, Pratapnagar, and Ukhimath reveals significant discrepancies in the Survey of India (SOI) dataset. Although many springs were verified, a large proportion were either inaccurately mapped or misclassified, particularly in Ukhimath where seasonal streams were mistaken for springs. Additionally, several new springs were discovered, underscoring gaps in existing data. The findings demonstrate that while SOI maps offer a basic framework, they lack the spatial accuracy and reliability needed for effective spring-shed management. Thus, comprehensive field verification is essential to ensure accurate spring mapping and to support sustainable water resource planning in the region.

(ii) ***Vulnerability assessment***

The spring vulnerability assessment across Bhilangana, Pratapnagar, and Ukhimath blocks highlights significant spatial disparities, crucial for prioritizing spring rejuvenation efforts. Bhilangana exhibited a predominance of moderately vulnerable springs (71.77%), while Pratapnagar presented an even split between moderate and high vulnerability. Ukhimath emerged as the most at-risk, with 75.86% of springs categorized as highly vulnerable due to geological fragility and heavy dependence. These insights underscore the urgency for targeted, site-specific interventions such as catchment protection, artificial recharge, and community-led initiatives, particularly in Ukhimath and southern Pratapnagar, to enhance spring resilience and ensure sustainable water resources for local communities.

(iii) Water quality and Hydrochemical Analysis

The comprehensive assessment of spring water quality in the Bhilangana and Pratapnagar blocks reveals that the majority of sources meet WHO drinking water standards, with Water Quality Index (WQI) values predominantly falling within the ‘Excellent’ to ‘Good’ categories. However, pockets of deterioration in water quality particularly in settlements like Ranidhang, Chamiyala, and the Majaf range highlight serious concerns. These include elevated concentrations of fluoride, nitrate, nitrite, and ammonium, which pose significant health risks such as fluorosis and methemoglobinemia, especially among vulnerable populations. Such exceedances are attributed to both geogenic factors and human-induced pressures, including deforestation, poor sanitation, and encroachment on recharge zones. Trace metal analysis further reinforces these concerns, with Aluminum and Iron levels surpassing WHO thresholds in several samples, and occasional exceedances observed for Manganese and Chromium. Although most samples remain within permissible limits for critical metals like Cadmium, Arsenic, and Lead, even minor exceedances highlight the need for regular surveillance due to their long-term toxicological implications. These findings necessitate the implementation of site-specific mitigation strategies, including source protection, artificial recharge interventions, and community-based water treatment solutions. Hydrochemical facies analysis using Piper diagrams classifies the spring water as predominantly $Ca–HCO_3$ and $Ca–Mg–HCO_3$ types, typical of geogenically derived, freshly recharged groundwater from carbonate-rich lithologies. The dominance of alkaline earth metals and bicarbonates over chlorides and sulfates indicates minimal anthropogenic impact and suggests a geochemically young water system. Weathering plots further confirm that carbonate dissolution is the primary geochemical process, with minor contributions from silicate weathering in select locations. Overall, the study highlights the high quality and recharge-driven origin of spring waters in these Himalayan blocks, while underscoring localized vulnerabilities. Continuous monitoring, community engagement, and integrated spring-shed management are essential to ensure safe, sustainable, and resilient spring water resources for the future.

As a significant outcome of this study, Annexure II: Spring Atlas of the Bhilangana Block has been developed as part of the project work. This atlas provides a comprehensive quantitative and qualitative description of the mapped springs across the block.

Scope of Future work

1. Formulate a State-Level Spring Rejuvenation and Monitoring Framework A coordinated spring-shed rejuvenation strategy should be developed to address the high vulnerability observed in several springs, especially in Bhilangana and Pratapnagar. This framework must integrate with existing government schemes such as Jal Shakti Abhiyan, MNREGA, PMKSY, and Namami Gange. It should include standardized protocols for spring protection, discharge enhancement, and catchment treatment. Additionally, the program should feature periodic monitoring and adaptive management based on local hydrogeological conditions.

2. Establish a Web-GIS Based Spring Atlas and Hydroinformatics Platform To facilitate real-time data sharing and decision-making, a Web-GIS-based Spring Atlas for Uttarakhand should be developed. This platform will consolidate spatial and attribute data related to spring discharge, water quality, vulnerability scores, and recharge zones. Integration with mobile-based data collection apps and periodic updates will support decentralized planning and empower local agencies, researchers, and planners with transparent, accessible information.

3. Mainstream Climate Change and Livelihood Vulnerability Assessment Future research should focus on climate-resilient spring management, incorporating long-term hydro-meteorological data and predictive climate models. The use of the Livelihood Vulnerability Index (LVI), aligned with the IPCC framework, is recommended to evaluate the socio-economic and climatic risks faced by communities dependent on spring water. This will enable the design of region-specific adaptation strategies for climate-sensitive watersheds in Uttarakhand.

4. Expand Survey Coverage and Enhance Scientific Techniques Spring inventory, water quality assessment, and vulnerability mapping should be expanded to neighboring blocks like Jakholi, Ghat, and Rudraprayag, to develop a basin-wide understanding of spring systems in the Garhwal Himalaya. Use of advanced technologies such as remote sensing, drones, geospatial modeling, and shallow geophysical resistivity surveys will be crucial in identifying recharge zones, subsurface structures, and areas requiring urgent interventions.

5. Promote Community-Led Restoration and Ecosystem-Based Conservation Strengthening community engagement and capacity building is key to sustainable spring management. Training local youth and water user groups in participatory monitoring, water quality testing, and spring protection techniques will foster ownership and stewardship. Restoration of spring catchments using ecosystem-based measures like native vegetation planting, infiltration trenches, and check dams will support recharge, reduce erosion, and enhance biodiversity. These nature-based solutions should be supported through convergence with forest and rural development programs.

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