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To
The Director General
National Mission for Clean Ganga (NMCG)
Ministry of Jal Shakti
Government of India
New Delhi

Subject: Submission of Final Project Completion Report of the project entitled "Rejuvenation of drying springs in Takoli Gad catchment of Tehri district, Uttarakhand using Geochemistry and Geophysical Techniques" (Project No. TE-11015/1/2019-TECH5NMCG)

Sir,

I am pleased to submit herewith the **Project Completion Report** for the research project entitled **"Rejuvenation of drying springs in Takoli Gad catchment of Tehri district, Uttarakhand using Geochemistry and Geophysical Techniques"**, sanctioned by the National Mission for Clean Ganga vide **Project No. TE-11015/1/2019-TECH5NMCG**.

The project has been successfully completed in accordance with the approved objectives, scope of work, and timelines. The study integrates geochemical and geophysical investigations to identify spring recharge mechanisms and proposes scientifically grounded, site-specific interventions for rejuvenation of drying springs in the Himalayan terrain. The findings and recommendations are expected to contribute meaningfully to sustainable spring-shed management and water security in the upper Ganga basin.

The Final Project Completion Report incorporates detailed methodology, results, interpretation, conclusions, and **specific actionable recommendations** for replication and policy-level consideration. All deliverables as per the sanction order have been duly complied with.

I request you to kindly accept the enclosed Final Project Completion Report and accord necessary approval. I shall be pleased to provide any further clarification or additional information, if required.

Thanking you.

Yours sincerely,

17/01/2026

Prof. A. S. Maurya
Principal Investigator
(Project: Rejuvenation of drying springs in Takoli Gad catchment)

Encl.: Final Project Completion Report

Submission of Final Project Completion Report and Specific Recommendation

On

Rejuvenation of drying springs in Takoli Gad catchment of Tehri district, Uttarakhand using Geochemistry and Geophysical Techniques.



Project No: ***TE-11015/1/2019-TECH5NMCG***

Funding Agency: Namami Gange, National Mission to Clean Ganga
Ministry of Jal Shakti (Government of India)

Principal Investigator

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Acronyms & abbreviations

IHR	Indian Himalayan Region
BIS	Bureau of Indian Standards
CBOs	Community-Based Organizations
EC	Electrical conductivity
GSI	Geological Survey of India
lpd	litres per day
lpcd	litres per capita per day
lpm	litres per minute
masl	metres above sea level
TDS	Total dissolved solids
ERT	Electrical Resistivity Tomography
LULC	Land Use Land Cover
GEE	Google Earth Engine
NBSS&LUP	National Bureau of Soil Survey and Land Use Planning
IDW	Inverse Distance Weightage IDW
CRU	Climatic Research Unit
TDS	Total Dissolved Solids
GMWL	Global Meteoric Water Line
LMWL	Local Meteoric Water Line
EC	Electrical conductivity
ICP–MS	Inductively Coupled Plasma–Mass Spectrometry
IRMS	Stable Isotope Ratio Mass Spectrometer
WHO	World Health Organisation
NMSHE	National Mission for Sustaining the Himalayan Ecosystem

1. Introduction

The Indian Himalayan Region (IHR) spans across 13 Indian states and union territories, stretching from Jammu & Kashmir in the west to Arunachal Pradesh in the east. It is home to some of the world's highest peaks, including parts of the mighty Mount Everest range. The region is known for its diverse landscapes, rich biodiversity, and unique cultures. It plays a vital role in regulating the climate, serving as a major source of freshwater through its glaciers and rivers. However, the IHR is also highly fragile and faces threats from climate change, deforestation, tectonic activities and unplanned development.

In Himalayan region where availability of fresh water is very less, as no such freshwater bodies (lakes, ponds, borewell) are abundant like that of plain areas and most of the rainwater flows downhill due to steep slopes of the mountain. Here the livelihood of people is mostly dependant on springs also known as “dhara”. Springs are groundwater discharge points that appear where the saturated zone of the aquifer intersects with the surface and water seeps out of rock pores, fissures, fractures, or depressions. The sources from which springs gets the water, mostly are unconfined aquifers where the water flows under the action of gravity. These springs play a vital hydrological role in maintaining the water flow during the hungry season across the Himalayan region.

In the past 2 decades Tehri district of Uttarakhand has witnessed a drastic change in the water flow of the springs in that region, Incidences of decreasing discharge of springs have been reported in Uttarakhand identified severe water shortage due to the drying of the springs, especially during the dry seasons. where in the lean seasons some of the springs have dried, vanished (shifted the flow direction) and which are perineal the water flow is insufficient to meet the current water demand of the people in those seasons (December – may).

Uttarakhand is a major source of freshwater for many perennial rivers such as the Bhagirathi, Ganga, Yamuna, Mandakini, Pinder, Kali, Kosi, Ramganga, Tons and their tributaries. The drying up of springs will also affect the flow of these rivers because large fraction of waters in these river systems is derived from springs in the form of groundwater or baseflow. Due to gradual drying up of Springs many rivers which are spring fed like Nayar in Pauri, Ramganga, Kosi and other small tributaries are facing low discharge particularly during lean season and many Perennial rivers and streams are becoming seasonal. This has been reported all across within the state of Uttarakhand.

The Spring water discharge fluctuations owe primarily due to rainfall pattern in the recharge area or more precisely stated, to variation in the amount of rainwater that can infiltrate the ground and recharge the ground water. Marked variation in the discharge following rainfall indicates rapid infiltration of rainwater and recharge of the groundwater. The drying of spring water sources can be ascribed to erratic rainfall patterns and reduction in winter rain, rising temperature; deforestation; changes in land use, and forest degradation, including changes in forest type. Thus, the water scarcity issues underscore the need to increase the understanding of spring hydrology, especially in the Himalayan region.

Over time, the pressure on the land has also increased significantly. Deforestation, overgrazing, and inadequate agricultural practices, altered land use pattern, population growth, urbanization, industrial and commercial activities, global impacts from climate and weather change, lack of rainfall, contributes to the degradation of land and water scarcity. Earthquakes are also responsible for the drying or displacement of water sources by disturbing the underground geology, something that was especially pronounced after the 2015 earthquake in Nepal.

However, the high-altitude areas have always faced water shortage for their domestic and agricultural demand. Large population from high altitude villages are migrating to the plain because of shortage of water particularly during the non-rainy summer. The rivers flowing through deep valleys are unable to fully meet the water needs of parched villages in the hills. Most of the mountainous villages in the state are dependent on natural water. Reports says almost 12000 springs are dried up during recent time, which is very alarming. So, the urgency of reviving the springs is at utmost as the present situation of the springs are very alarming.

This present study has emerged with a new approach, innovative and robust methodology for assessing the status of springs, its provenance and the flow path. where it is including available state of art techniques like isotopes, geo-chemistry, geological field mapping, LULC using remote sensing, ERT (Electrical Resistivity Tomography) and numerical atmosphere-hydrological modelling of impacts of LULC and climate change on rainfall-run off dynamics. So far, this type of integrated approach is not being used in India and abroad to rejuvenate the springs. Not only the scientific part, here a ground level action plan also has been included where a cadre of young professionals and community-based resource persons(para-worker) will be created through training and capacity building programs. This will help in efficient use of resources allocated for spring-shed management and also build social sustainability to ensure committed & capable group of people who would manage their spring-shed on their own in long run.

Main objectives of the study

1. To assess the impact of land use land cover change or impact of natural or anthropogenic precipitation variable discharge depletion.

2. Identifying the frequency of inherent and superimposed structural attributes to enhance porosity and permeability along the stream path for localizing the recharge zones.

3. To identify the recharge zone and flow path of drying/dried-up springs using stable and unstable (^{3}H) isotopes, hydro geochemical, geological and ERT technics.

4. To develop a cost effective standard operative procedure (SOP)to implement in other Himalayan area and strengthen local water governance and participatory spring shed management approach.

5. To prepare Water budget of the watershed villages for prediction of sustainability of village water resources**.**

1.1.Magnitude of the Problem – Major Issues and Challenges in the Takoli Gad Watershed

Springs constitute the lifeline for the rural households of the Takoli Gad watershed and serve as the primary source of drinking water and irrigation. A large proportion of the local population is dependent on natural springs, with no reliable access to perennial streams or piped water supply. The upland villages of Takoli Gad are particularly disadvantaged, as the snowmelt-fed rivers and seasonal streams flowing through the valleys are either too distant or inaccessible due to steep topography. Consequently, people rely almost exclusively on springs for meeting their daily water requirements. Agriculture remains the dominant livelihood activity (Fig. 1), and since the irrigated area is limited, spring-fed irrigation plays a critical role in sustaining productivity.

The situation has become increasingly precarious. Many of the springs in Takoli Gad have shown marked decline in discharge over the past two decades, while several perennial sources have turned seasonal. Oral histories and community observations point to drastic reductions in spring flow, with local estimates suggesting that more than half of the springs that once supported multiple households are now either drying up or yielding insufficient water during lean months. This has led to frequent water shortages for both domestic use and farming.



Fig. 1: Contour Farming within Takoli Gad watershed.

The challenges of spring depletion in Takoli Gad must be understood in the broader context of fragile mountain environmental systems. The watershed lies in the structurally complex Lesser Himalayan belt, where tectonic activity, steep slopes, and shallow aquifers make groundwater highly sensitive to land-use changes, seismic disturbances, and climate variability. Increasing deforestation, road construction, and changing rainfall patterns have all contributed to reduced recharge and disrupted natural discharge regimes. The problem is not confined to households alone; springs in the forests and grazing areas that serve as wildlife watering points are also under stress, causing ecological imbalance.

Cultural and social dimensions further underline the importance of springs in Takoli Gad. Community festivals and traditional water-sharing arrangements often revolve around these sources, reflecting the deep-rooted relationship between people and their springs. The decline

of spring discharge not only threatens water security but also erodes cultural values and traditional practices associated with these natural sources.

To cope with shortages, households have resorted to short-term and often unsustainable measures, such as transporting water from distant sources by pack animals or motorcycles, and in extreme cases, purchasing water from tankers. The burden falls disproportionately on women, who must walk longer distances to fetch water when local springs run dry, adding to their already heavy responsibilities of collecting firewood, fodder, and managing households.

Water quality concerns are also emerging. Anthropogenic pressures such as livestock activity, septic leakage, and increased use of fertilizers on terraced fields pose risks of microbial and nitrate contamination in spring water. Although systematic studies are limited, community feedback suggests deteriorating taste and occasional health issues linked to unsafe drinking water. Geogenic risks, such as elevated iron or fluoride, though less common, cannot be ignored given the local geology.

The implications extend beyond the watershed. Since the Takoli Gad springs ultimately contribute to larger streams and rivers in the Alaknanda basin, depletion has downstream impacts on base flows and river hydrology. Without adequate spring recharge, the perennial character of these rivers is jeopardized. Thus, spring revival in Takoli Gad is not only a matter of local water security but also an important element in safeguarding regional hydrology.

Addressing the problem requires a shift from short-term coping strategies to long-term rejuvenation measures. Community-based aquifer mapping, recharge interventions, and catchment protection are crucial steps. Given the heavy reliance on springs by both rural households and nearby towns, spring rejuvenation in Takoli Gad offers a sustainable, low-cost, and culturally rooted approach to ensuring water security for the region.

1.2.Gaps in Knowledge, Practice and Policy – from Takoli Gad, Tehri Garhwal

The Takoli Gad watershed in Tehri Garhwal district, Uttarakhand, is a representative case of the broader Himalayan water crisis. While the population here depends heavily on springs (Fig. 2) for drinking water, irrigation, and livestock needs, the depletion of these natural sources has not been addressed adequately in knowledge systems, development practice, or policy frameworks. The absence of springs in mainstream water discourse has resulted in fragmented efforts, leaving major gaps in both scientific understanding and governance.

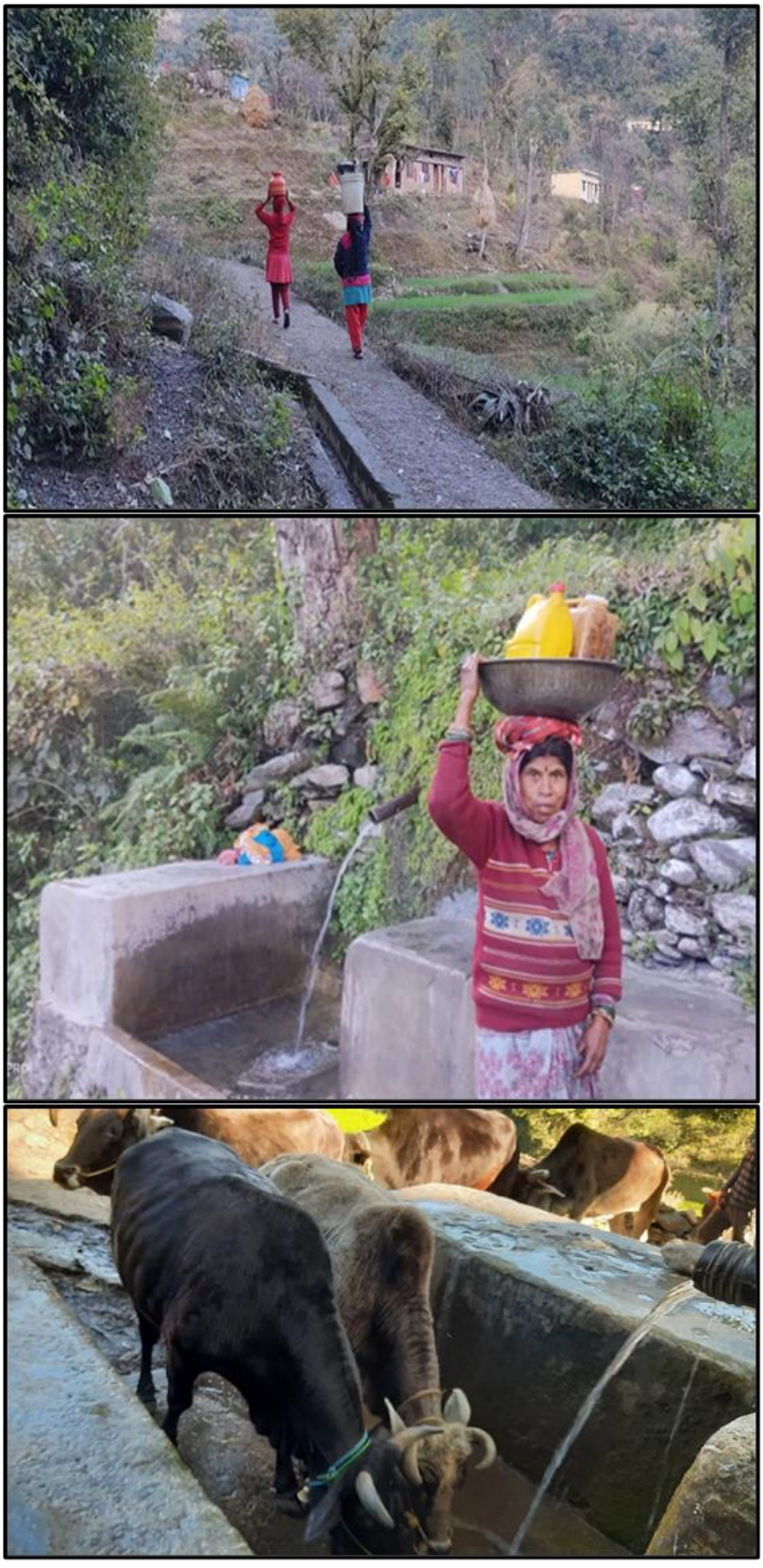


Fig. 2: Showing the importance of springs in our study for daily household and animal husbandry

Unlike wells or handpumps that are human-made structures for groundwater access, springs in Takoli Gad are natural discharge points of aquifers. Their flows cannot simply be engineered through pumping but are determined by recharge conditions in the surrounding catchment. However, water policies in India have traditionally focused on "development" in the form of wells, tube wells, and large storage structures. This orientation has sidelined natural groundwater discharge systems like springs, particularly in steep mountain terrains such as Tehri Garhwal. For decades, groundwater assessments by the Central Ground Water Board (CGWB) excluded areas with slopes greater than 20%, thereby disregarding the very regions where springs form the mainstay of water supply. Although recent revisions to the Groundwater Estimation Committee (2016) have attempted to rectify this, practical frameworks for spring monitoring in regions like Takoli Gad are still missing.

Knowledge Gaps

Scientific understanding of springs in Takoli Gad remains inadequate. While it is well acknowledged that springs represent groundwater discharge, their functioning as part of larger aquifer systems has not been systematically studied. Aquifer geometry in the Lesser Himalaya, where Takoli Gad lies, is highly variable, influencing spring behaviour in complex ways. Yet, most interventions in the region have focused only on the supply side—developing spring boxes and pipelines—rather than studying recharge dynamics and aquifer sustainability.

Another overlooked dimension is the socio-cultural value of springs. In Takoli Gad, traditional water-sharing practices and community norms exist, but these have rarely been documented or integrated into scientific planning. Similarly, the role of vegetation and land cover in spring recharge has not been studied in detail, even though deforestation and road construction in the area are visibly affecting infiltration and recharge. Spring hydrology in Tehri Garhwal, therefore, demands an interdisciplinary approach—linking hydrogeology, ecology, and community traditions.

Data limitations remain another critical gap. Long-term discharge monitoring of Takoli Gad springs is absent, and climate records at fine resolution are sparse. Without such data, establishing robust relationships between rainfall variability, climate change, and spring depletion is difficult. Documentation of local initiatives, including community recharge structures, is also inadequate, making it challenging to replicate or scale successful models.

Practice Gaps

In practice, the neglect of springs is evident in rural water supply schemes in Tehri Garhwal. While springs provide the most cost-effective and sustainable sources for scattered villages in Takoli Gad, engineering-driven solutions often dominate, such as plans to lift water from rivers located far below or pump groundwater from deep aquifers. These approaches are not only expensive but also unsustainable given the region's topography and fragile ecology.

Another practice gap is the lack of recognition that springs and wells often tap into the same aquifers. Increasing bore well drilling in the hills for agriculture and domestic use has intensified competition between natural (springs) and artificial (wells) discharge points. This has direct consequences in areas like Takoli Gad, where the drying of springs coincides with a rise in bore well dependence, creating a paradox where policies support one source while neglecting the other.

Policy Gaps

At the policy level, spring management has not been explicitly integrated into national or state water frameworks. The National Water Policy (2012) only refers to the Himalayas in terms of environmental safeguards, with no specific mention of springs or spring sheds. Similarly, under the National Mission for Sustaining the Himalayan Ecosystem (NMSHE), springs are addressed in passing, mainly under urbanization, with little focus on rural communities such as those in Takoli Gad who face the brunt of spring depletion.

Urban water supply planning for hill towns in Uttarakhand further illustrates the policy neglect. Typically, projects are designed to pump water from distant rivers, even when nearby springs could serve as reliable, gravity-fed sources. Protecting and rejuvenating local springs in Takoli Gad would provide cheaper, decentralized, and sustainable alternatives, yet these remain absent from planning documents.

The lack of a clear policy paradigm for spring-shed management perpetuates fragmented interventions. While the science of hydrogeology is gradually entering practice through NGOs and research institutions, it has yet to be embedded within government schemes at scale. Without this shift, areas like Takoli Gad will continue to struggle with water insecurity, despite being located in the "water tower" of India.

2. Study area

The investigation was done in Takoli Gad watershed, Tehri Garhwal district, Uttarakhand (Fig. 3). The area, covering around 131.43 km2 enclosed between 30º 14' North to 30º23' North latitudes to 78º 37' to 78º 46' East longitudes in the Survey of India topographic map 53J/11, 53J/12, 53J/15 territories in height from 550 m to 2301 m above mean sea level . The area falls within inner lesser Garhwal Himalayas and is characterized by gentle and mature topography. The watershed originates in the upper catchment of the Alaknanda River. The Alaknanda River flows in southernmost part of the region boundary. Jakhand and Dagar Gad are the tributaries of the Takoli Gad. Drainage is mainly controlled by major perennial river Alaknanda and its tributaries. The most common drainage pattern in the area is sub dendritic to sub trellis. The watershed consists of roughly 68 villages with population density of 135 person/km2. Maximum precipitation is recorded during the month of July to September, and the average annual precipitation of the area is 1395 mm. The temperature ranges from 4.6ºC-19.60ºC in winters and 32ºC – 36.5ºC in summers. Agriculture is the most common occupation of the villagers in the study area. Rice, wheat, barley, and maize are the principal crops. Location map of the study area is shown in (Fig.3).

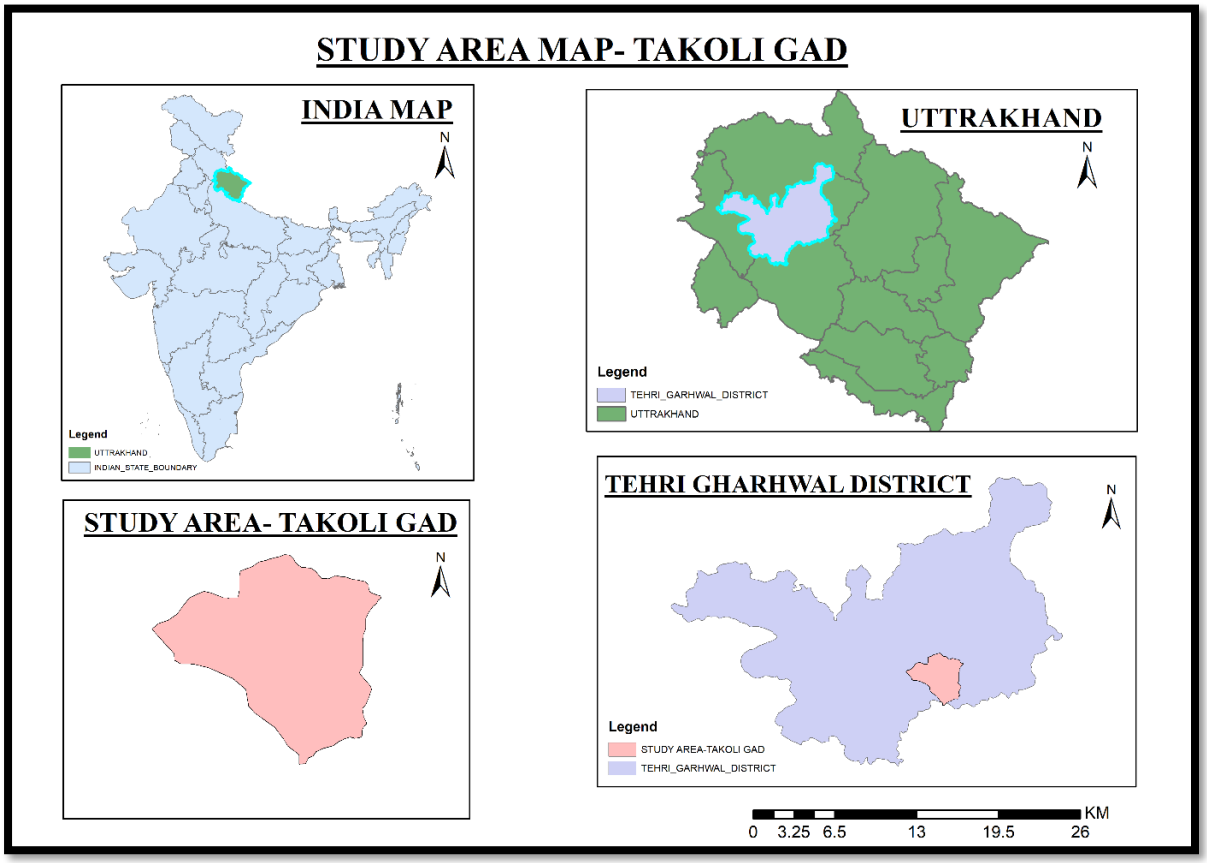


Fig. 3. Study area map of Takoli Gad watershed

2.1 Types of springs in the study area:

The total springs that have been identified and marked are 162, of which the springs have been classified as follows-

1. Contact spring: Contact springs emerge at contacts where relatively permeable rocks overlie rocks of low permeability. Spring water emerges at such contacts (Fig. 4a).

2. Fracture spring: Fracture springs occur due to existence of permeable fracture zones in low permeability rocks. Movement of groundwater is mainly through fractures that constitute the porosity and permeability of aquifers (Fig. 4b). Springs are formed where these fractures intersect the ground surface.

3. Depression spring: Depression springs are formed in unconfined aquifers when the topography intersects the water table, usually due to the surface stream incision. As the Springs are formed because of earth's gravitational pull they are named depression or gravity springs (Fig. 4c). These are usually found along the hillside and cliffs.

3. Materials & Methodology:

3.1 Data collection

Various thematic layers were required along with field data to determine the various data for knowing the exact source location and flow path of the springs, primarily all the layers were digitized and pre-processed using technology namely GIS. (Table 1) describes the data sources of thematic layers. This study considered 7 thematic layers, and the field collected data including elevation, slope, drainage density, land use and land cover, geology, soil and rainfall that were identified as an influencing parameter for locating the most approx. pathways of spring flow zones and the factors that drive it. Survey of India (SOI) topographic sheets (53J/11, 53J/12 and 53J/15, 1:50,000 scale) have been used for extraction of drainage network and delineation of the Takoli Gad watershed. The study area falls under UTM zone of 44N. The thematic layer maps were in UTM projection and WGS84 reference system (UTM-WGS84-44N). Geo-referenced with precisely orthorectified Global Digital Elevation Model of SRTM DEMs which offer two primary spatial resolutions: 3 arc-seconds (approximately 90 meters) for the global dataset and 1 arc-second (approximately 30 meters resolution) for higher-resolution products, of which 1 arc-second have been used for the present study providing greater detail for various topographic analyses. The data has been downloaded from the United

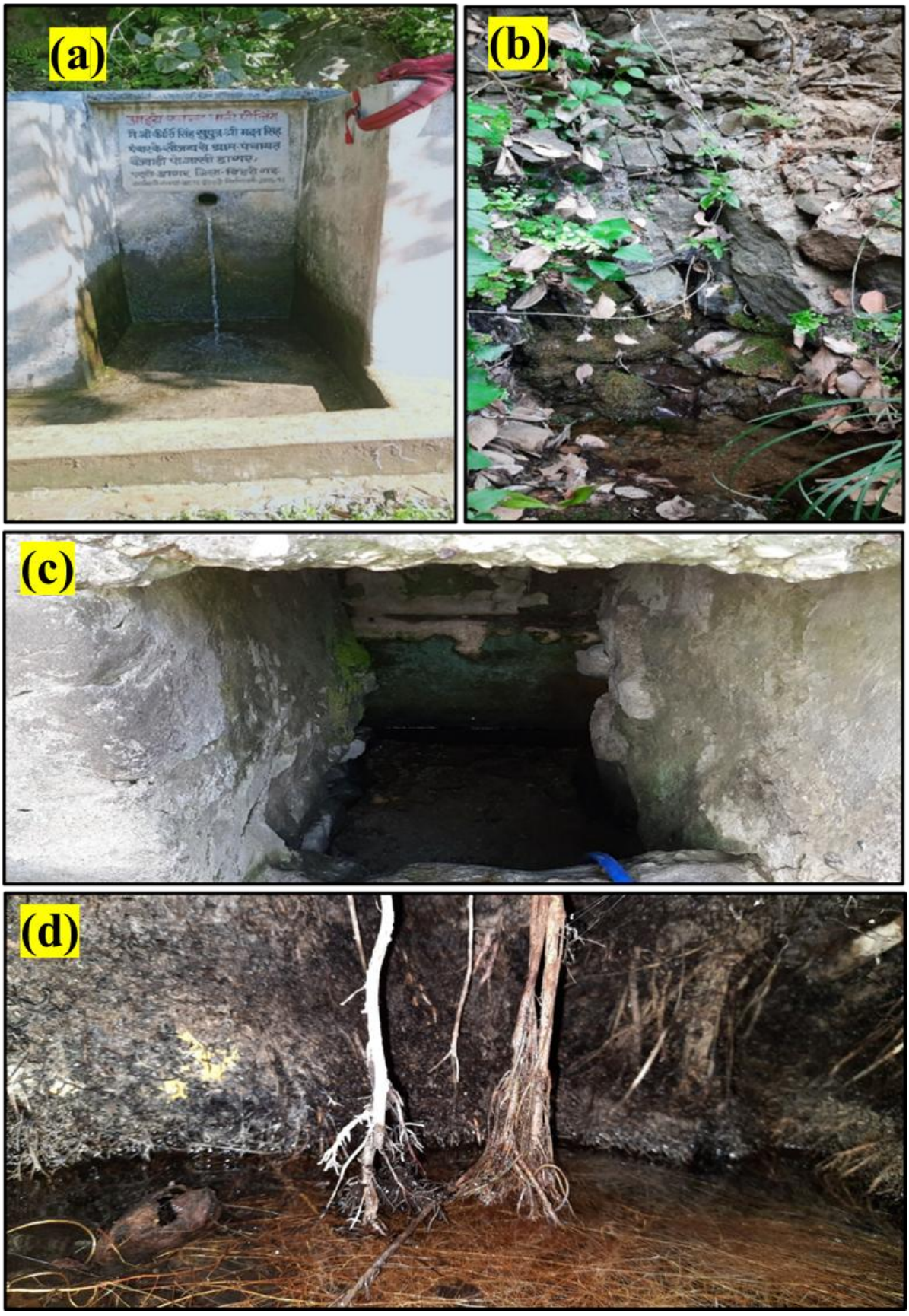


Fig. 4: Representative spring types from study area, (a). Contact Spring (b) Fracture Spring (c) Deperssion Spring (d) Spring created by intense action of soil root zone

State Geological Survey (USGS) website. Land use and land cover map is prepared using ESA Copernicus(European Space Agency) Sentinal-2 data of November 2015 and November 2024, geology map from Geological Survey of India (Geological Survey of India) also Bhukosh, and soil map was produced by NRSA-IIRS (Indian Institute of Remote sensing) have been geometrically rectified and geo-referenced as per the world's space coordinate system using image processing and GIS software (GEE and Arc GIS). These geo-rectified maps have been digitized in the GIS environment to produce thematic layer i.e. soil, geology, drainage density, rainfall and land use land cover. Using Global Digital Elevation Model of SRTM DEM 30 m slope and elevation map were prepared. Basic morphometric features such as area, perimeter, basin length, stream length, and stream numbers have been obtained for the watershed. The stream order was assigned to each stream using Strahler (1964) stream order technique in GIS (Chauhan et al. 2016). The Inverse Distance Weightage (IDW) tool in ArcGIS 10.8 was used to generate the spatial distribution of the rainfall data, which was collected from CRU (Climatic Research Unit) data. Using ArcGIS tool, the thematic layers were transformed from vector data to raster data. The field data ERT were processed using Wenner method in software RES2DINV and the spring water and rainwater samples were subjected to isotopic analysis for tritium analysis which were collected the methodology used for the present study is described in flowchart (Fig 5).

Table 1. List of data and sources

Parameters	Data source
Stream order	USGS, Shuttle Radar Topography Mission (SRTM) Digital Elevation Model
Elevation	USGS, Shuttle Radar Topography Mission (SRTM) Digital Elevation Model
Slope	USGS, Shuttle Radar Topography Mission (SRTM) Digital Elevation Model
Geology	Bhukosh, Geological Survey of India
Drainage Density	USGS, NASA Shuttle Radar Topography Mission (SRTM) Digital Elevation Model
Rainfall	CRU – Rainfall datasets
Soil	NRSA-Indian Institute of remote sensing

LULC	ESA-Copernicus Sentinal-2 TAO and Sentinal-2 data of November 2015 and November 2024.
ERT	Field Data, RES2DINV
Geo-chemistry	Field data sampling (rain/spring water), Lab Analysis
Stable and Unstable isotope Analysis	Lab Analysis

3.2 Methodology

The methodology adopted in this study integrates remote sensing data, conventional data sources, and field-based investigations to identify the source and causes of dying springs. The workflow (Fig.5) involves data collection, processing, preparation of thematic maps, and validation of results.

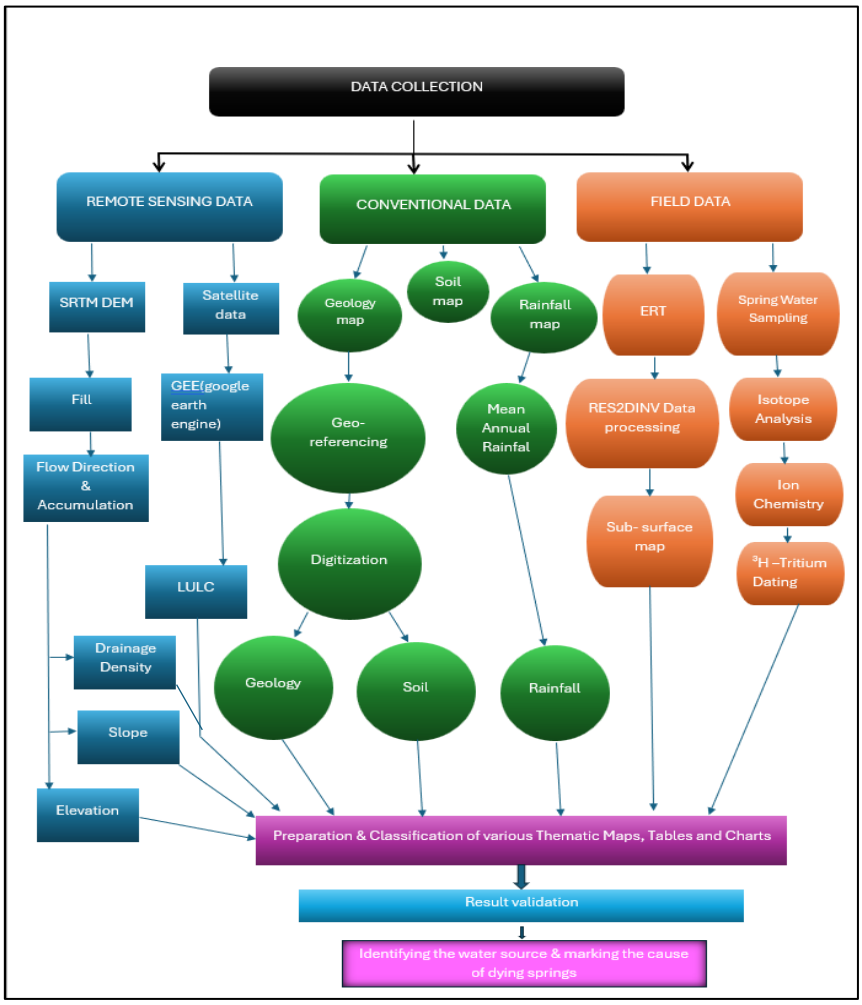


Fig. 5: Methodology Flow Chart of our study

3.2.1. Remote Sensing Data Analysis

(a) Digital Elevation Model (DEM)

The Shuttle Radar Topography Mission (SRTM) DEM was used to extract terrain parameters essential for hydrological analysis. The DEM was pre-processed using a filling algorithm to remove sinks and ensure hydrologically correct surfaces. This facilitated the derivation of flow direction and flow accumulation maps, which are crucial for delineating drainage networks.

(b) Drainage and Slope Analysis

From the processed DEM, drainage density, slope, and elevation maps were generated. These morphometric parameters provide insights into the terrain's influence on groundwater recharge and discharge processes.

(c) Land Use/Land Cover (LULC)

Multi-temporal satellite data were analysed through Google Earth Engine (GEE) for land use/land cover classification. The LULC maps were used to evaluate anthropogenic pressures and natural vegetation cover, both of which significantly influence groundwater recharge and spring health.

3.2.2. Conventional Data Sources

(a) Geology and Soil Maps

Geological and soil maps from the Geological Survey of India (GSI) and National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) were digitized and geo-referenced in GIS. Geological settings help identify lithological control over groundwater movement, while soil types influence infiltration and runoff.

(b) Rainfall Data

Mean annual rainfall data were collected from the Indian Meteorological Department (IMD) and other secondary sources. The spatial distribution of rainfall was mapped, which is a critical input for understanding recharge patterns.

3.2.3. Field Data Collection

(a) Electrical Resistivity Tomography (ERT)

ERT surveys were conducted to map subsurface resistivity variations and delineate aquifer zones. Data processing was carried out using RES2DINV software, and subsurface profiles were generated which is show in (Fig. 6). This method helps in identifying fracture zones and groundwater-bearing formations as well as the depth at which it is present.

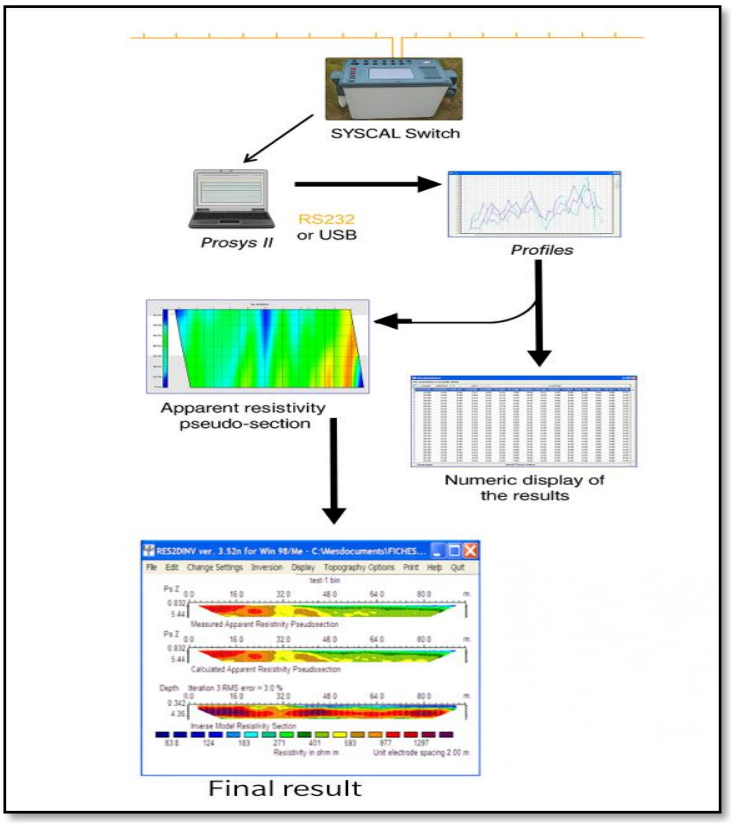


Fig. 6: ERT Flow Chart

(b) Spring/Rainwater Sampling

Representative spring and rainwater samples were collected for hydrochemical and isotopic analysis. Parameters such as ion chemistry and isotopes were analyzed in laboratory conditions.

- Total 155 Springs are identified in study area.
- Total 77 rain gauges were installed in 67 villages of the study area.
- Isotope Analysis ($\delta^{18}O$, δD) was conducted to understand recharge sources and groundwater-surface water interactions.
- Tritium Dating (^{3}H) was used to estimate groundwater residence time and recharge dynamics.

- Major cation anion for tack the water quality and impact geologic and geogenic impact of springs

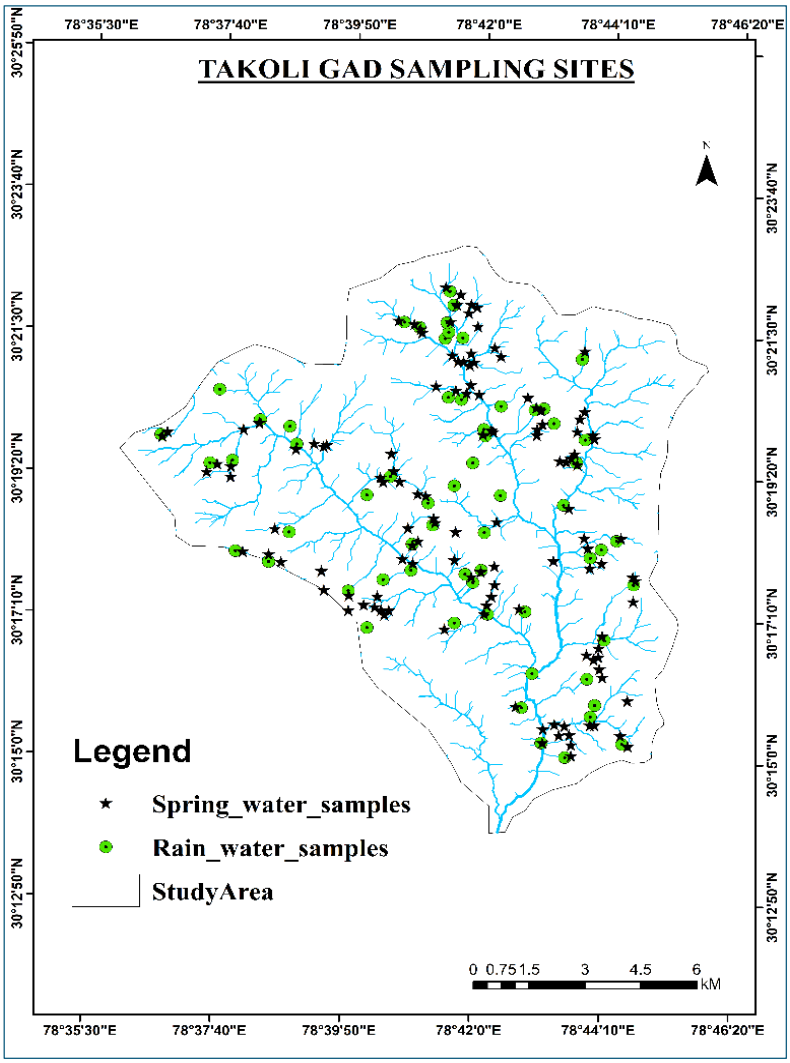


Fig. 7: Sampling sites for spring/Rainwater

Representative spring and rainwater samples were systematically collected across the Takoli Gad watershed for detailed hydro-chemical and isotopic analysis (Fig. 7). The sampling locations were identified through extensive field surveys (Fig. 8), where each spring outlet was mapped using a handheld GPS device. These mapped points were subsequently incorporated into the study area map (Fig. 7) to represent the distribution of spring and rainwater sampling sites. The involvement of local villagers played a crucial role in identifying perennial and seasonal springs, thereby ensuring representative coverage of the catchment.



Fig. 8: Spring investigation and marking before the sampling.

Rainwater sampling was carried out with the installation of 77 rain gauges across 67 villages within the watershed (Fig. 9 & 10). These gauges were strategically placed to account for variations in altitude, aspect, and micro-climatic conditions, enabling a robust dataset of precipitation inputs. The collected rainwater samples were preserved and analysed for stable isotopes ($\delta^{18}O$, δD), which provided insights into recharge sources, evaporation effects, and groundwater–surface water interactions. Similarly, spring water samples were subjected to both hydro-chemical and isotopic analysis to evaluate the influence of lithology, recharge altitude, and seasonal variability on groundwater chemistry.



Fig. 9: Rain gauge installation for rainwater sampling.



Fig. 10: Rainwater sampling from installed rain gauge with measurement of insitu parameters.

In addition, tritium (^{3}H) analyses were also performed on twenty-nine unfiltered samples collected in one-litre pre-cleaned HDPE sample bottles and securely sealed to prevent exposure to air. The analysis was carried out at Nuclear Hydrology Laboratory at the National Institute of Hydrology (NIH), Roorkee. Tritium measurements which were conducted on selected spring water samples to estimate groundwater residence time and to infer recharge dynamics within the aquifer system. These isotopic investigations, when combined with hydro-chemical parameters such as pH, EC, and TDS, provided a comprehensive understanding of the processes governing spring water quality and its linkages with rainfall recharge. Thus, the integration of field-based mapping, community support, systematic sampling, and advanced laboratory analysis ensured the reliability and representativeness of the geochemical dataset. A flow chart of the sampling and the procedure which was followed for the analysis of the sample data is described (Fig. 11).

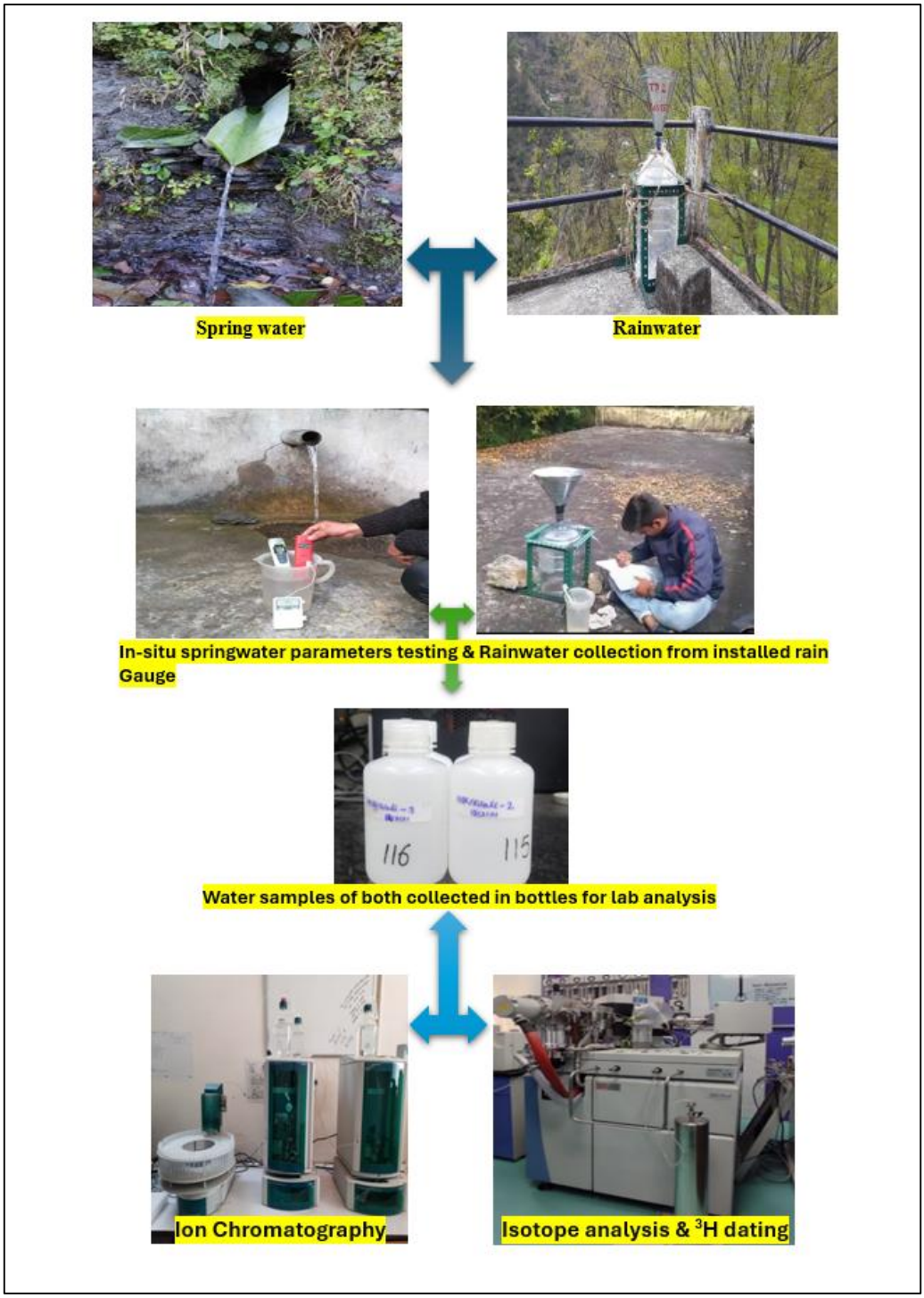


Fig. 11: Methodology of Spring/Rainwater sampling and its analysis

3.2.4. Geochemistry

- **<u>Sampling strategy (spring water, rainwater).</u>**

Rainwater was collected using standard rain collectors placed at strategic locations to avoid contamination, while Springwater samples were collected directly from natural discharge

points. All samples were stored in pre-cleaned polyethylene bottles, sealed immediately to prevent atmospheric interaction, and transported to the laboratory under controlled conditions.

- **Parameters analysed (pH, EC, TDS, major ions, trace elements).**

Each water sample was analysed for the following parameters:

In-situ measurements: pH, electrical conductivity (EC), total dissolved solids (TDS), and temperature using portable field meters.

Major cations: Na^+, K^+, Ca^{2+}, Mg^{2+}. Major anions: HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, F^-. Isotopic composition: $\delta^{18}O$, δD, and derived parameter d excess.

- **Analytical methods (ion chromatography, IRMS).**

The analyses were carried out in both field and laboratory settings. Field parameters (pH, EC, TDS, temperature) were measured using calibrated multiparameter probes. In the laboratory: Ion Chromatography (IC) was employed for the determination of major

anions (Cl^-, SO_4^{2-}, NO_3^-, F^-). Flame Atomic Absorption Spectroscopy (FAAS)/ICP–OES was applied for major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}).

Stable isotopes ($\delta^{18}O$ and δD) were measured using a Stable Isotope Ratio Mass Spectrometer (IRMS). All analyses followed standard protocols with repeated measurements and quality control checks (blanks, standards, duplicates) ensuring accuracy.

- **Purpose: To identify water type, quality, and geochemical processes.**

The geochemical analyses were designed to:

a) Identify the hydro-chemical facies and classify water types (using Piper/Durov diagrams).

b) Assess water quality for drinking and agricultural purposes through TDS, EC, and ionic composition.

c) Evaluate geochemical processes such as water–rock interaction, ion exchange, dissolution/precipitation, and anthropogenic influences.

d) Understand recharge mechanisms and rainfall–Springwater linkages using stable isotopes ($\delta^{18}O$, δD, d-excess).

3.2.5. Data Integration and Thematic Mapping

The datasets from remote sensing, conventional sources, and field surveys were integrated in a GIS platform and other software's. The process included:

- Digitization of geological, soil, and rainfall maps.
- Preparation of drainage, slope, elevation, and LULC maps.
- Generation of subsurface profiles from ERT.
- Preparation of ions charts (piper, Durov) from geochemistry data.

These inputs were classified into thematic layers and integrated to prepare comprehensive maps, tables, and charts that represent hydrogeological settings and spring characteristics.

3.2.6. Result Validation and Interpretation

Validation of the generated thematic outputs was carried out through field verification and comparison with secondary data. The final step involved identifying the source water and causes of dying springs, which was interpreted through an integrated analysis of hydro-geomorphological, geochemical, geophysical and isotopic parameters.

4.0. Result & Discussion:

4.1. Morphometry

Based on the drainage map, survey of India topographic map, remotely sensed data - morphometric analysis for the present study are estimated (Table 2 & 3). According to Strahler stream ordering method, the Takoli Gad has fifth order stream order (Fig 12.). The total length of the stream segment is maximum in first order streams and decreases as the stream increases. The value of the bifurcation ratio (Rb) is 5.1, which means the characteristics of the watershed suffered structural disturbances. The drainage density of the watershed is 1.75 km/km2 which means the area is coarse texture which occurs in regions with high permeable sub soil under dense vegetation cover. The elongation ratio obtained is 0.86 which indicates that the catchment is oval. The circulatory ratio value of the study area is 0.75 which indicated that the basin is less elongated in shape. The lowest relief value is 507m and highest relief value is 2497m. The total basin relief of the catchment is 1990m which indicates that the basin is having high relief and steep slope topography which causes more runoff in the basin. The study area is having 3.48 as the Ruggedness number. This value indicates that the study area is having moderately prone to erosion. All the results of the morphometric analysis are in (Table 4).

Table 2: Morphometric analysis parameters and formulae

Morphometric Aspects	**Parameters**	**Formulae**	**References**
Linear aspect	Stream order (u)	Hierarchical rank	Strahler (1964)
	Stream number (Nu)	Number of stream of particular order 'u'	Strahler (1964)
	Bifurcation ratio (Rb)	Rb = Nu/Nu+1	Schumm (1956)
	Stream Length (Lu)	Total length of streams (km) of particular order (u)	Horton (1945)
Areal aspect	Drainage density (Dd)	Dd = L/A; where L = length of the streams (km), A = Basin area (km^2)	Horton (1945)
Relief aspect	Ruggedness index (Ri)	Ri = Dd*H/1000; where Dd = drainage density of the basin, H = relative relief	Schumm (1956)

4.2 Elevation

Elevation is one of the most critical physiographic factors controlling water resource potential in mountainous catchments. It directly governs the direction of surface water flow, groundwater recharge, and the spatial occurrence of springs. In general, water flows from higher elevations toward lower elevations, accumulating in valleys and low-lying areas. Previous studies have demonstrated that groundwater potential zones tend to increase in lower topographic zones, where discharge is concentrated, and permeability is often enhanced due to depositional environments and fractured rock systems.

The Takoli Gad watershed exhibits an elevation range from approximately 507 m to 2,497 m above mean sea level (MSL). For detailed analysis, the watershed was classified into six elevation subclasses: 507–920 m, 920–1,155 m, 1,155–1,384 m, 1,384–1,629 m, 1,629–1,924 m, and 1,924–2,497 m (Fig. 13). The spatial distribution clearly highlights that the lower and middle elevations (920–1,384 m) are more extensive and form the core valley regions where surface runoff converges and groundwater discharge in the form of springs is more common. In contrast, the higher elevations (>1,629 m) are relatively restricted in area and represent the recharge zones where rainfall infiltration initiates the groundwater flow system.

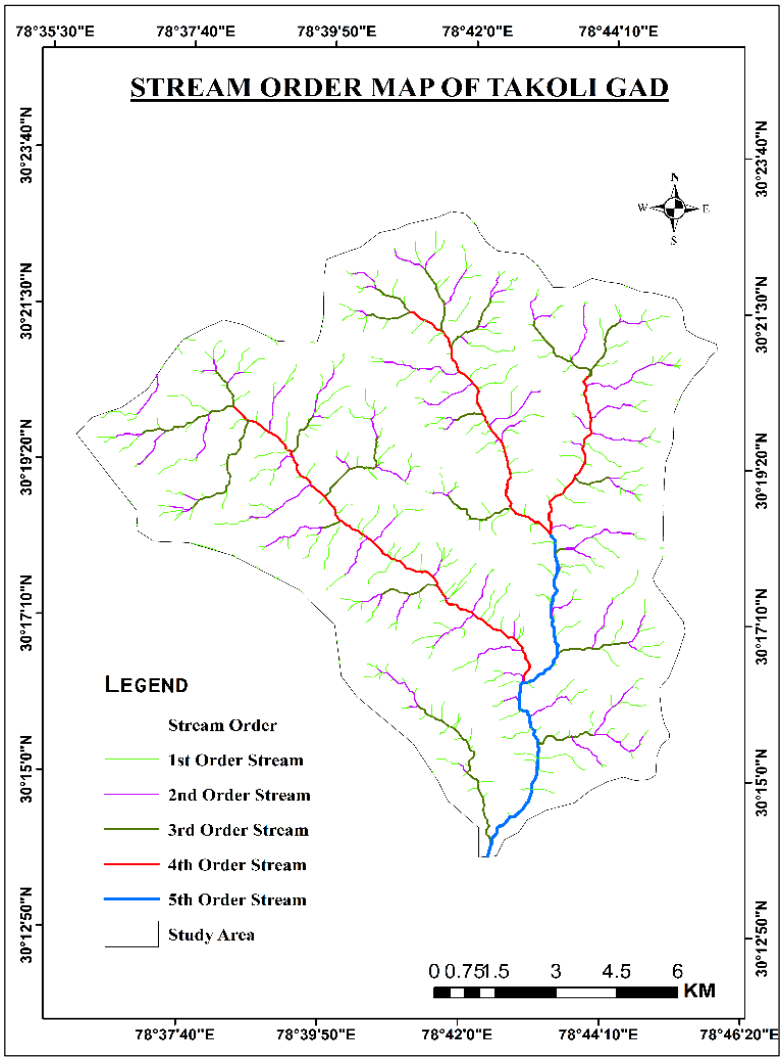


Fig. 12: Stream order Map of Takoli Gad

Table 3: Computed linear morphometric aspects of Takoli Gad watershed

Takoli Gad Watershed	**Stream Order(U)**					**Stream Length(Lu)(in Km)**				
	I	II	III	IV	V	I	II	III	IV	V
	387	119	23	4	1	123.75	69.56	26.25	23.76	7.3

Takoli Gad Watershed	**Bifurcation Ratio (Rb)**				**Mean Bifurcation Ration (Rbm)**
	I/II	II/III	III/IV	IV/V	5.1
	3.25	5.66	7.66	4	

Parameters	Takoli Gad Watershed
Basin perimeter(p) (km)	53.94
Basin Area(A) (km^2)	142.7
Basin Length (Lb) (km)	15.2
Drainage Density (Dd)	1.75
Lowest relief(R) (m)	507
Highest relief(r) (m)	2497
Basin relief(H) (m)	1990
Ruggedness index (Ri)	3.48

Table 4: Computed Areal and relief aspect of the Takoli Gad watershed

Elevation exerts a strong influence on both spring water and rainwater characteristics within the watershed. Springs located at lower altitudes generally exhibit higher discharge due to accumulation of subsurface flow from upper catchments. These zones often coincide with agricultural settlements, making them critical for water supply. In contrast, springs at higher elevations are fewer, smaller in discharge, and more sensitive to seasonal variability. Similarly, rainfall distribution is influenced by orographic effects, with higher elevations receiving comparatively greater precipitation. This enhances recharge potential at upper slopes, which subsequently feeds the springs at mid to lower elevations. The combination of high rainfall input at upper elevations and favourable discharge conditions at lower elevations creates a vertically integrated hydrological system linking rainwater and spring water.

Thus, the elevation factor not only controls surface water flow but also governs the recharge-discharge dynamics of the aquifer system. Mapping the watershed into elevation subclasses provides an important basis for understanding spatial variations in spring occurrence, discharge potential, and overall water availability across the Takoli Gad watershed.

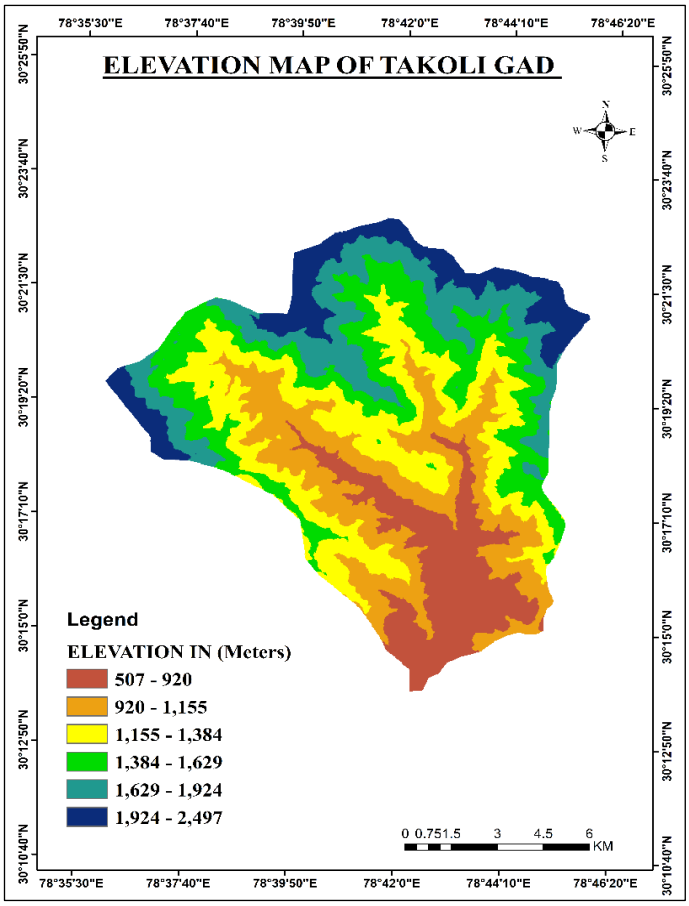


Fig. 13: Elevation Map of Takoli Gad

4.3. Slope

Slope is one of the most critical morphometric parameters because it directly controls the hydrological processes of surface runoff, infiltration, and groundwater recharge. In mountainous watersheds like Takoli Gad, slope strongly governs how rainfall is partitioned between infiltration and runoff, which in turn influences spring discharge and recharge dynamics.

Steeper slopes are generally considered poor recharge zones. This is because water drains rapidly downslope as surface runoff, leaving little time for infiltration into the subsurface. These regions are more prone to soil erosion, mass wasting, and gullying, which further reduce infiltration capacity and subsurface storage. Springs located in very steep or strong slope zones are often seasonal, displaying high variability in discharge during rainfall events but drying up quickly in lean seasons (Dec-May).

Conversely, gentle to moderate slopes allow more rainwater infiltration and percolation through soil and fractured rock zones. Such areas act as important recharge zones, replenishing

groundwater and sustaining perennial springs, especially in the Indian Himalayan Region. Rainwater in gentle slope regions has a longer residence time, favouring percolation into aquifers, while surface runoff is reduced, thereby enhancing recharge potential.

The slope map of the Takoli Gad watershed (Fig.14) shows a highly variable topography, ranging from **0.0° to 77.9°**, and has been classified into five slope categories in order of dominance: **strong slope > very steep slope > steep slope > moderate slope > gentle slope**.

- **Strong and very steep slope classes** dominate large portions of the watershed, leading to rapid runoff and minimal infiltration.
- **Steep slopes** exhibit intermediate behaviour, where localized infiltration may occur in fractured zones, but runoff still remains high.
- **Moderate and gentle slope zones** are limited in spatial extent but are the most effective recharge zones for springs, as they favour infiltration and subsurface storage.

In terms of spring hydrology, slope influences both the location and discharge behaviour of springs. Steep slopes often host springs that are perched or fracture-controlled, responding quickly to rainfall but with limited storage capacity. Gentle slopes, on the other hand, sustain more reliable spring flow as infiltration is higher and subsurface storage is better developed. The **slope map** serves as an essential tool in watershed and spring-shed management. It helps identify recharge zones (gentle to moderate slopes) that can be prioritized for artificial recharge structures such as percolation tanks, contour trenches, and recharge pits. It also highlights runoff-prone and erosion-prone zones (steep to very steep slopes) where soil conservation measures like check dams, vegetative barriers, and afforestation should be implemented to reduce runoff velocity and enhance infiltration.

Thus, slope not only governs the hydrological response of a watershed but also provides critical guidance for planning soil and water conservation measures, especially in hard rock terrains and undulating Himalayan topography. Integrating slope analysis with drainage density and land use/land cover assessments provides a holistic understanding of recharge-discharge dynamics in spring-fed watersheds.

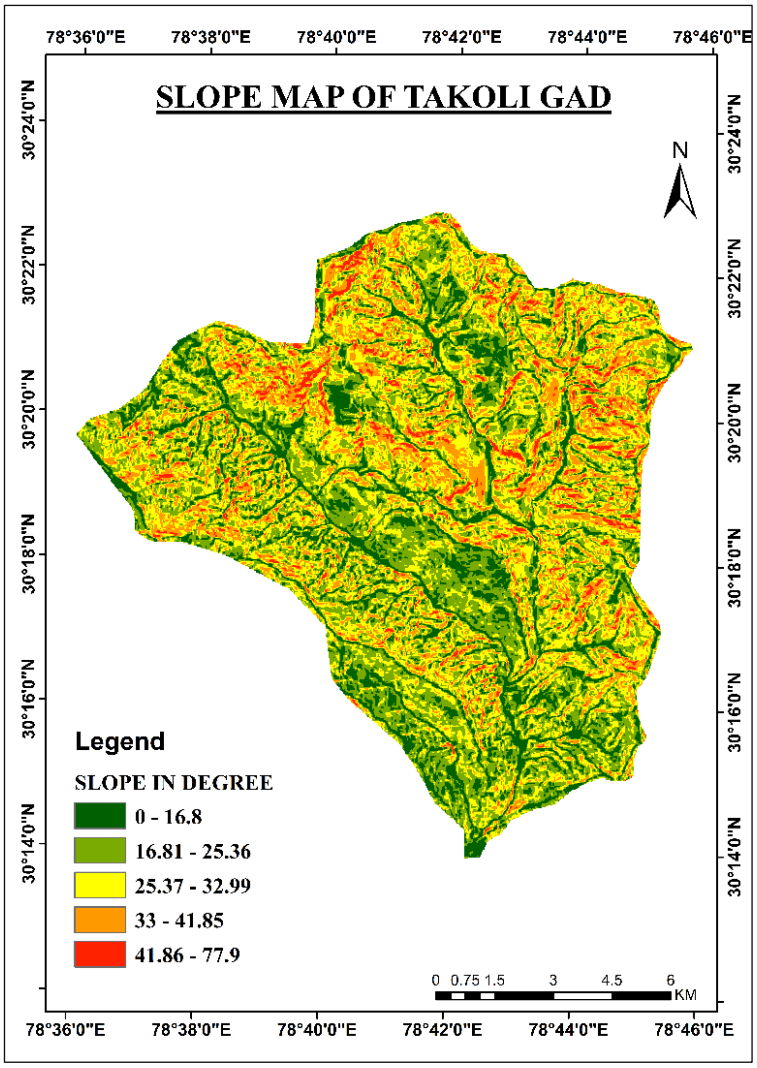


Fig. 14: Slope Map of Takoli Gad

4.4. Geology

Among all the aspects, geology is considered as the one of the leading factors by controlling the water percolation which has an impact on resource potential zones. It has a direct effect on the porosity and permeability of aquifer rocks. The geology map (Fig. 16) was developed from the Bhukhosh, Geological Survey of India (GSI) using the topographic sheets (53J/11, 53J/12 and 53J/15, 1:50,000 scale). Takoli Gad catchment is a thrusted block and bifurcated into almost two equal halves by North Almora Thrust (NAT) which make it tectonically active. Phyllite, Basic meta-volcanics, grey Sand, silt and clay, Shale, slate Limestone and shale, Quartzite are the different geological formation discovered in the Takoli Gad watershed , which controls the infiltration of water. Individual weights for each geological formation have been determined according to their groundwater prospects. The area with sand and sandy clay is a percolation zone due to its high porosity and high permeability. Phyllite rock is permeable and undergone high weathering due to its highly foliated structures (Fig. 15). Basic meta-volcanics

are good aquifer as it is highly weathered and fractured. Quartzite is a hard rock, which generally does not have primary porosity. Secondary porosity in the form of fractures and weathering only allow groundwater occurrence. These rocks have low porosity.

Lithologically area comprises both metamorphic and sedimentary rocks with primary and secondary porosity.



Fig. 15: Fracture & Chemical weathering

4.5. Drainage density

The drainage density (km^{-1}) is defined as the total stream length divided by the total basin area (Fig. 17). In the Takoli Gad watershed, the drainage pattern is predominantly dendritic to sub-dendritic type, which is characteristic of regions underlain by relatively homogeneous lithology. Drainage density is a critical morphometric parameter as it reflects the interplay between rainfall, infiltration, surface runoff, relief, and vegetation cover.

Low drainage density typically indicates permeable subsurface materials, dense vegetation, and gentle slopes. Such conditions promote infiltration of rainwater into the subsurface, thereby enhancing groundwater recharge and sustaining spring discharge, especially during lean flow periods (Dec-May). In the Himalayan context, many springs are perched on fracture zones and

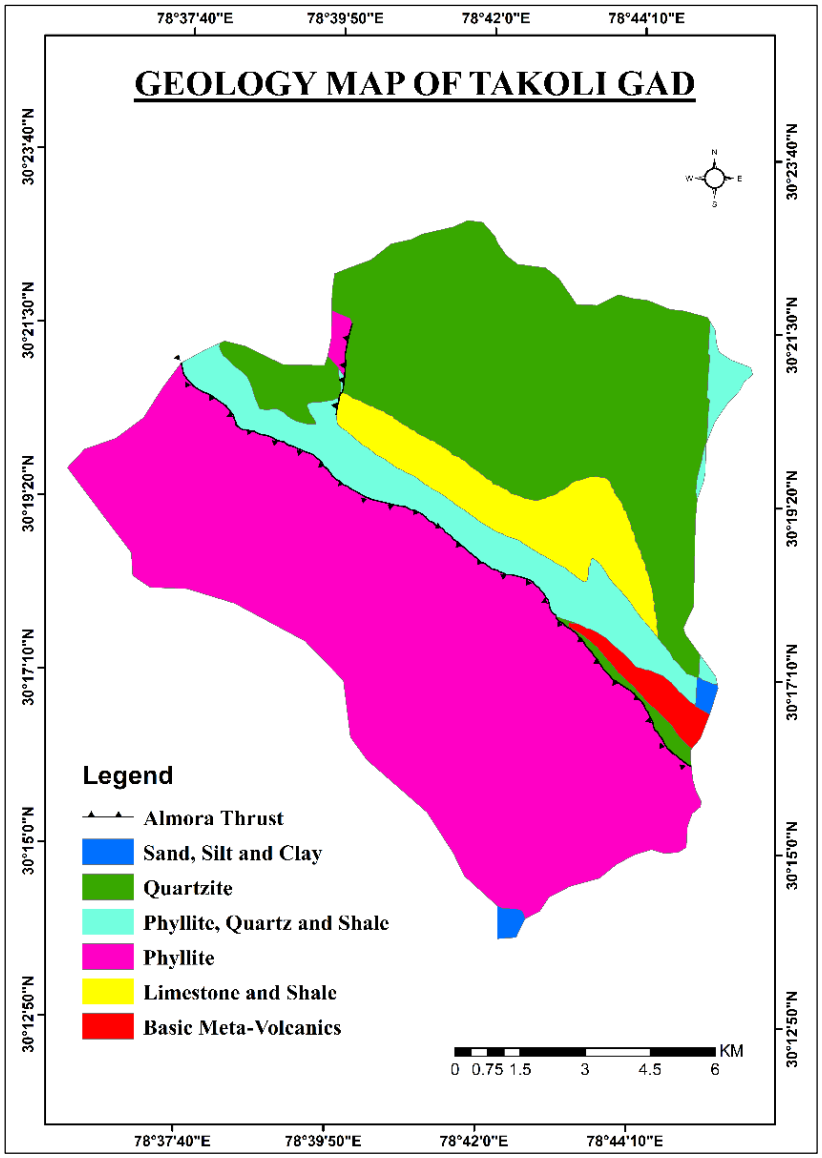


Fig. 16: Geology Map of Takoli Gad

weathered horizons; hence, low drainage density areas act as recharge zones, allowing infiltrated rainfall to percolate through the soil and fractured rock system before emerging as spring flow downstream.

In contrast, high drainage density suggests impermeable subsurface material, thin soils, sparse vegetation, and steep relief. These areas generate more surface runoff during rainfall events, limiting infiltration and thereby reducing groundwater recharge. Springs in such terrains are often seasonal, with sharp fluctuations in discharge due to limited subsurface storage. Additionally, high drainage density accelerates soil erosion, further lowering the recharge potential and altering the natural hydrological regime.

So, the drainage density map is highly useful in hydrogeological and spring-shed management studies. It helps to identify recharge-prone zones (low drainage density) and runoff-prone zones (high drainage density). Such mapping is particularly important in the Indian Himalayan Region, where springs constitute the primary source of drinking water and irrigation. Recharge zones identified through drainage density analysis can be targeted for artificial recharge interventions such as check dams, contour trenches, and infiltration tanks. Conversely, high drainage density areas can be prioritized for soil conservation and slope stabilization measures to minimize erosion and improve infiltration.

Thus, drainage density serves as a diagnostic indicator of recharge potential and water availability. Its integration with rainfall data, spring discharge observations, and land use/land cover analysis offers a holistic framework for understanding spring hydrology and for designing sustainable watershed management strategies in fragile Himalayan ecosystems.

4.6. Rainfall

Rainfall is the key component of hydrogeological cycle and main source of recharge. Rainfall intensity and duration have a significant impact on infiltration and runoff volume. Rainfall distribution along with the slope gradient has a direct impact on the runoff water infiltration, increasing the possibility of water resource potential zones. Because rainfall has a positive influence on water recharge, with the increase in the duration of the rainfall the infiltration of the rainwater increases depending upon the various factors like the slope, vegetation, soil/land surface in contact. In past few decades the rainfall amount and the pattern of rainfall of the area has been drastically affected by the climatic changes and irregular rainfall pattern. Over the period of last 5 years, the study area is receiving less rainfall than it is expected/normal rainfall and through the map (Fig. 18) it can be concluded that the north-west region of Takoli Gad catchment is receiving highest amount of rainfall than the other parts of the study area, while in the south part of the area shown in map (Fig. 18). This finding is also supported by LULC study of area. This could impact the spring water as well as its discharge rate of this region. Proper rainwater harvesting, small trenches can be a primary solution to this. So that the springs of this region does not get more effected by the erratic and less rainfall.

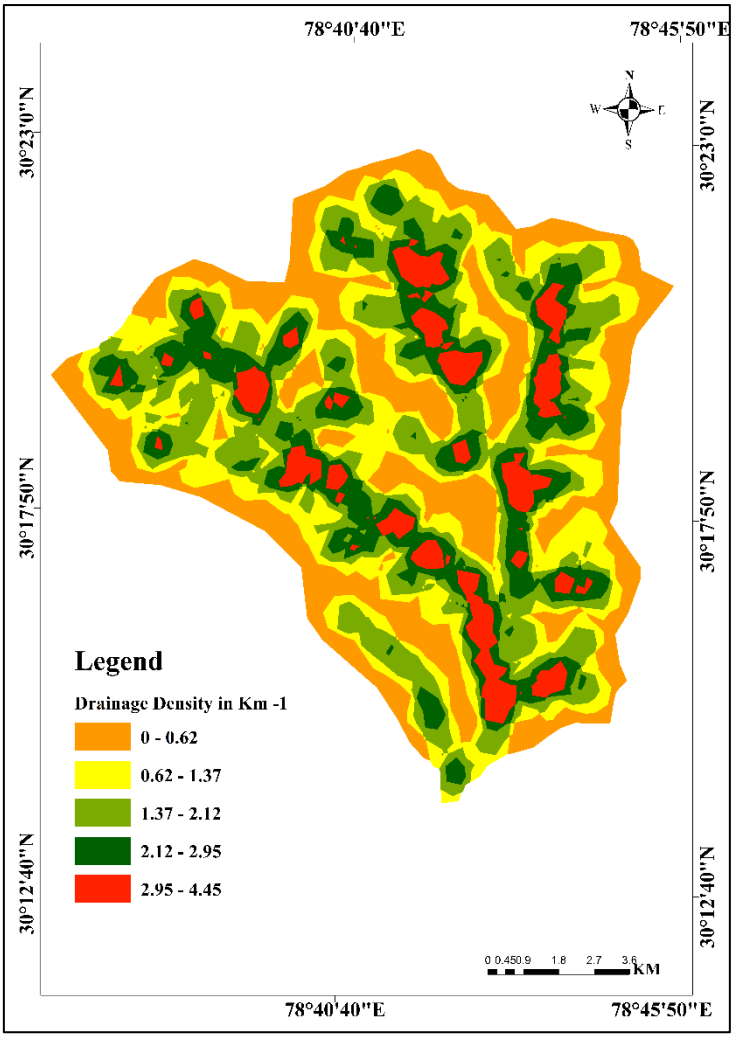


Fig. 17: Drainage Density Map of Takoli Gad

4.7. Soil

The Takoli Gad watershed contains two soil categories (Fig. 20) that is Dystric Eutrudepts and Typic Udorthents (National Bureau of Soil Survey and Land Use Planning (ICAR). Dystric Eutrudepts are relatively shallow, well-drained, thermic, fine loamy, slightly rocky. Typic Udorthents are moderately shallow, excessively drained, moderate erosion, slightly stony, loamy, and sandy skeletal soil. Mostly the area is covered by Typic Udorthents soil. These traits and distributions (Eutrudepts on mid-slopes and benches; Udorthents on upper convexities) have been documented for Tehri Garhwal, including blocks adjoining the watershed. ("Compendium of Soil Resources for Sustainable Land Management of Uttarakhand")

During monsoon events, much of the incident rainfall on these hillslopes' seeps through these permeable horizons and colluvial mantles to recharge shallow hillslope aquifers and fracture

networks that feed perennial and seasonal springs in the catchment. A vertical cross-section of soil was captured during the field visit (Fig. 19). Studies on Himalayan springs note that

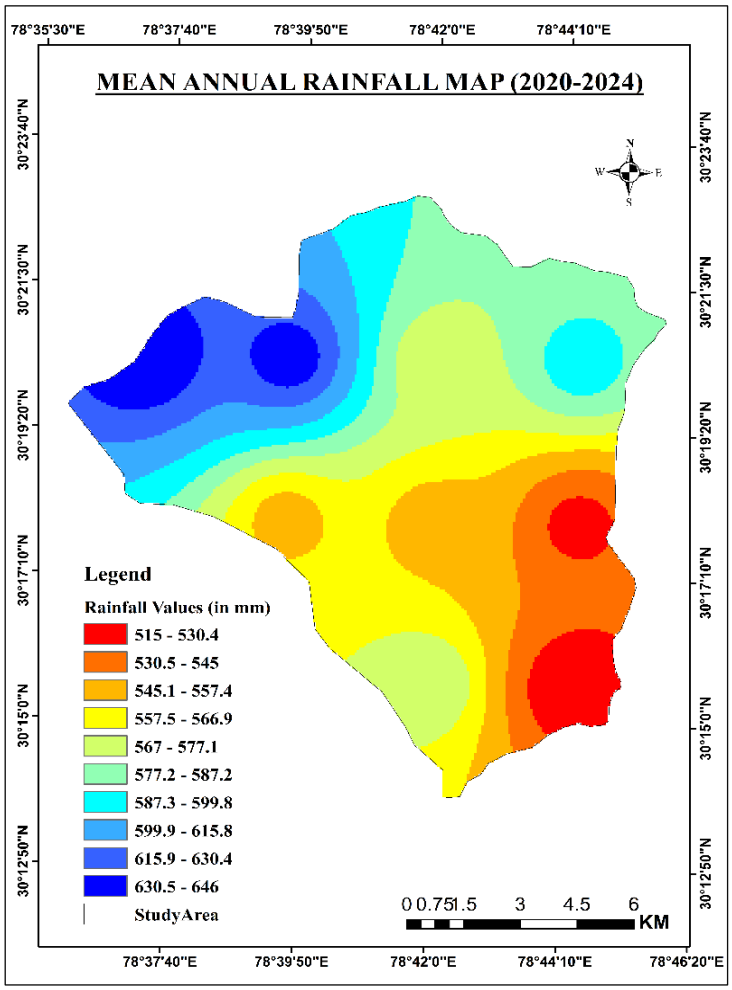


Fig. 18: Mean Annual Rainfall Map of Takoli Gad (2020-2024)

colluvial and shallow bedrock pathways respond quickly to rainfall, with marked post-storm increases in spring discharge—evidence of fast infiltration and near-surface recharge typical of these soil–slope settings. (Geo-Hydrological Studies for Augmentation of Spring Discharge in the Western Himalaya)

However, where Udorthents dominate on steep, sparsely vegetated slopes, infiltration benefits can be offset by rapid overland flow and soil loss if surface cover is poor. Conservation measures such as contour trenches, staggered pits, vegetative barriers (e.g., Napier/hedgerows), mulching, and maintaining forest/leaf-litter cover on mid- and upper-slopes help retain fine fractions, increase residence time of stormwater, and enhance percolation to spring-feeding storages. Local district and watershed assessments in Tehri Garhwal consistently emphasize erosion control and rainwater harvesting on these soils to sustain baseflow and spring yields.

In short, the fine-loamy, well-drained Dystric Eutrudepts and the skeletal excessively drained Udorthents that “mostly cover” the area collectively acts as efficient infiltration media over fractured Himalayan bedrock—an arrangement that is naturally conducive to spring rejuvenation, provided slope erosion is checked and vegetative cover is maintained.



Fig. 19: Vertical Cross-section View of Soil Profile

4.8. LULC (land use and land cover)

Land Use and Land Cover (LULC) analysis is a crucial tool for understanding the dynamic interaction between the natural environment and anthropogenic activities. It provides insights into how urbanization, deforestation, agricultural expansion, and degradation of natural ecosystems are reshaping the landscape. These changes directly affect hydrological processes, biodiversity, soil stability, and water resources. LULC studies are therefore essential for environmental management, watershed planning, agricultural sustainability, and conservation of natural resources.

In the Takoli Gad watershed, the LULC comparison between 2015 and 2024 reveals substantial landscape transformations (Fig.21 & 22) and (Table 5). The accuracy of the lulc maps of 2015 & 2024 are 92% and 88% (approx.) respectively and the post-monsoon data were taken for LULC map preparation.

Computing Change % for each Class of LULC:-

Absolute change = 2024 Area of class – 2015 Area of class

Fraction = Absolute change / 2015 Area of that class

Change Percentage = Fraction * 100

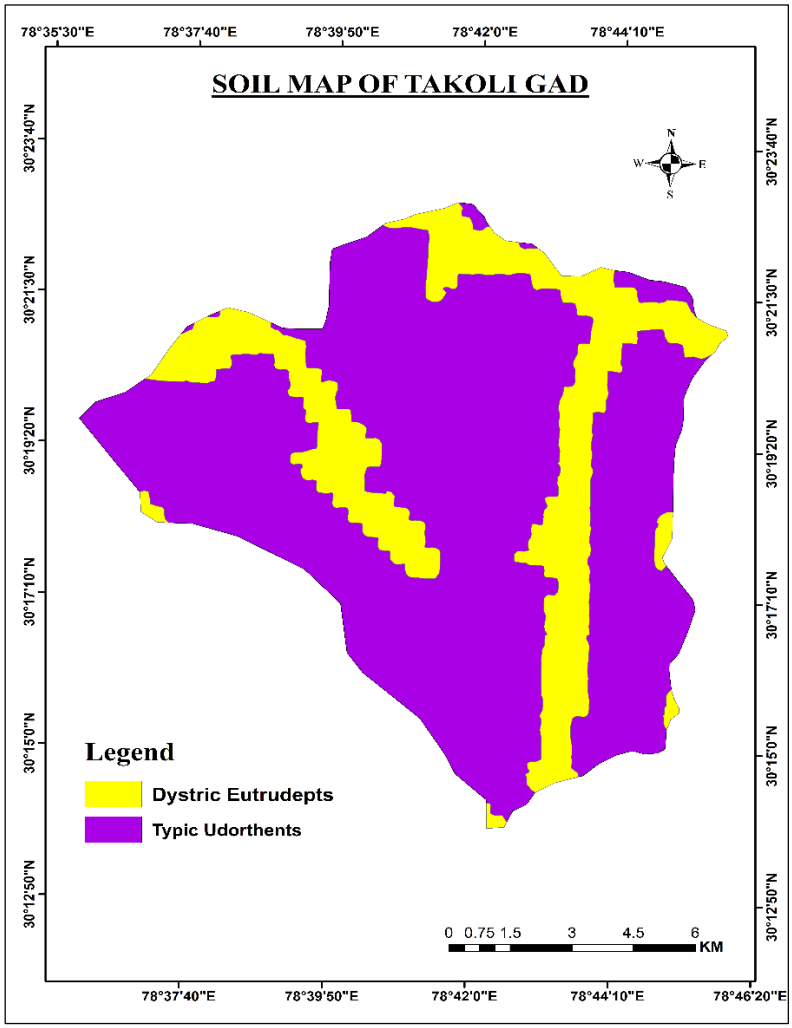


Fig. 20: Soil Map of Takoli Gad

Five major classes were identified: dense forest, moderately dense forest, agricultural land, built-up/settlement, and barren land. The LULC classification accuracies of 93.6% (2015) and 88.4% (2024) validate the reliability of the dataset (Table 6 and Table 7). Over the past decade, dense forest cover decreased drastically from 66.33 km² in 2015 to 26.52 km² in 2024, a reduction of ~60%. Conversely, moderately dense forest increased by ~121%, suggesting a transition of degraded dense forest areas into moderately dense cover. While this shift reflects, partial success of afforestation and conservation programs—such as ***Our Tree Our Wealth Scheme***, ***Ek Ped Maa Ke Naam*** campaign, and tree plantation drives during the ***Harela festival***—the sharp loss of dense forest still raises ecological concerns. Agricultural land decreased by ~9%, likely due to land abandonment or conversion into settlements and degraded

areas. Built-up/settlement areas slightly declined (~11%), which may reflect either migration trends or reclassification errors. More concerning is the significant increase in barren land (+49.9%), which indicates soil degradation, erosion, and expansion of unproductive areas.

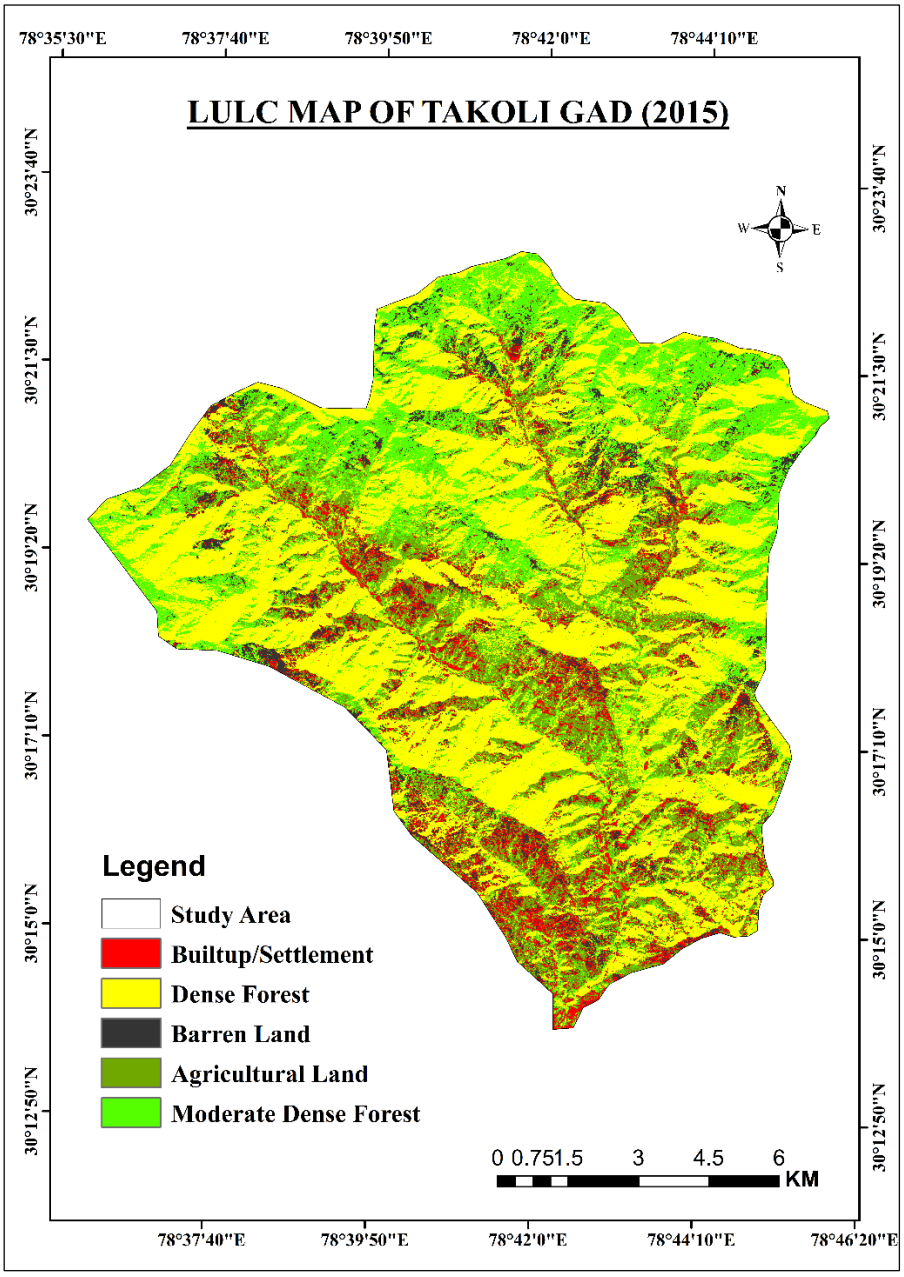


Fig. 21: LULC Map of Takoli Gad (2015)

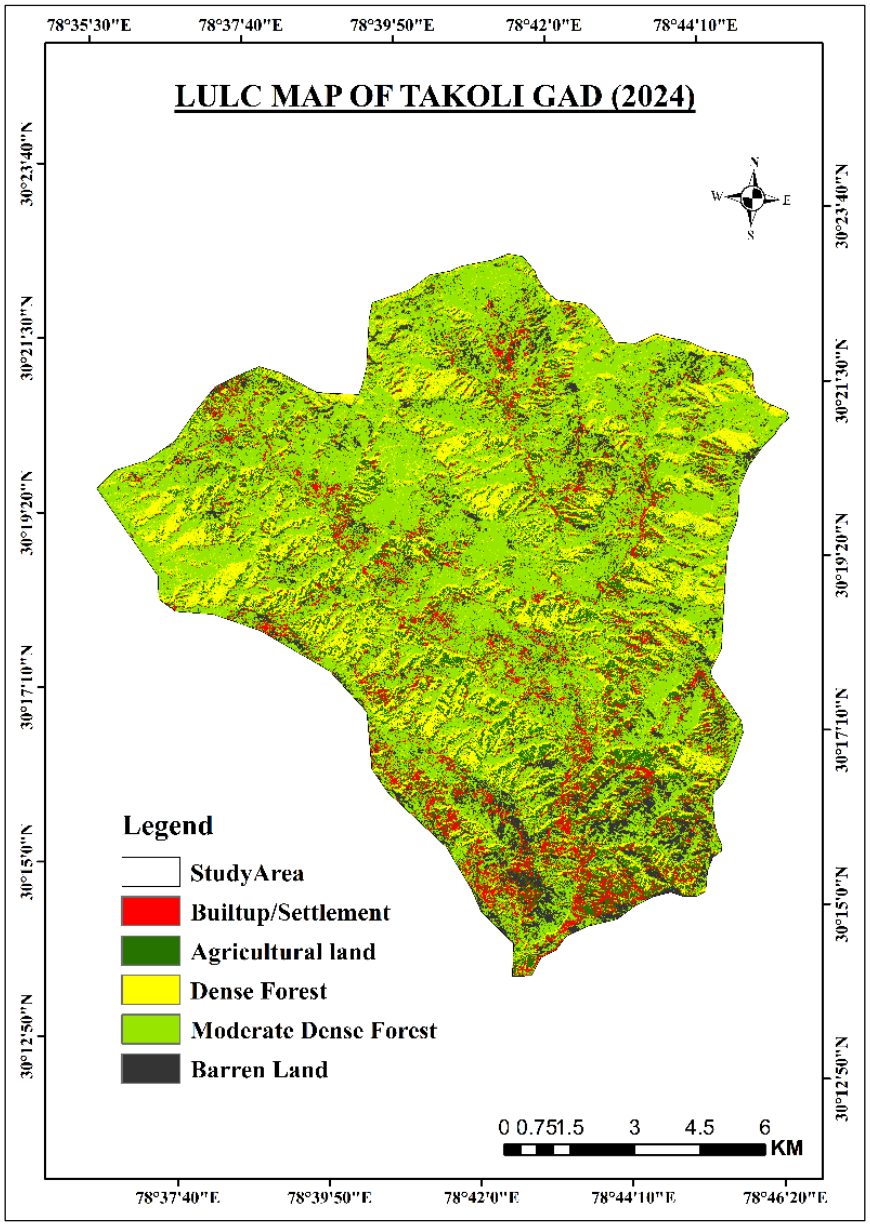


Fig. 22: LULC Map of Takoli Gad (2024)

Table 5: Areal Classification of different LULC categories and Change % of LULC

Year	Dense Forest	Moderate Dense Forest	Agricultural land	Builtup/ Settlement	Barren land	Total Area of Study Area
2015	66.33km²	32.35km²	23.02km²	12.69km²	8.33km²	142.72Km²
2024	26.52km²	71.45km²	21.00km²	11.26km²	12.49km²	142.72Km²
Change %	−60.02%	+120.87%	−8.77%	-11.26%	+49.94%	

Table 6: Confusion matrix showing Accuracy assessment of LULC classification for 2015

	Built-up	Dense Forest	Barren land	Agricultural land	Moderate Dense Forest	Total	User Accuracy (%)
Built-up	34	2	2	0	0	38	91.89
Dense Forest	0	983	0	2	36	1021	96.37
Barren land	2	0	68	0	0	70	94.44
Agricultural land	1	1	0	30	2	34	81.08
Moderate Dense Forest	0	34	2	5	187	228	83.1
Total	37	1020	72	37	225	1391	
Producer Accuracy (%)	89.47	96.27	97.14	88.23	82.01		93.60% (Overall accuracy)

Table 7: Confusion matrix showing Accuracy assessment of LULC classification for 2024

	Built-up	Agricultural land	Dense Forest	Moderate Dense Forest	Barren land	Total	User accuracy(%)
Built-up	153	20	0	14	2	189	82.7
Agricultural land	17	235	13	35	6	306	77.81
Dense Forest	1	10	527	107	0	645	82.21
Moderate Dense Forest	13	37	101	1835	4	1990	91.97
Barren land	1	0	0	4	193	198	94.14
Total	185	302	641	1995	205	3328	
Producer Accuracy (%)	80.95	76.79	81.7	92.21	97.47		88.43% (Overall Accuracy)

Confusion Matrix 2015

- **Observed Agreement (Po)** = 0.9360 → 93.60% overall accuracy
- **Expected Agreement (Pe)** = 0.5687
- **Kappa Coefficient (κ) = 0.8516**

Confusion Matrix 2024

- **Observed Agreement (Po)** = 0.8843 → 88.43% overall accuracy
- **Expected Agreement (Pe)** = 0.4109
- **Kappa Coefficient (κ) = 0.8036**

Interpretation:

Both years show **strong agreement** between classified and reference data.

- The **2015 Kappa Coefficient (0.85)** indicates *very strong* classification accuracy.
- The **2024 Kappa Coefficient (0.80)** still represents *substantial agreement*, though slightly lower, suggesting minor changes or reduced classification precision over time.

These LULC shifts have direct implications for spring water systems in the Indian Himalayan Region (IHR). Forest cover, especially dense forest, plays a critical role in regulating infiltration and sustaining spring recharge. The reduction in dense forest cover reduces the capacity of soils to retain moisture and enhances surface runoff, ultimately leading to the drying or seasonal fluctuation of springs. The increase in barren lands further exacerbates this issue, as thin soils in barren zones are prone to higher surface runoff and erosion, reducing groundwater recharge and thereby lowering spring discharge. On the other hand, the conversion of some degraded areas into moderately dense forest may provide partial recharge benefits, but these cannot fully compensate for the loss of mature dense forest ecosystems.

Location-specific impacts are also visible. Lower elevation zones, where agricultural and settlement areas are concentrated, are dependent on springs for irrigation and domestic water supply. Any reduction in recharge due to deforestation at mid to upper elevations directly affects these springs. The maps also show increased fragmentation of natural cover, which disrupts hydrological pathways and may alter the flow direction of spring-fed streams. In

addition, new construction or expansion of built-up areas along recharge zones poses the risk of blocking or diverting natural flow paths, further threatening spring sustainability.

To mitigate these impacts, a combination of strategies is necessary. Forest protection and restoration programs must prioritize the conservation of dense forest patches, as these areas are the primary recharge zones. Barren land management through soil conservation, contour trenching, and afforestation can reduce runoff and promote infiltration. Monitoring and regulating construction activities in spring recharge zones are essential to avoid blockage or contamination of natural discharge pathways. Community-led watershed management and spring-shed development programs, already gaining traction in the Indian Himalayas, can be scaled up to integrate scientific planning with traditional knowledge.

In conclusion, the LULC changes in the Takoli Gad watershed over the past decade highlight both progress and challenges. While government and NGO-led initiatives have partially slowed forest degradation, the increasing barren land and decreasing dense forest cover remain major concerns. These changes are not only transforming the landscape but are also directly influencing the recharge and discharge dynamics of spring water systems, which are vital for the livelihood and sustainability of Himalayan communities. Effective control and management require coordinated efforts in land restoration, water conservation, and careful regulation of human activities in critical recharge zones.

4.9. ERT (Electrical Resistivity Tomography)

The resistivity method is one of the oldest and most widely applied geophysical survey techniques. The primary objective of electrical surveys is to determine the subsurface resistivity distribution by carrying out measurements at the ground surface. From these measurements, the apparent resistivity of the subsurface can be obtained, which is subsequently inverted into two-dimensional subsurface resistivity models using specialized inversion software.

Igneous and metamorphic rocks typically exhibit higher resistivity values than sedimentary rocks, although the actual resistivity is strongly influenced by the degree of fracturing and the percentage of water-saturated fractures.

In this study, a **2D Electrical Resistivity Tomography (ERT)** survey was carried out using a multi-electrode resistivity system. The system consisted of a series of electrodes connected to the resistivity meter via a multi-core cable. Measurements were made by injecting current into the ground through two current electrodes, while the resulting potential difference was measured using two potential electrodes. These current and voltage measurements were then

converted into apparent resistivity values using a geometric factor dependent on the electrode array configuration. Systematically varying electrode spacing and measurement positions along the profile obtained a continuous pseudo-section of apparent resistivity.

Several array configurations are commonly used in resistivity surveys, including Wenner, Wenner–Schlumberger, dipole–dipole, and pole–pole arrays. Among these, the Wenner array is often reported to provide the best signal response and the highest resolution of horizontal structures, so it was used in our study area.

For data processing, the **RES2DINV software** was employed to automatically invert the field apparent resistivity data into two-dimensional resistivity models. The program incorporates multiple inversion algorithms and also allows the inclusion of surface topography by adjusting surface mesh nodes to match actual ground elevations.

In the present investigation, ERT surveys were conducted across selected dry springs to delineate the horizontal and vertical extent of aquifers beneath them. Springs identified to be in a critical condition or at the verge of disappearance were documented, and their precise locations were marked using Google Earth for improved visualization and analysis. A total of 72 electrodes were taken to the study area for conducting the ERT and the RMS value for the ERT profiles of different locations were below 20%.

These are the ERT imaging of the springs -

1. Araili 1

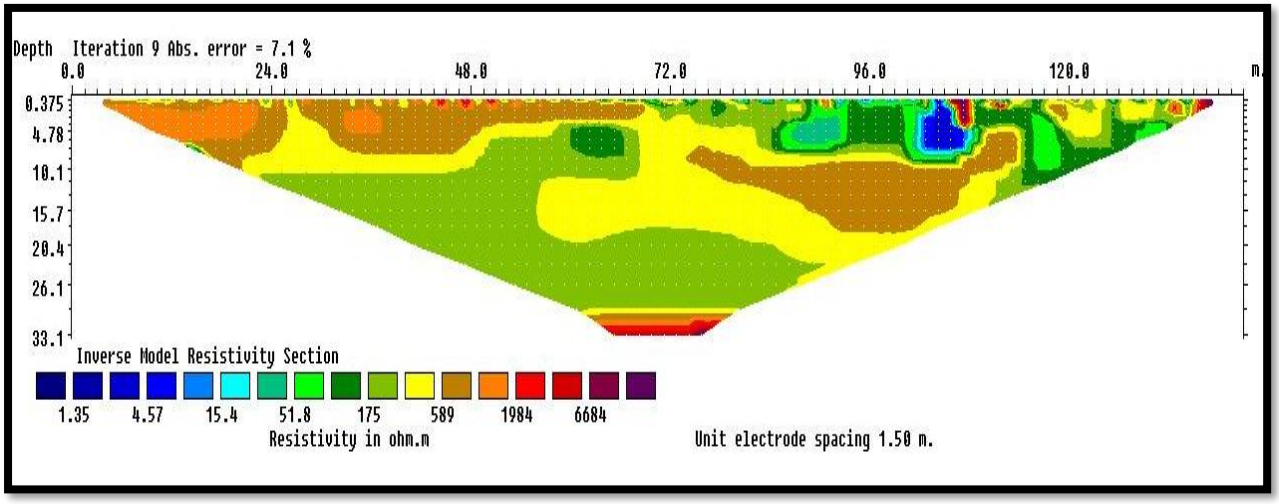


Fig. 23: ERT data of Araili 1 spring



Fig. 24: Spring of ARAILI 1

The Electrical Resistivity Tomography (ERT) profile consists of 92 electrodes and keeps the space between each electrode at 1.5m, which indicates a distinct low-resistivity zone, represented in blue, which corresponds to a potential groundwater-bearing formation (Fig. 23). This zone is observed between the electrodes placed along the 87 m to 110 m section of the profile length. However, the results reveal that only a limited number of groundwater sources are present in this segment, suggesting restricted groundwater availability. This observation is a matter of concern, as it highlights the vulnerability of the area to groundwater scarcity. The current condition of the spring is shown in (Fig. 24).To address this issue, strategic interventions are necessary—such as enhancing groundwater recharge through artificial infiltration structures, soil–water conservation measures, and afforestation in recharge zones. Such approaches would not only improve infiltration capacity and raise the groundwater table but also play a crucial role in rejuvenating and sustaining the spring discharge in the long term.

2. Talyamandal

The potential groundwater aquifers in the **Talyamandal** area are identified across the profile at an average depth ranging between **4 m and 14 m**. 41 electrodes were used with spacing between each as 3m. These aquifers are represented by bluish patches on the ERT section (Fig. 25), indicating zones of relatively low resistivity associated with groundwater saturation. The occurrence of groundwater at these comparatively shallow depths can be linked to the unique physiographic setting of the region. Since the spring is in a steeply sloping terrain at higher altitude, rainfall infiltration is considerably limited. The steep slopes promote rapid surface runoff, reducing the residence time of rainwater and consequently minimizing its percolation into deeper strata. As a result, the aquifers tend to develop at shallower levels where water temporarily accumulates before draining downslope. The current condition of the spring is

shown in (Fig. 26). This highlights the importance of implementing measures such as check dams, recharge trenches, and vegetation restoration to slow down surface runoff, increase infiltration, and improve the sustainability of groundwater reserves in this high-relief environment.

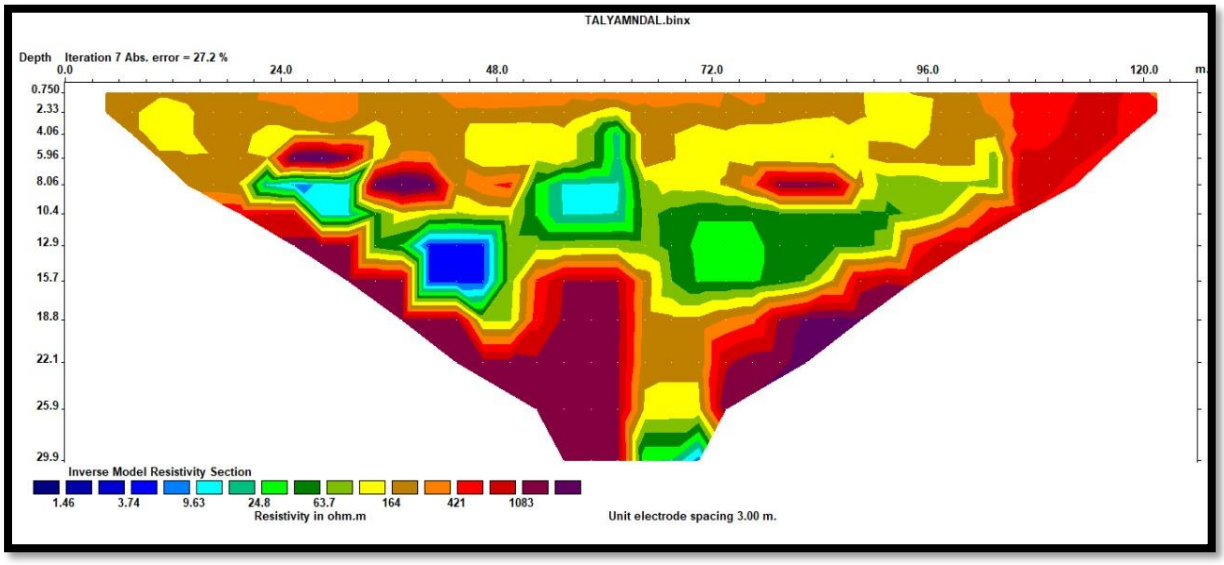


Fig. 25: ERT data of Talyamandal spring



Fig. 26: Spring of Talyamandal

3. Paindula 2

The Paindula 2 spring is presently a dry spring, characterized by a depression-type setting. The ERT was done using 44 electrodes with spacing between each was 3m. Although this spring itself no longer exhibits discharge, its hydraulic connection is evident, as water emerges from another spring within the same village, situated approximately 15 meters lower in elevation.

The ERT profile reveals bluish patches that represent groundwater aquifers within low-resistivity zones (Fig. 27), indicating the presence of subsurface water. The drying up of the Paindula 2 spring can be attributed to a decline in the local groundwater table, which has fallen below the elevation of the spring outlet (Fig 28). Consequently, the natural discharge point has shifted to a lower altitude where the water table intersects the surface. This behaviour underscores the sensitivity of springs in hilly terrains to even minor fluctuations in groundwater levels. To revive such springs, it is essential to adopt groundwater recharge interventions—such as contour trenches, percolation pits, and vegetative measures—that enhance infiltration, stabilize the groundwater table, and sustain spring discharge over time.

4.10. Geochemistry

Hydro-geochemistry plays a vital role in understanding the interaction between water and the surrounding geological environment. The chemical composition of natural waters is largely governed by processes such as **rock–water interaction, atmospheric contributions, precipitation, evaporation, and anthropogenic activities**. Among these, the dissolution of bicarbonate and silicate minerals, ion exchange, and inputs from rainfall are the dominant mechanisms that control the major ion chemistry of spring and groundwater systems. Seasonal variations in hydrochemistry often reflect differences in recharge, residence time, and external

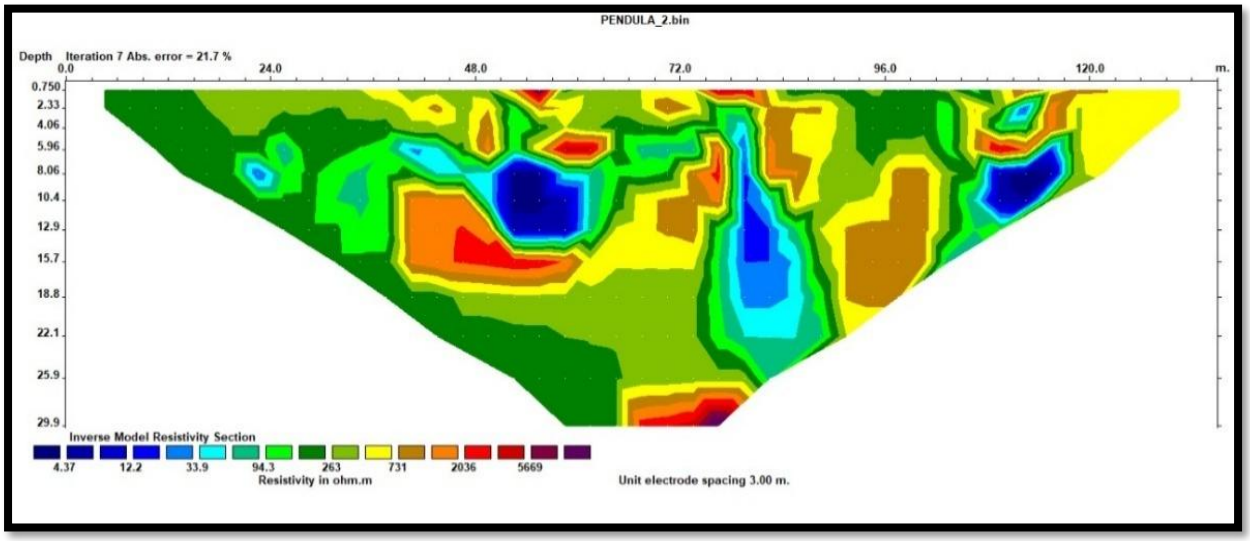


Fig. 27: ERT data of Paindula 2 spring



Fig. 28: Dried Spring of Paindula 2

inputs such as agricultural practices, making hydrogeochemical studies essential for evaluating groundwater evolution, quality, and sustainability.

4.10.1. TDS variations:

Total Dissolved Solids (TDS) represent the combined content of all inorganic salts, minerals, and small amounts of organic matter dissolved in water, serving as an important indicator of overall water quality. TDS plays a key role in determining the palatability of water, its suitability for drinking and irrigation, and in reflecting both natural geochemical processes and anthropogenic inputs. In the study area, TDS variations are observed across seasons (Fig. 29):

- Pre-monsoon: 20–300 mg/L
- Monsoon: 31–360 mg/L
- Winter: 24–535 mg/L

All values remain within WHO permissible limits (<500 mg/L), though winter occasionally approaches the upper limit, this increase may be due to the fertilizer used by the farmers in Rabi crops after the monsoon season, suggesting longer residence time or anthropogenic influence.

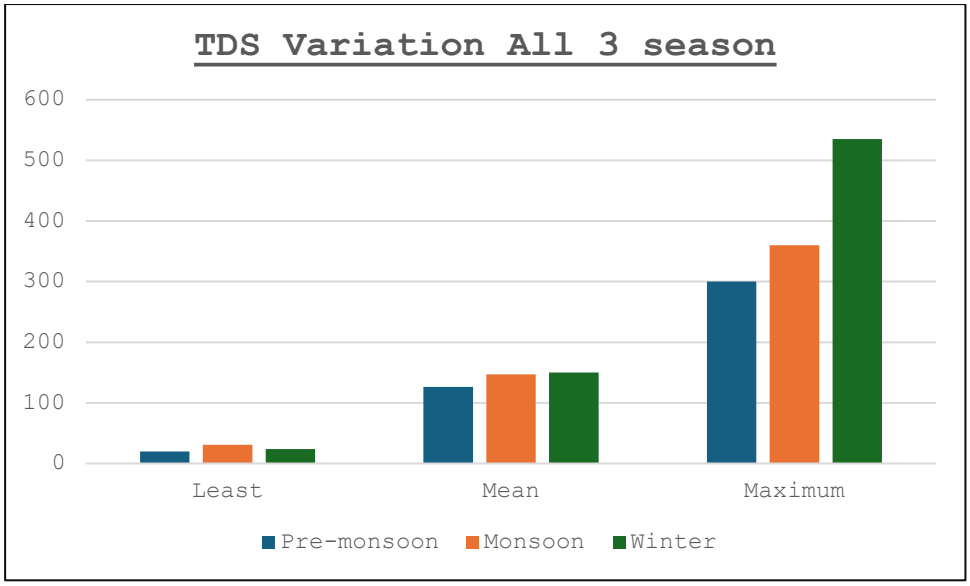


Fig. 29: TDS mean data across the season

Seasonal variation reflects input from fresh rainfall (monsoon acidity), evaporation effects (pre-monsoon), and buffering from chemical weathering (winter).

Overall, the chemistry suggests chemical weathering dominance, rainwater recharge, and limited anthropogenic inputs.

4.10.2. Durov and Piper Plots (All Three Seasons)

The **Durov diagram** (Fig. 30) demonstrates that the majority of the spring water samples across all three seasons fall within the **Ca–Mg–HCO_3 facies**, a clear indication that the hydro-geochemistry is largely governed by chemical weathering and dissolution of lithologies. This facies are typical of groundwater originating from shallow circulation within fractured carbonate rocks, where rainwater and snowmelt act as the principal recharge sources.

Seasonal patterns are discernible within the plot:

- **Pre-monsoon samples** cluster toward relatively enriched compositions, reflecting **evaporation and concentration effects** during dry conditions when recharge is minimal and residence time within the aquifer is longer.
- **Monsoon samples** are shifted toward diluted compositions, driven by **direct recharge from precipitation** that rapidly infiltrates through permeable formations. This dilution is evident from the comparatively lower TDS values and less enriched isotopic signatures.

- **Winter samples** exhibit subtle deviations, suggesting the influence of **agricultural return flow** and potential fertilizer leaching during the Rabi season, as reflected in slightly elevated nitrate and phosphate concentrations.

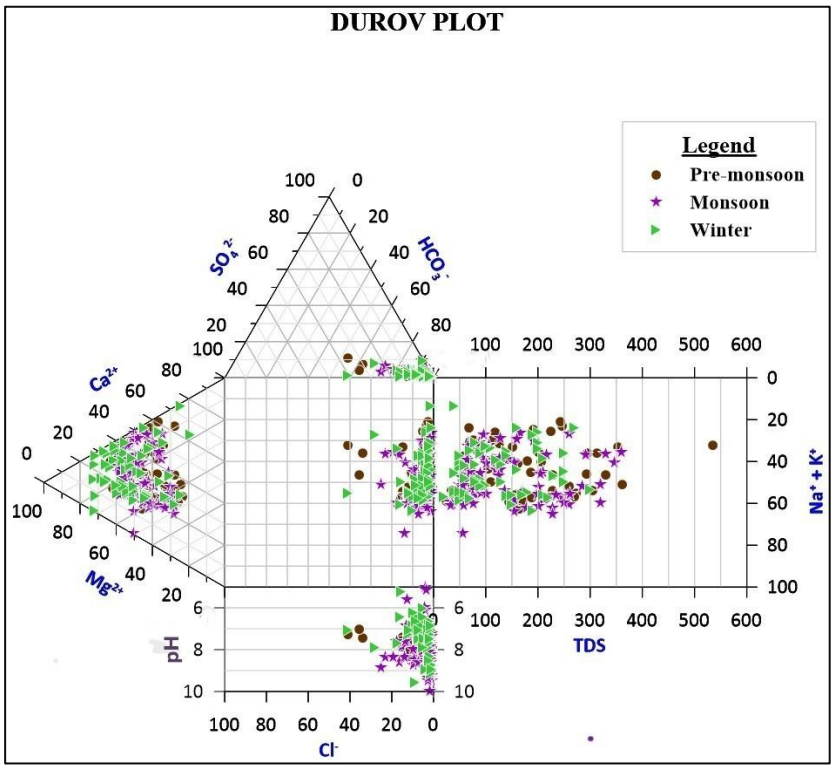


Fig. 30: Durov diagram acroos the season

Similarly, the **Piper trilinear plot** (Fig. 31) classifies the water predominantly as **alkaline earth bicarbonate type**. This classification further corroborates the dominance of chemical weathering and meteoric recharge. The lower-left cation triangle shows the majority of samples plotting within the Ca^{2+}–Mg^{2+} field, while the anion triangle demonstrates bicarbonate dominance, confirming water–rock interaction as the primary control on chemistry.

Notably, both **high- and low-altitude springs** align within the same facies, reinforcing the interpretation that recharge is primarily derived from **rainwater infiltration**, albeit with modifications due to altitude-dependent processes such as evaporation at lower elevations and isotopic depletion at higher elevations.

Together, the Durov and Piper diagrams demonstrate that the hydro-chemical character of spring waters in the Takoli Gad watershed is remarkably consistent across seasons, with chemical weathering as the governing mechanism, supplemented by seasonal modifications arising from evaporation, monsoon recharge, and anthropogenic influences.

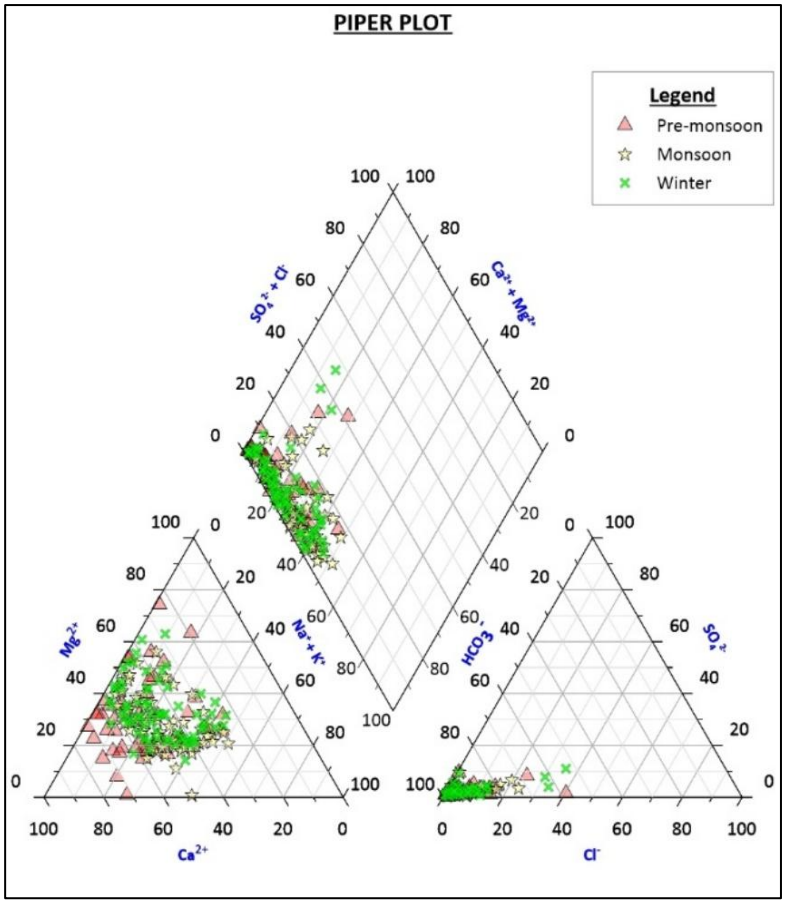


Fig. 31: Piper diagram of all season

So, the overall water type of the springs is **$CaMgHCO_3$**.

4.10.3. EC vs Altitude (All Three Seasons)

Electrical conductivity (EC) decreases with altitude, reflecting reduced water–rock interaction in higher catchments and dilution by recent recharge. Lower altitudes show higher EC due to evaporation and longer residence time. Seasonal variations show lowest EC in the monsoon due to dilution and highest in winter (Fig. 32).

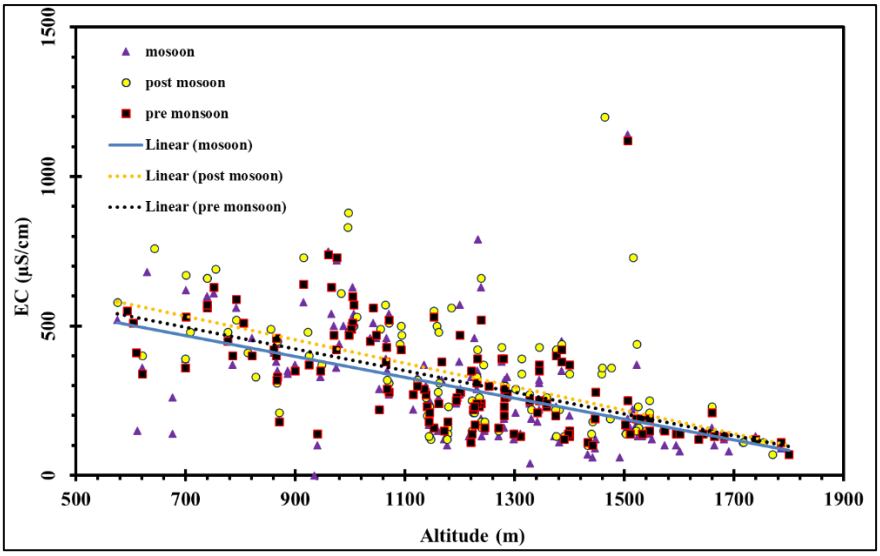


Fig. 32: EC V/S Altitude graph of all season

4.10.4. pH of Spring Water (3 Seasons)

- **Pre-monsoon**: Highest variability (5.9–9.7), influenced by evaporation and concentration effects.
- **Monsoon**: Acidic tendency (5.1–9.1), linked to rainfall input and dilution.
- **Winter**: Neutral to alkaline (6.9–8.4), reflecting carbonate buffering and reduced dilution.

The variation of pH is shown in chart (Fig. 33).

4.10.5. Interpretation of Gibbs' Plots (all 3 seasons)

Gibbs' plots are widely used to identify the dominant natural mechanisms controlling the chemistry of groundwater and surface water systems. They establish a relationship between Total Dissolved Solids (TDS) — plotted on the logarithmic y-axis (mg/L) — and the ratio of key ionic species — plotted on the x-axis. Two specific ionic ratios are commonly used:

$Na^+/ (Na^+ + Ca^{2+})$ for cations

$Cl^-/ (Cl^- + HCO_3^-)$ for anions

- These plots categorize water samples into three principal hydrogeochemical fields representing different environmental processes:

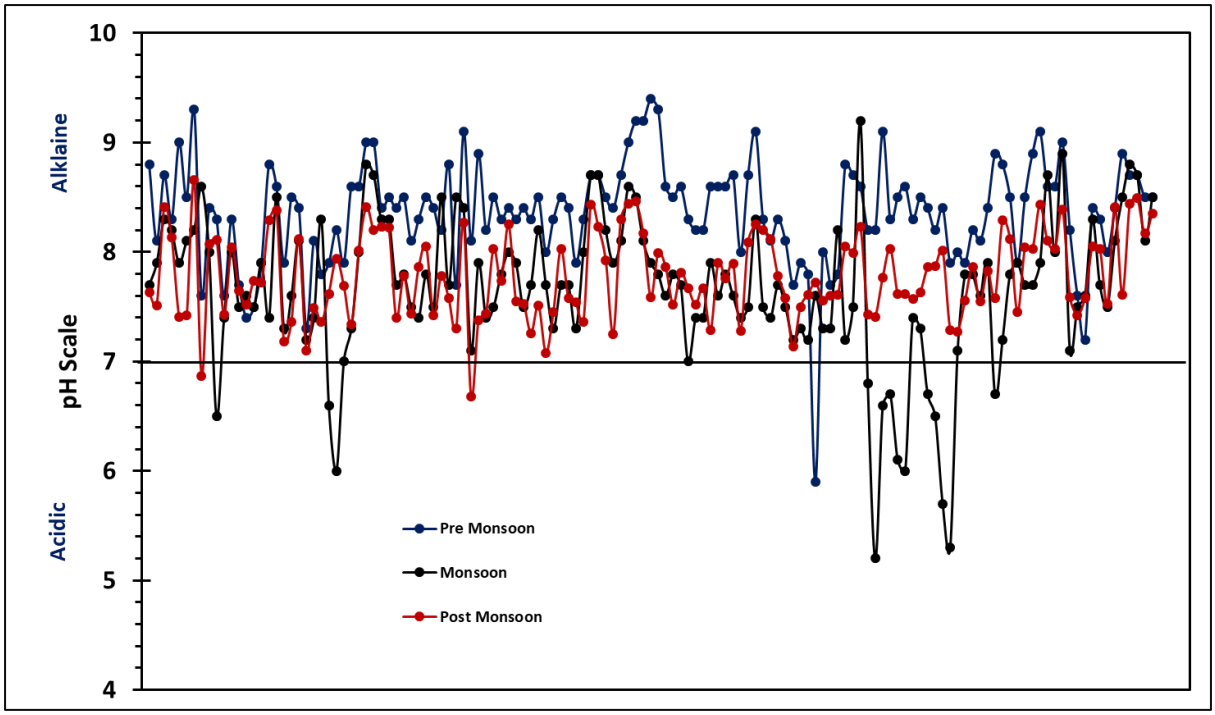


Fig. 33: pH of Spring water graph of 3 seasons

1. Precipitation Dominance (lower left corner):

Characterized by low TDS and low ionic ratios, indicating that rainfall and direct atmospheric input primarily control water chemistry. Such waters are typically fresh, with minimal interaction with rocks or soils.

2. Rock–Water Interaction Dominance (central zone):

Represents intermediate TDS and moderate ionic ratios, reflecting active dissolution of rock-forming minerals, ion exchange processes, and equilibrium reactions between groundwater and the host aquifer materials. This is the most common process in groundwater systems.

3. Evaporation Dominance (upper right corner):

Characterized by high TDS and elevated ionic ratios, signifying that evaporation and concentration effects (often in semi-arid regions or shallow systems) play a major role in increasing dissolved solids.

(a) Pre-Monsoon Season Gibbs' plots

Two Gibbs' plots were analysed for the pre-monsoon period (Fig. 34):

TDS vs. $Na^+/(Na^+ + Ca^{2+})$: The majority of samples cluster within the Rock–Water Interaction field. TDS values mostly range from 50 to 300 mg/L, indicating moderate mineral dissolution

from the aquifer matrix. A few samples show slightly lower TDS values and lower ionic ratios, suggesting a minor influence of precipitation and the influx of relatively fresh recharge water.

TDS vs. $Cl^-/(Cl^- + HCO_3^-)$: All data points are confined to the Rock–Water Interaction zone, with TDS values between 50 and 400 mg/L. This concentration pattern indicates that carbonate and silicate weathering are the primary contributors to ionic composition, with limited anthropogenic or evaporative impact.

During the pre-monsoon, the groundwater chemistry is predominantly influenced by Rock–Water Interaction, likely through the dissolution of minerals such as calcite, dolomite, feldspars, and mica from the aquifer lithology. Limited rainfall recharge and lower humidity during this period minimize dilution and evaporation effects.

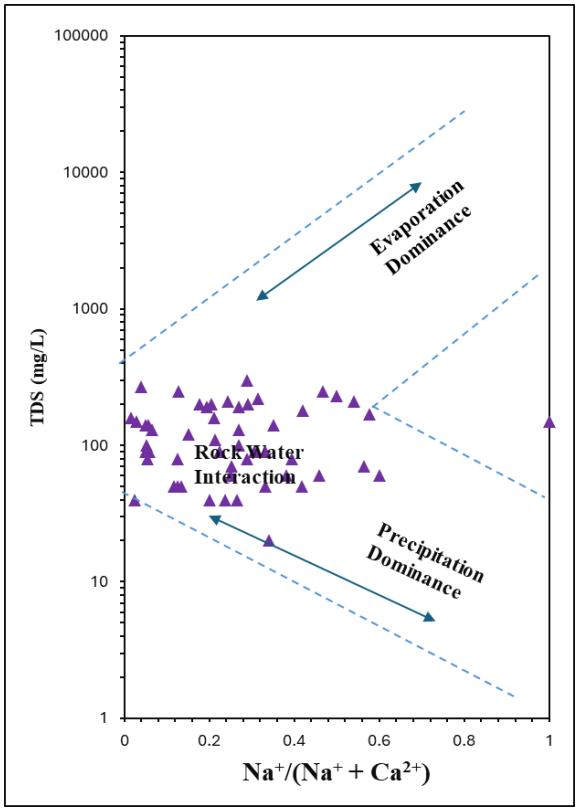


Fig.: 34(a)

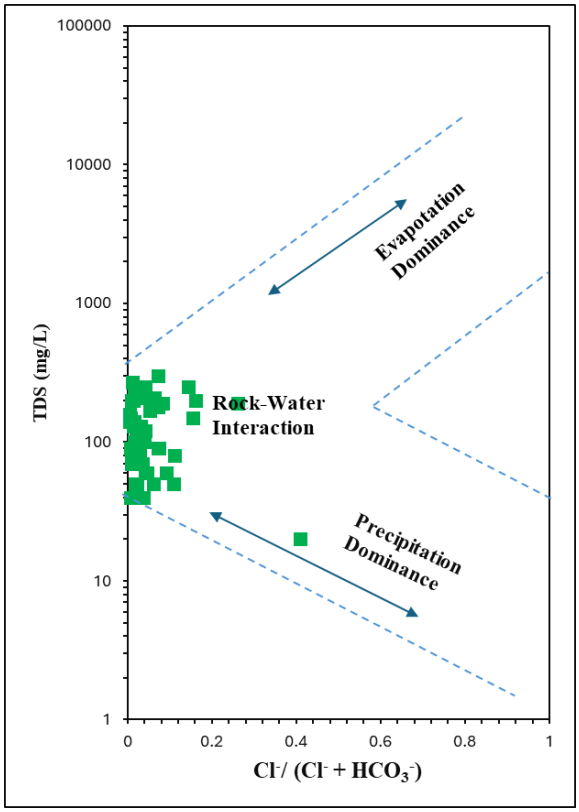


Fig.: 34(b)

Fig. 34: Gibbs plot for pre-monsoon season.(a) shows the TDS vs. $Na^+/ (Na^+ + Ca^{2+})$, and (b) shows the TDS vs. $Cl^-/ (Cl^- + HCO_3^-)$

(b). Monsoon Season Gibbs' plots

The Gibbs' plots for the monsoon period show a consistent geochemical pattern (Fig. 35):

TDS vs. $Na^+/ (Na^+ + Ca^{2+})$: All data points lie tightly within the Rock–Water Interaction field, with TDS values ranging between 40 and 400 mg/L. The narrow spread of points suggests a

stable geochemical regime where mineral dissolution continues to dominate, despite the influx of fresh recharge water from rainfall.

TDS vs. Cl^-/ (Cl^- + HCO_3^-): Similar to the cation plot, all samples occupy the Rock–Water Interaction field, indicating that rainwater dilution does not significantly alter the ionic dominance pattern. The uniformity of TDS values suggests that rapid infiltration and limited residence time restrict major geochemical changes during the monsoon.

Even under conditions of high rainfall and enhanced recharge, Rock–Water Interaction remains the governing mechanism. This implies that the water-rock equilibrium processes are fast and resilient, maintaining consistent hydro-chemical characteristics across seasonal variations.

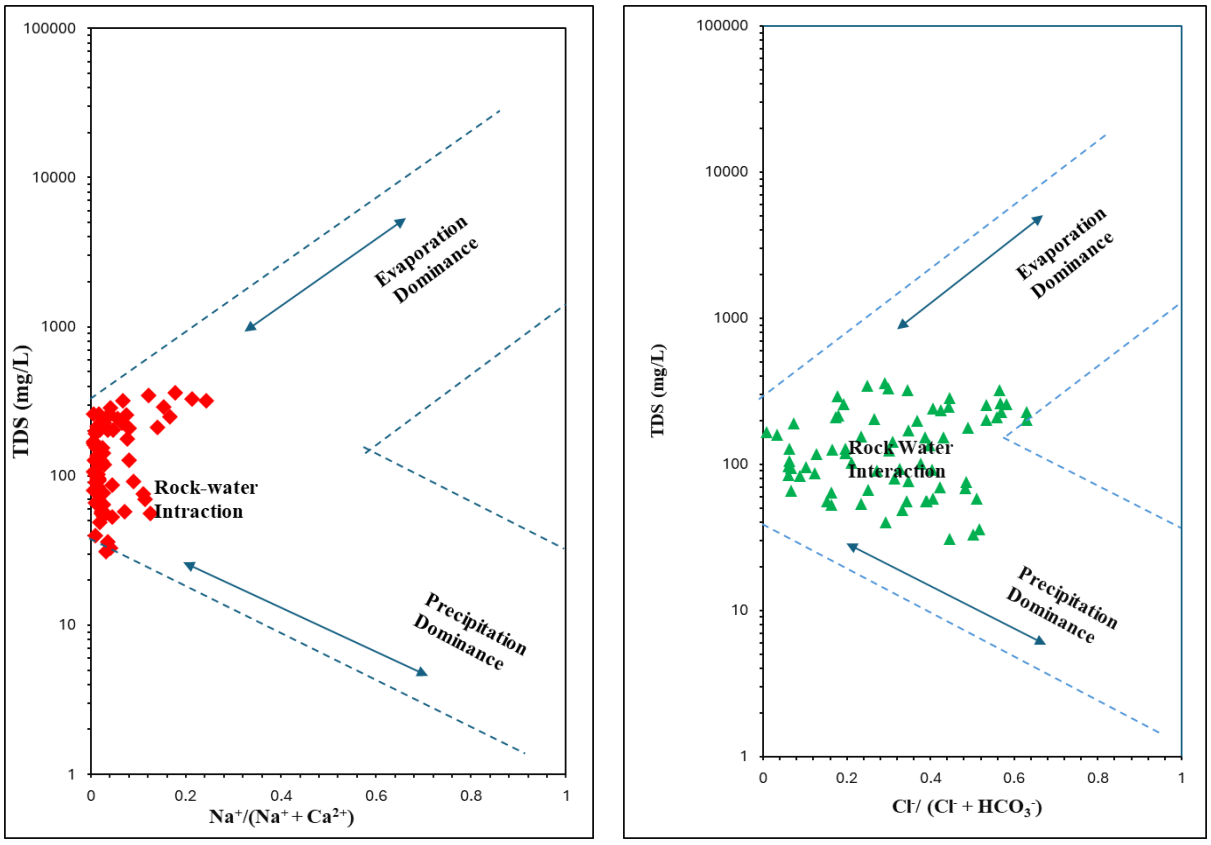


Fig.: 35(a) **Fig. :35(b)**

Fig. 35: Gibbs plot for monsoon season.(a) shows the TDS vs. Na^+/ (Na^+ + Ca^{2+}), and (b) shows the TDS vs. Cl^-/ (Cl^- + HCO_3^-)

(c) Winter Season Gibbs' plots

The winter plots display a slightly wider spread in TDS values, hinting at minor seasonal variations (Fig. 36):

TDS vs. $Na^+/ (Na^+ + Ca^{2+})$: Most samples fall within the Rock–Water Interaction zone, with some showing marginal shifts toward Evaporation Dominance (higher TDS) and Precipitation Dominance (lower TDS). TDS ranges between 40 and 400 mg/L, with a few higher values possibly due to reduced recharge, longer residence time, or slight concentration effects from evapotranspiration during the dry season.

TDS vs. $Cl^-/ (Cl^- + HCO_3^-)$: All samples remain in the Rock–Water Interaction field, reinforcing the interpretation that weathering of host rock minerals continues to dictate ionic composition. The absence of high $Cl^-/ (Cl^- + HCO_3^-)$ ratios suggests negligible evaporative or anthropogenic chloride enrichment.

In winter, Rock–Water Interaction persists as the key controlling process, with minor contributions from evaporation and precipitation influences. The slightly broader spread in TDS indicates seasonal variations in recharge and residence time but not a change in dominant geochemical process.

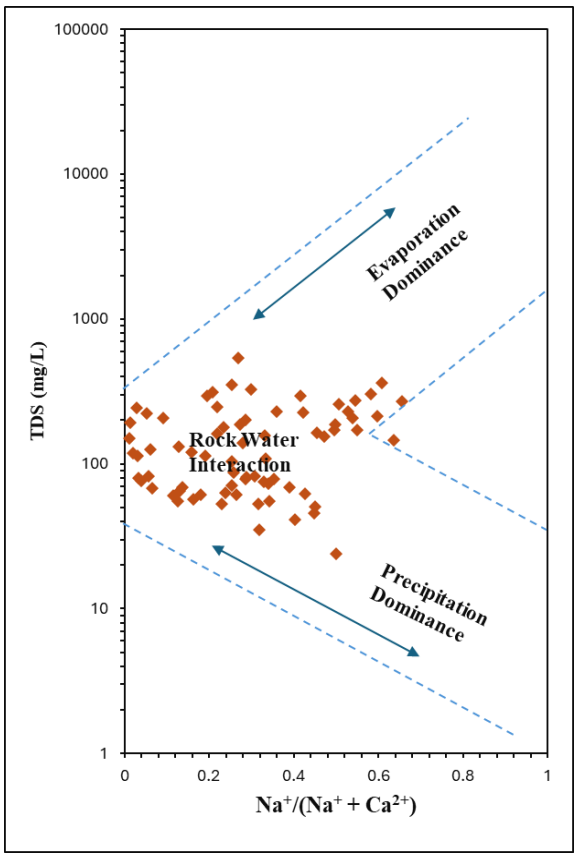


Fig. 36(a)

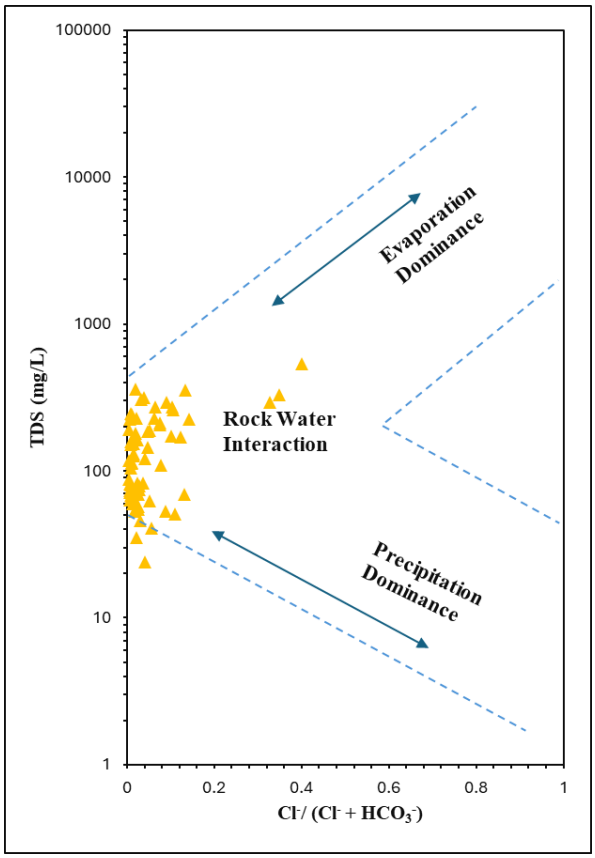


Fig. 36(b)

Fig. 36: Gibbs plot for winter season. (a) shows the TDS vs. $Na^+/ (Na^+ + Ca^{2+})$ and (b) shows the TDS vs. $Cl^-/ (Cl^- + HCO_3^-)$

Overall analysis of Gibb's plot for all 3 seasons:

- Across all three seasons — pre-monsoon, monsoon, and winter — the Gibbs' plots reveal a consistent geochemical pattern dominated by Rock–Water Interaction. This uniformity underscores that:
- The dissolution of aquifer minerals (such as carbonates, feldspars, and silicates) is the principal mechanism controlling the concentration of dissolved ions in the springwater.
- The low to moderate TDS values (below 400 mg/L) indicate that the springwaters are fresh and slightly mineralized, typical of systems where groundwater interacts with weathered rock materials rather than saline or evaporitic deposits.
- Evaporation Dominance is minimal, suggesting that the study area does not experience significant evaporative concentration or salinization.
- Precipitation Dominance is observed in only a few samples with lower TDS, reflecting the dilution effect of recent rainfall recharge.
- The tight clustering of data points within the central field of all plots demonstrates a stable hydrogeochemical regime, with limited seasonal variability.

So overall, the Gibbs' plots confirm that the springwater chemistry is primarily governed by lithological control and mineral weathering processes, rather than by climatic or anthropogenic influences. The persistence of this trend through all seasons suggests a balanced and resilient hydrogeological system, where rock–water interaction remains the dominant factor regulating springwater quality.

4.10.6. d-excess vs $\delta^{18}O$ (All Three Seasons)

- **Precipitation**: Shows increasing d-excess with altitude, indicating contributions from recycled moisture and ISM (Indian Summer Monsoon) dominance in monsoon rainfall and higher d-excess values of winter precipitation show the influence of western disturbances in winter months (Fig. 38).
- **Spring water**: d-excess values track precipitation but with reduced variability, reflecting mixing, infiltration, and storage effects within the aquifer (Fig. 37).

At lower elevations, evaporation lowers d-excess, while at higher elevations recycled moisture dominates.

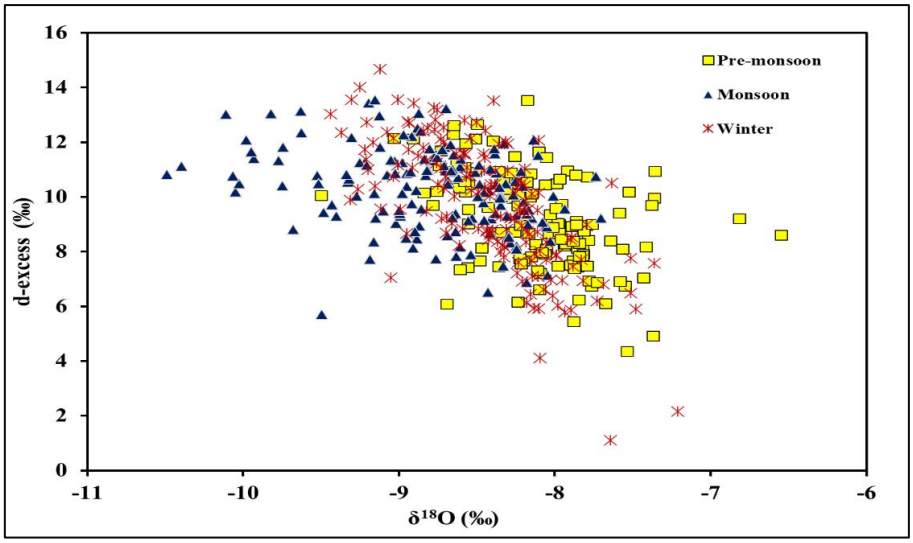


Fig. 37: d-excess vs $\delta^{18}O$ of Spring water graph of all seasons

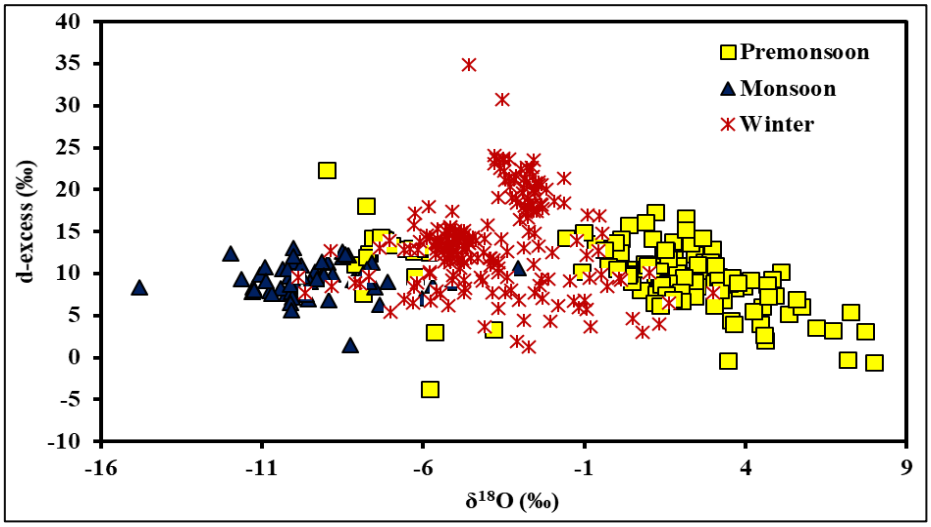


Fig. 38: d-excess vs $\delta^{18}O$ of Precipitation graph of all seasons

4.10.7. $\delta^{18}O$ and δD along the Global Meteoric Water Line (GMWL)

- **Spring water**: Plots close to the Local Meteoric Water Line (LMWL), confirming rainfall recharge. Pre-monsoon samples are isotopically enriched due to evaporation, while monsoon samples are most depleted, reflecting the "amount effect." Winter samples reflect recycled moisture input (Fig. 39).
- **Precipitation**: Aligns with the LMWL but shows altitude-dependent depletion. High-altitude rainfall is isotopically lighter, confirming altitude as a control (Fig. 40).

The slope and intercept of the Takoli LMWL resemble those of the Western and Kashmir Himalayas.

We plotted the Local Meteoric Water Line (LMWL) for all three seasons (Premonsoon, Monsoon, Post-monsoon) based on collected rain samples and compared it with the Global Meteoric Water Line (GMWL). The LMWL slope is generally lower than the GMWL, indicating regional variations. In winter, when evaporation is minimal due to low temperatures, the LMWL slope is closest to the GMWL. However, the slope of the Spring Water Line is consistently lower than that of the LMWL across all seasons, suggesting evaporation of raindrops and surface water before percolation.

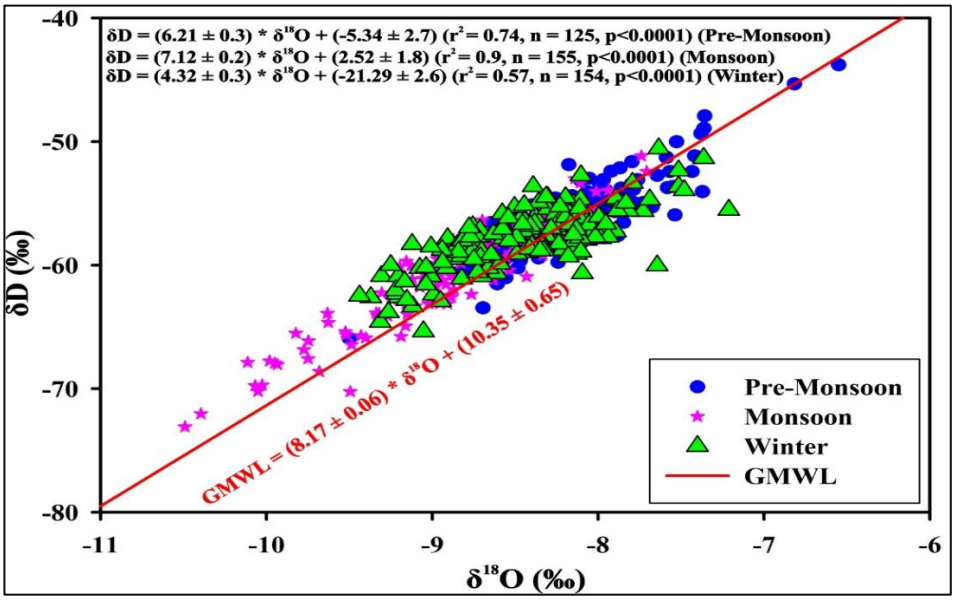


Fig.39: $\delta^{18}O$ and δD values of Spring water along with Global Meteoric Water Line (GMWL) graph of 3 seasons

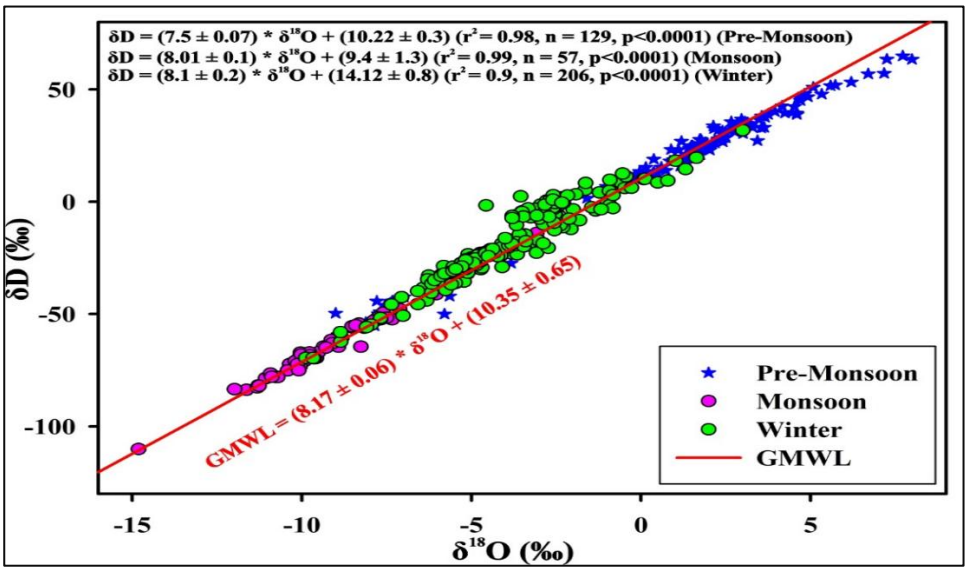


Fig.40: $\delta^{18}O$ and δD values of precipitation water along with Global Meteoric Water Line (GMWL) graph of 3 seasons

4.10.8. Discharge vs EC variation

The variation pattern observed between spring discharge and electrical conductivity (EC) across Maikhandi, Chawki, and Dalkyari villages reflects the combined influence of hydrogeological setting, recharge mechanism, and aquifer characteristics controlling spring behaviour. In Maikhandi village, both discharge and EC exhibit low variation (Fig.41), indicating a stable and well-buffered groundwater system. This stability suggests that the springs are mainly fed by a deep, confined, or semi-confined aquifer where recharge occurs slowly through percolation and subsurface flow. As a result, seasonal rainfall fluctuations exert minimal influence on discharge, and the chemical composition remains nearly constant since the water has undergone long residence time and rock–water interaction under equilibrium conditions. The uniform geology and limited surface runoff infiltration further contribute to maintaining both steady discharge and stable EC values throughout the year.

In contrast, Chawki village shows high variation in both discharge and EC (Fig.42), which indicates that the spring system here is shallow, unconfined, and highly responsive to seasonal recharge. During the monsoon, increased rainfall rapidly infiltrates into the aquifer, causing a sudden rise in discharge accompanied by dilution of ions, while in the dry season, reduced recharge and enhanced evaporation lead to lower discharge and higher EC values. This reflects direct coupling between hydrological and geochemical responses typical of springs controlled by fractured or weathered rock aquifers with limited storage capacity. The strong dependence on rainfall and surface recharge processes makes the Chawki springs highly variable and sensitive to climatic conditions.

Meanwhile, Dalkyari village displays high variation in discharge but low variation in EC (Fig.43), implying that while the volume of water fluctuates seasonally, the chemical composition remains relatively stable. This may occur in systems where multiple recharge pathways feed a chemically homogeneous aquifer—for instance, rainfall infiltration might control discharge variability, but since all recharge water undergoes similar rock–water interactions before emerging at the spring, the EC remains nearly constant. Another possibility is that rapid mixing and buffering within the aquifer maintain a consistent ionic concentration despite changes in flow volume. Therefore, the discharge and EC behaviour in these three villages collectively highlight how aquifer depth, lithology, recharge rate, and residence time govern both hydrodynamic and hydrochemical stability of spring systems, revealing the intricate relationship between hydrology and geochemistry in varied geological settings.

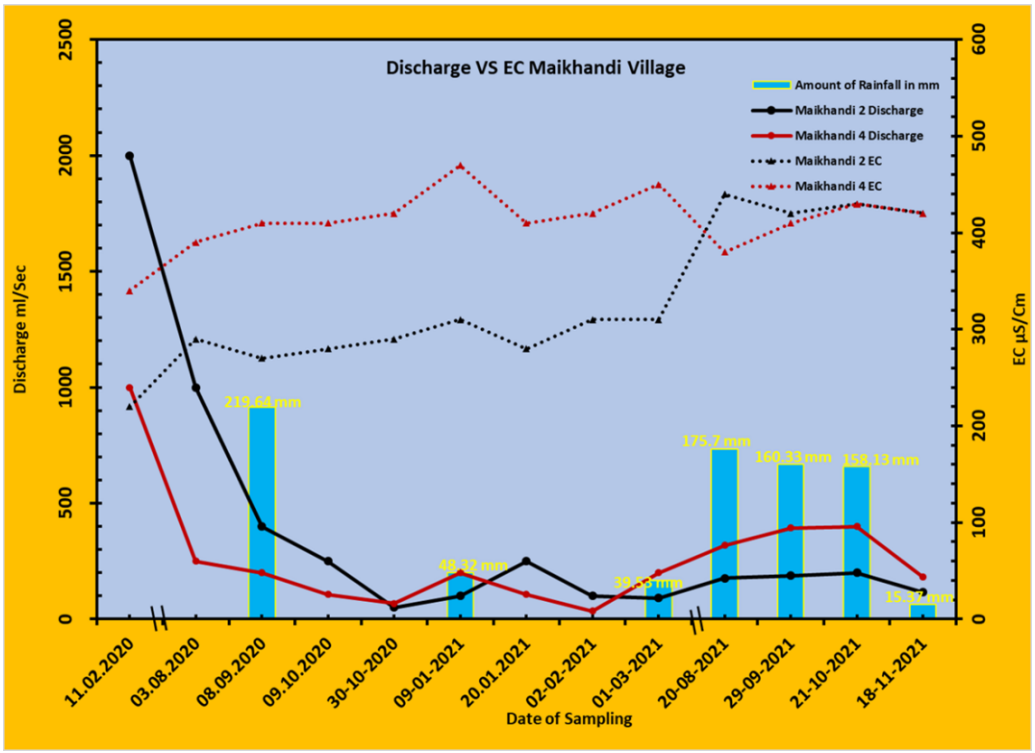


Fig. 41: Discharge vs EC (Maikhandi village)

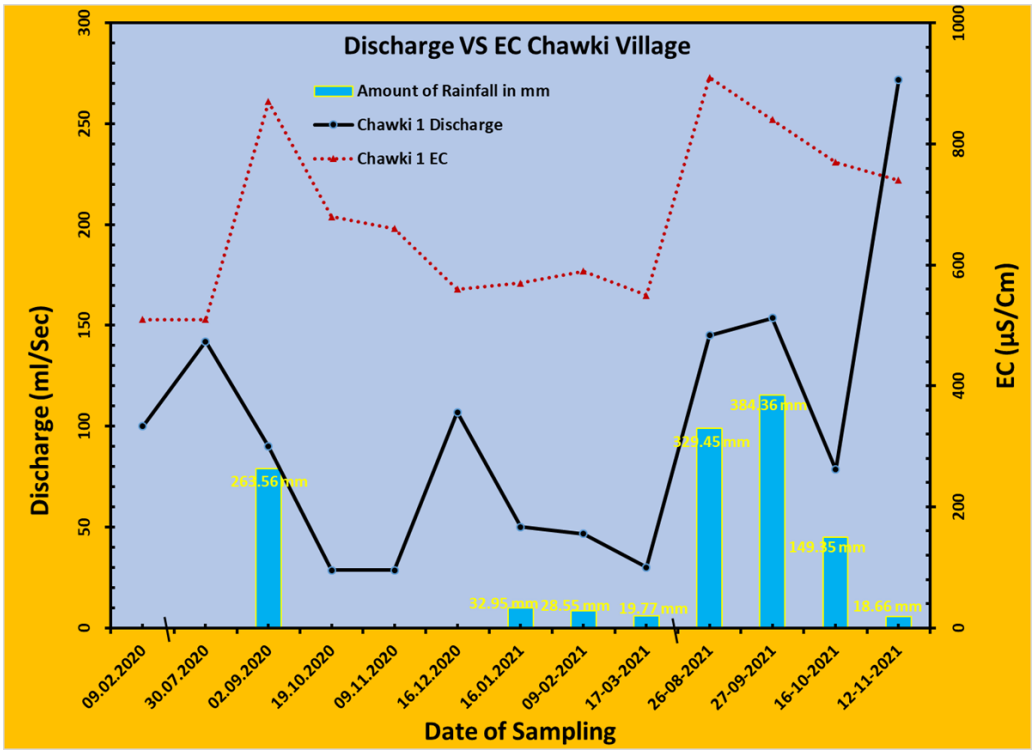


Fig. 42: Discharge vs EC (Chawki village)

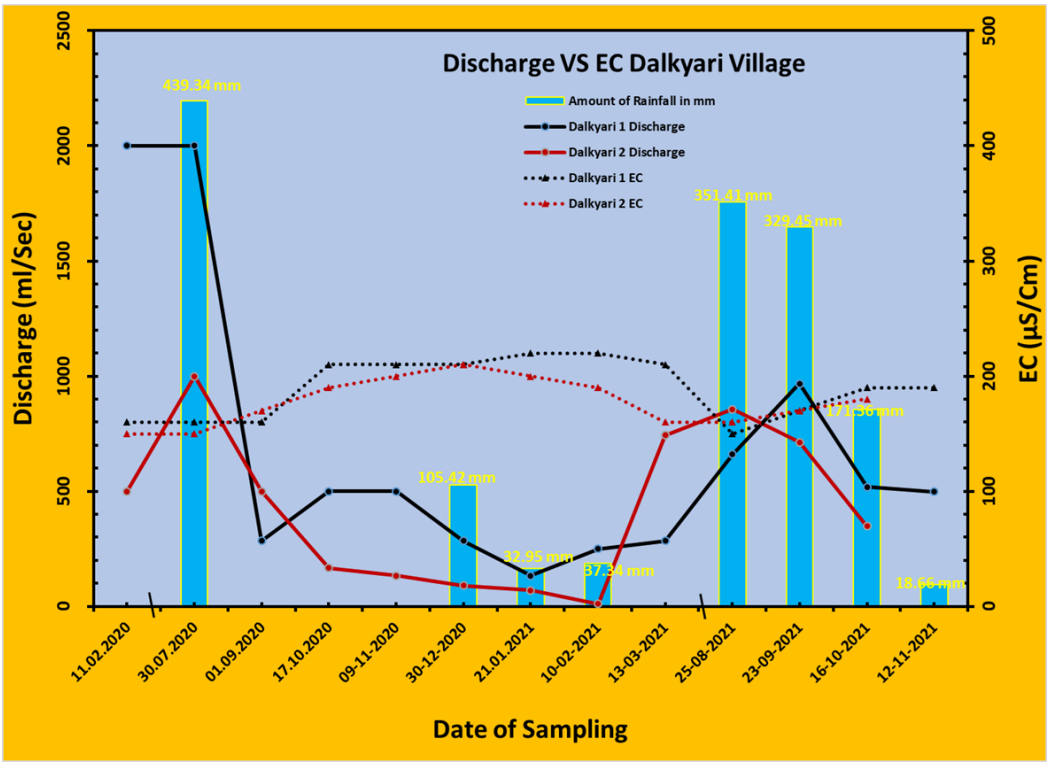


Fig.43: Discharge vs EC (Dalkyari village)

4.10.9. Annual Precipitation variation in study area (1990-2015)

The analysis of average total precipitation from 1990 to 2015 reveals distinct seasonal trends across the monsoon, winter, and pre-monsoon periods in the study area. During the monsoon season (Fig.44), a noticeable downward trend in July and August indicates a decline in the number of rainfall days and overall precipitation intensity. These two months are crucial as they also contribute the maximum rainfall and serve as the principal recharge period for springs, particularly in rain-fed mountainous and hill slope regions. From 1990 to 2000 it is seen that July and august are the major contributor and later from 2000 onwards till 2015 September has also joined. The range of precipitation varies – lowest of 15mm in September and highest of 395mm in July. A reduction in rainfall frequency during this critical period implies less infiltration and groundwater recharge, leading to a progressive decline in spring discharge during subsequent months. If this downward trend continues, it could result in seasonal drying of springs, delayed recharge timing, and increased vulnerability to spring flow reduction or complete cessation during dry periods, especially in lean pre-monsoon months.

In contrast, the winter season exhibits upward trends (Fig.45) in January and February, likely influenced by an increase in western disturbances bringing moisture. However, the decline in October, November, and December indicates reduced post-monsoon rainfall, which usually

sustains residual soil moisture and supports late recharge. This pattern suggests a shift in rainfall timing, potentially leading to uneven recharge distribution and stress on the spring-fed systems.

The pre-monsoon season (March–May) shows a consistent downward trend (Fig.46), as these fall in the summer months and no or very little rainfall occurs during these months. The absence of this early recharge can exacerbate drying conditions and cause springs to exhibit delayed response or diminished discharge before the main monsoon onset.

Overall, the declining rainfall trends in key recharge months, especially during the monsoon, signify a gradual weakening of natural replenishment processes for rain-fed springs. If this pattern persists, it may lead to reduced groundwater storage, declining spring yields, and increased water scarcity, particularly during pre-monsoon and summer periods. The results underscore the need for spring-shed management, artificial recharge interventions, and catchment conservation measures to mitigate the impact of changing precipitation regimes on the spring systems.

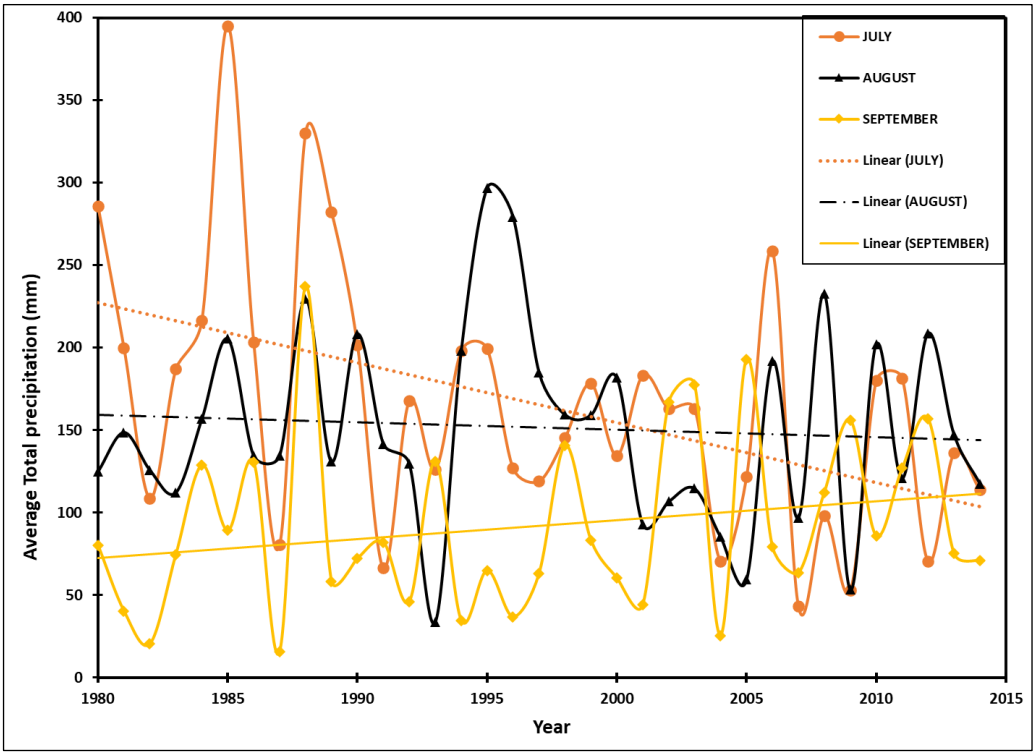


Fig.44: Average total precipitation (in mm) of monsoon season from 1990-2015

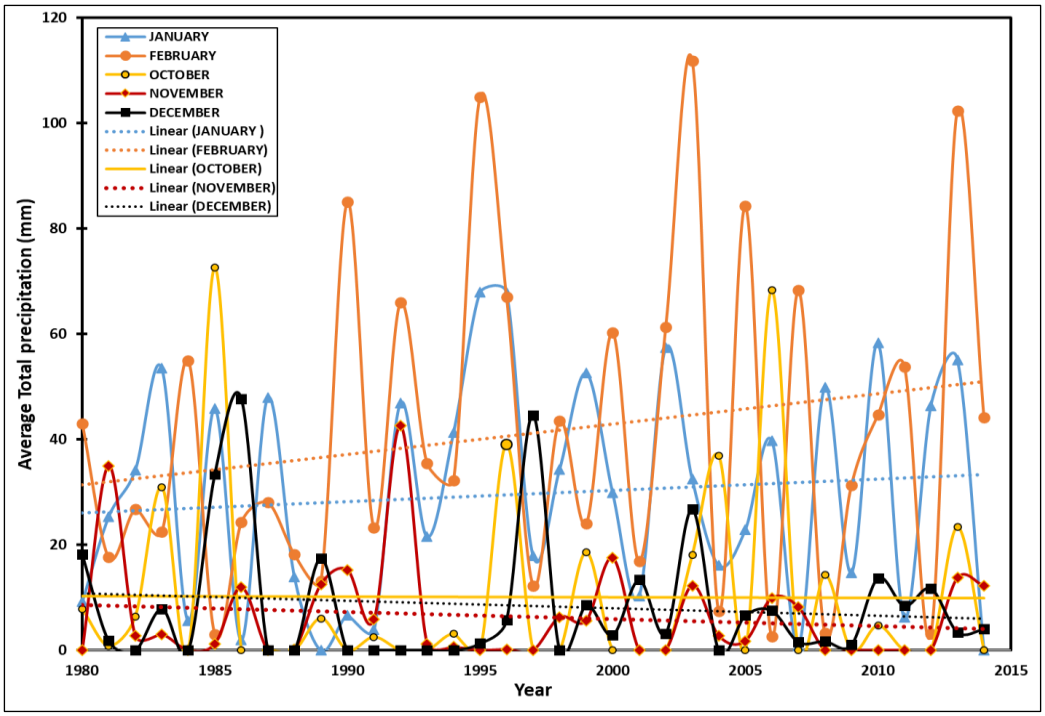


Fig.45: Average total precipitation (in mm) of winter season from 1990-2015

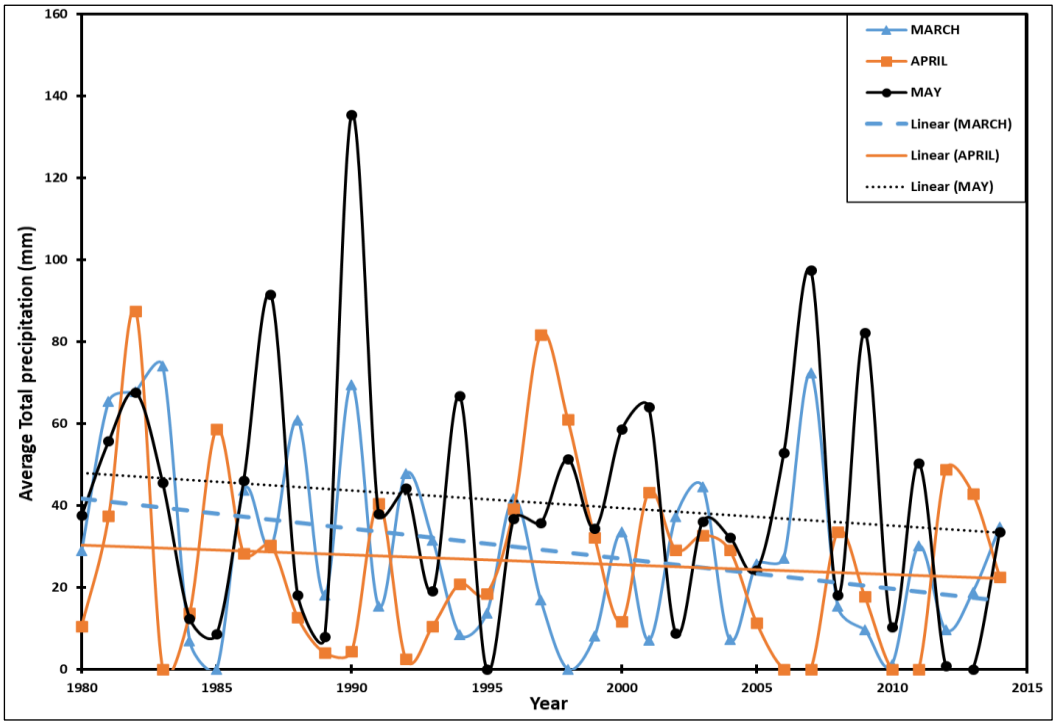


Fig.46: Average total precipitation (in mm) of pre-monsoon season from 1990-2015

4.10.10. Daily Precipitation Intensity Index Analysis

The analysis of the Daily Precipitation Intensity Index (DPII) from 1990 to 2025 reveals notable seasonal variations in rainfall intensity and frequency across the monsoon, winter, and pre-monsoon periods. The index, defined as (Total Precipitation / Number of Rainfall Days), serves as a proxy to understand the distribution of rainfall events — where an upward trend indicates fewer rainfall days with more intense precipitation per event, and a downward trend indicates more frequent but less intense rainfall events.

During the monsoon season, all months exhibit a positive (upward) trend (Fig.47), suggesting that while the total rainfall amount may not have significantly reduced, the number of rainy days has declined, leading to more intense and short-duration rainfall events. This shift towards high-intensity, low-frequency rainfall profoundly affects rain-fed spring systems. Intense rainfall promotes greater surface runoff rather than infiltration, thereby reducing groundwater recharge efficiency. Consequently, although heavy rainfall events may appear to provide adequate water input, the subsurface recharge processes that sustain spring flow weaken, resulting in lower base flow and reduced spring discharge during non-rainy periods. If this pattern continues, the region may experience flashy hydrological responses — brief periods of high flow followed by extended dry spells, ultimately causing decline or seasonal drying of springs and depletion of shallow aquifers.

In the winter season, February shows an upward trend (Fig.48), while October, November, and December display downward trends. This indicates a shift in winter precipitation timing, possibly linked to the increasing frequency of late winter western disturbances. The decline in early winter months suggests reduced post-monsoon recharge opportunities, while increased precipitation in February may offer delayed but localized recharge, though less effective due to lower soil permeability and evapotranspiration in cooler months.

For the pre-monsoon season, April and May show an upward trend (Fig.49), indicating fewer but more intense convective rainfall events. This pattern diminishes the early recharge potential of the aquifers and reduces antecedent soil moisture, which is crucial for spring sustainability before the monsoon onset. The lack of steady, moderate pre-monsoon rainfall results in increased surface runoff and decreased infiltration, further lowering spring yields at the start of the dry period.

So overall, these results suggest a transition toward a more erratic and concentrated rainfall regime, characterized by short, intense precipitation events and fewer rainy days. Such a

climatic shift reduces the natural recharge window for rain-fed springs, alters catchment hydrology, and enhances spring flow variability. If this trend persists, the long-term implications include declining spring discharge, delayed recharge timing, and possible drying of perennial springs, especially in small catchments with shallow aquifers. This emphasizes the urgent need for spring-shed management, soil–water conservation structures, and artificial recharge interventions to counterbalance the reduced infiltration potential caused by changing rainfall patterns.

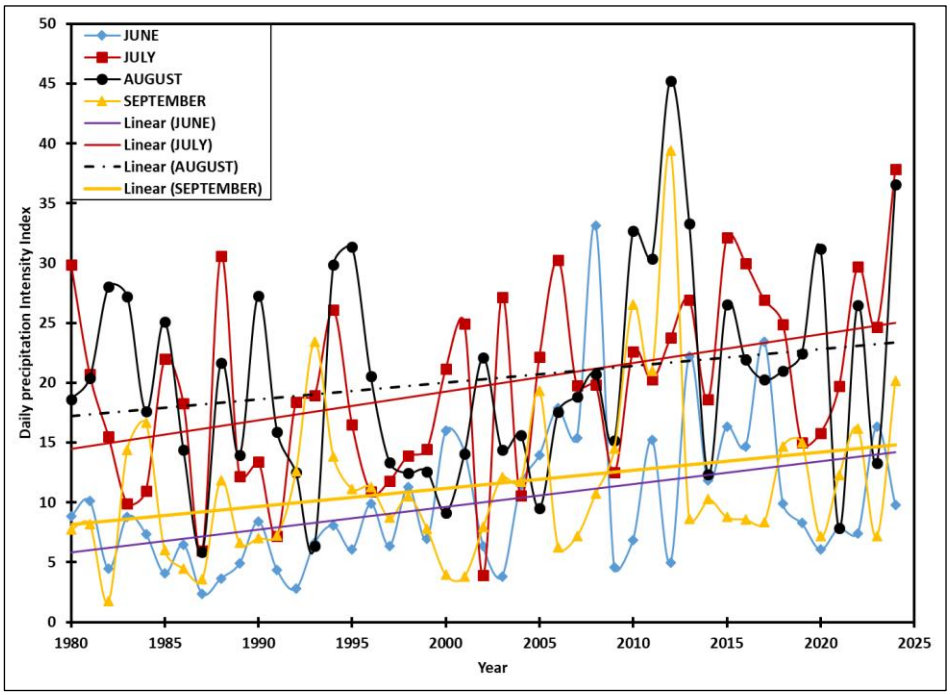


Fig.47: daily precipitation intensity index of monsoon season (total precipitation / no. of wet days)

4.10.11. Monthly Spring Discharge

The monthly spring discharge data recorded from December 2021 to December 2022 shows a clear and well-defined seasonal pattern in the flow characteristics of the springs. Upon preparing and analysing the discharge charts, it becomes evident that the pre-monsoon months—particularly January, February, March, and May 2022—exhibit relatively higher discharge rates in most of the monitored springs (Fig.50), with values frequently exceeding 500 mL/sec. This suggests that during the late winter to early summer period, the springs maintain a steady baseflow, possibly sustained by delayed groundwater release from well-recharged aquifers and limited evapotranspiration losses. Such behaviour may indicate a strong hydraulic connection between the recharge zones and the spring outlets, allowing for consistent discharge even under pre-monsoon climatic conditions.

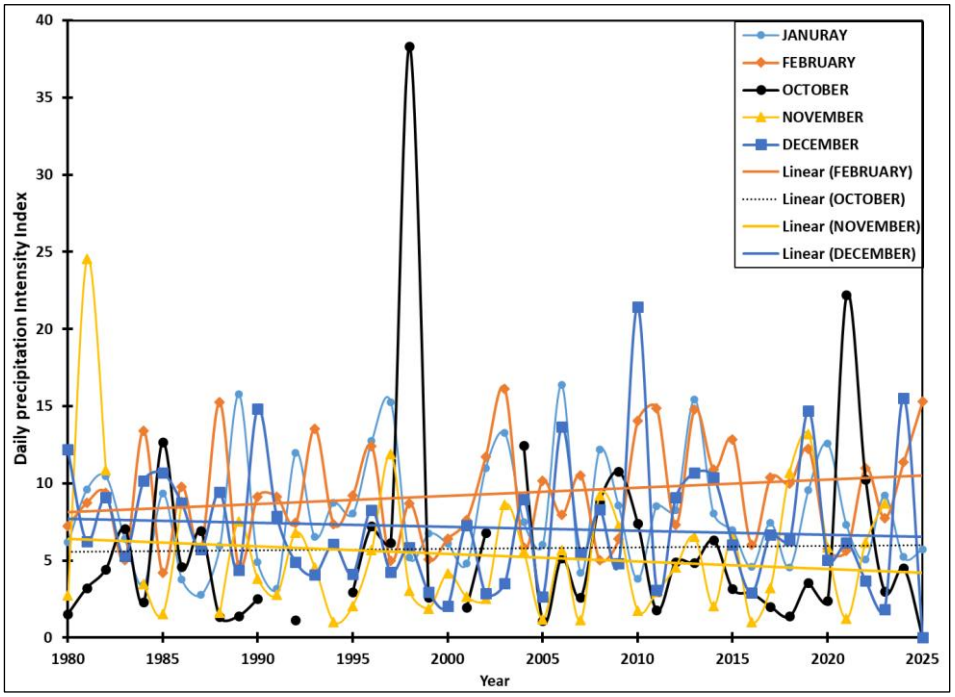


Fig.48: Daily precipitation intensity index of winter season (total precipitation / no. of wet days)

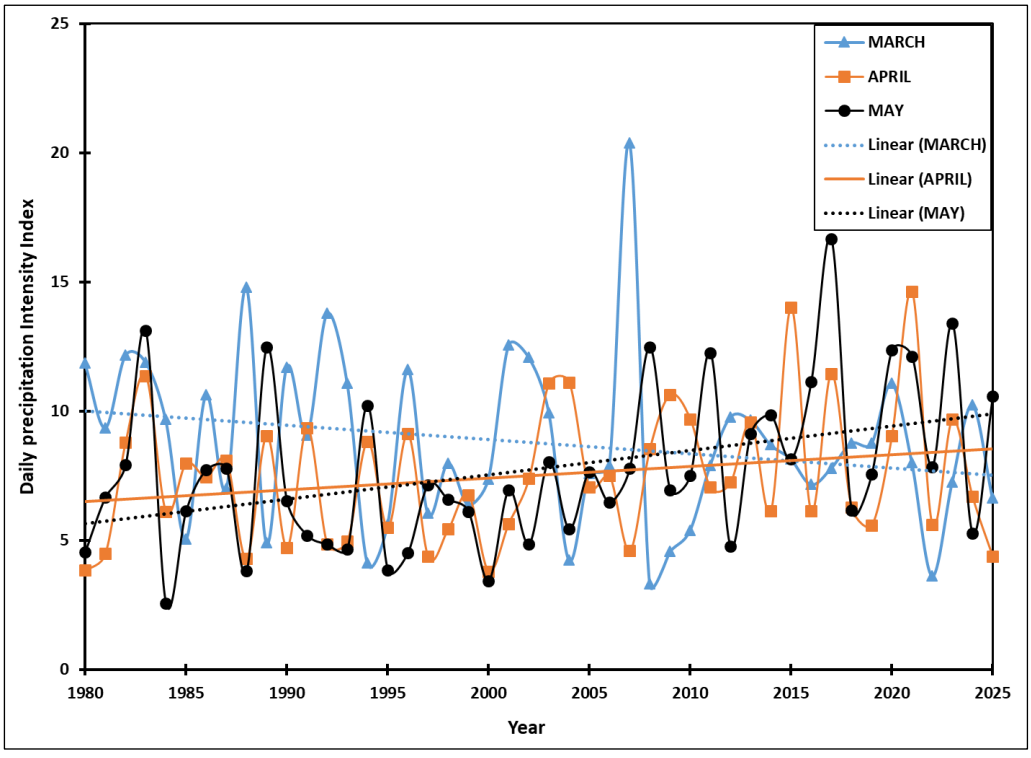


Fig.49: Daily precipitation intensity index of pre-monsoon season (total precipitation / no. of wet days)

Interestingly, another distinct phase of high discharge is observed during the monsoon and early post-monsoon months, particularly in September, October, and November 2022, where the majority of springs again show discharge values above 500 mL/sec (Fig.51). This peak corresponds to the direct influence of monsoonal rainfall, which replenishes the aquifers and enhances subsurface flow, leading to increased spring output. The elevated discharge during this period reflects active recharge processes and efficient transmission of infiltrated rainwater through the hydrogeological system. Overall, the observed discharge pattern highlights the dual influence of sustained groundwater storage during pre-monsoon months and active recharge during monsoon months, demonstrating the seasonal dependence and dynamic response of the spring systems to both climatic and hydrogeological factors.

4.10.12. Relative contribution of precipitation (during different season) of the spring water budget:

The estimation is carried out using the average $d^{18}O$, d-excess compositions of the precipitation and that of the spring water and a three-component mixing mass balance equation, similar to Maurya et al.,2011.

Under the assumption that the average $d^{18}O$, d-excess signatures of the spring water is the result of the mixing of precipitation during pre-monsoon, monsoon and winter precipitation.

The mass balance equation can be expressed as:

$C_{PM}+C_M+C_W=S$

$C_{PM}+C_M+C_W=1$

Where,

C_{PM}= Contribution of pre-monsoon precipitation

C_M= Contribution of monsoon precipitation

C_W= Contribution of winter precipitation

S= Spring water

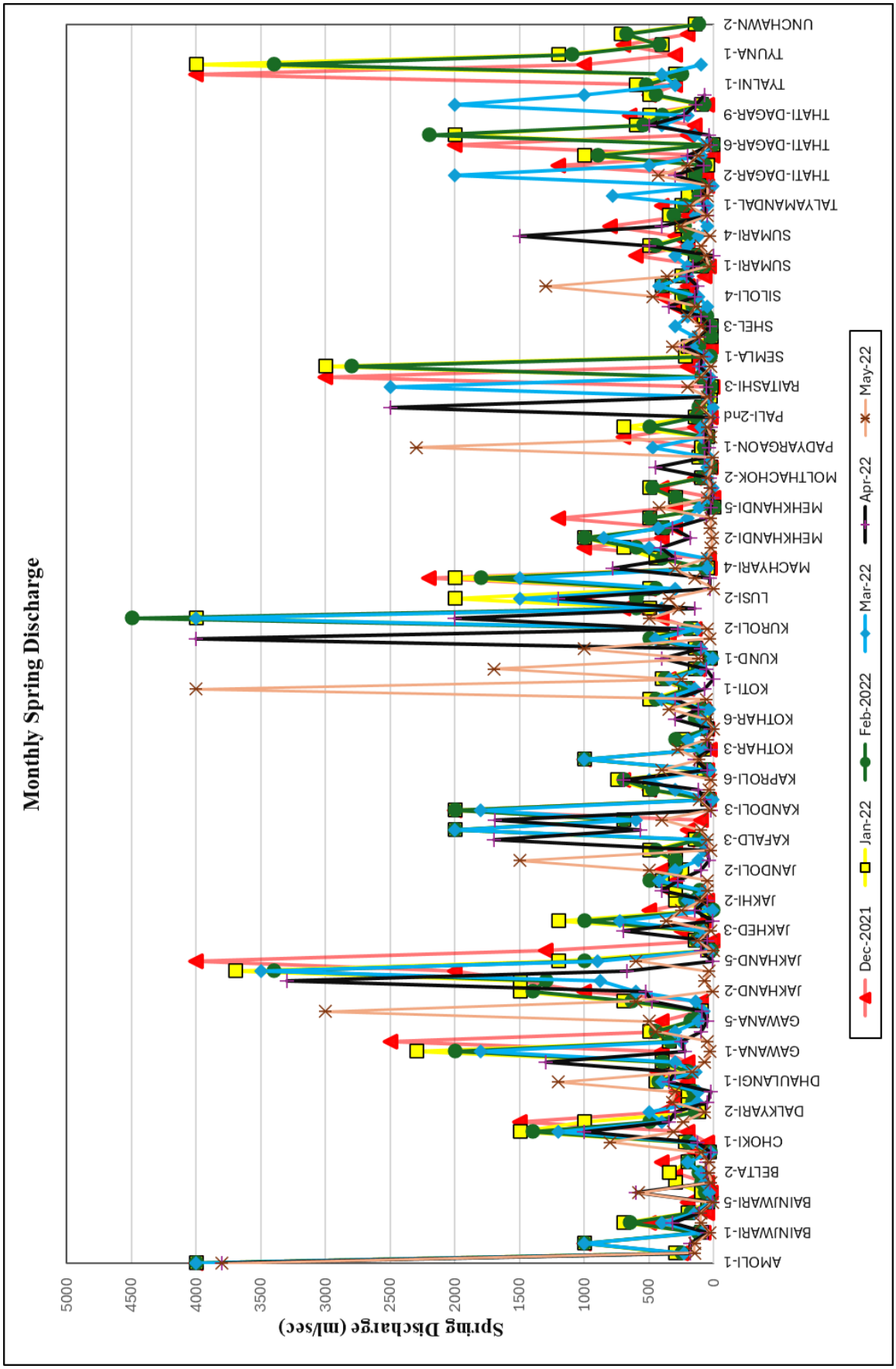


Fig.50: Monthly spring discharge (Dec2021 to May 2022)

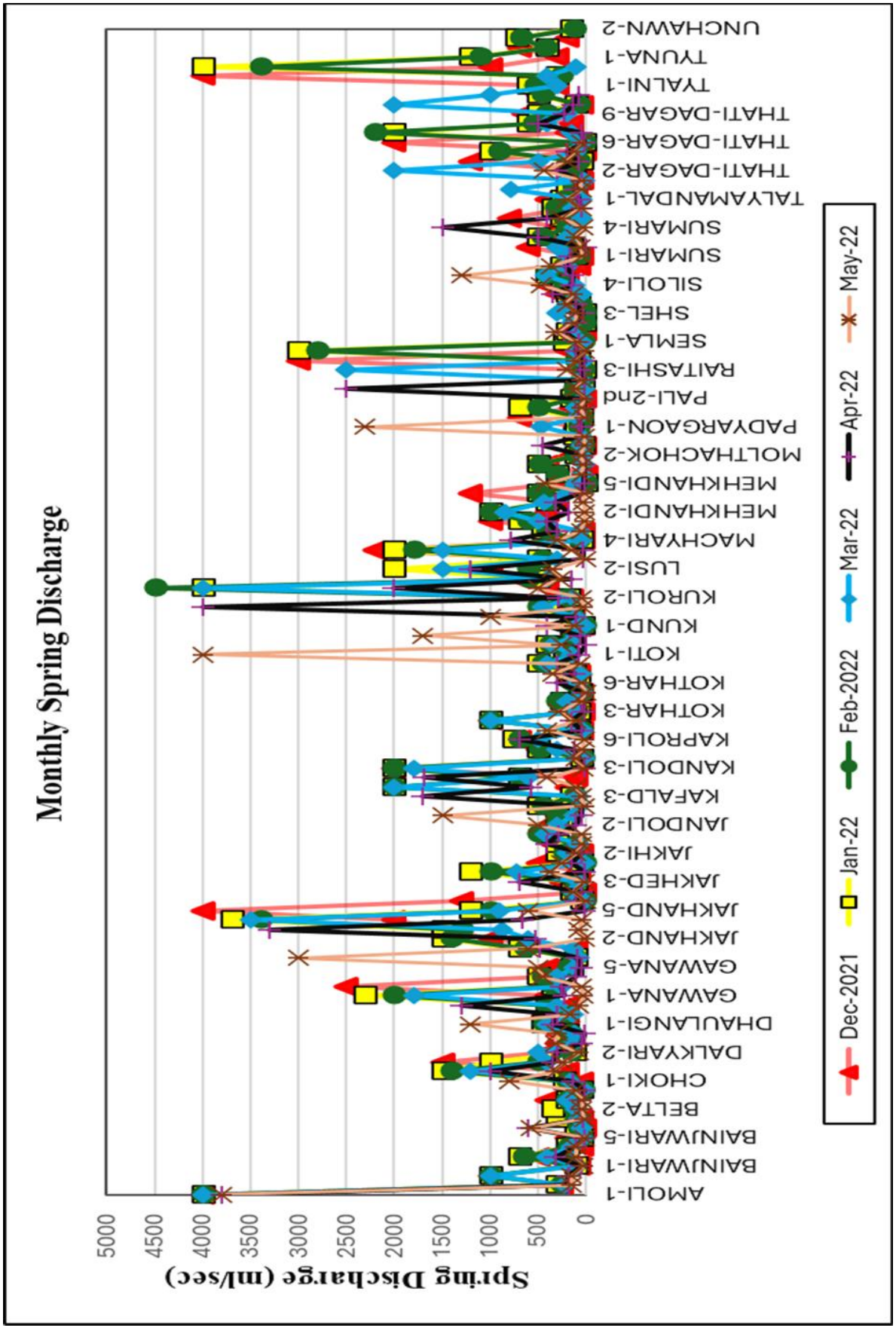


Fig.51: Monthly spring discharge (June 2022 to Dec 2022)

Relative Contribution estimation of Precipitation in Spring Water budget

- $C_{PM} \times \delta^{18}O_{PM} + C_M \times \delta^{18}O_M + C_W \times \delta^{18}O_W = \delta^{18}O_S$
- $C_{PM} \times d_{PM} + C_M \times d_M + C_W \times d_W = d_S$
- C_{PM}, C_M, C_W, yields

$$C_W = \frac{[(\delta^{18}O_S - \delta^{18}O_{PM})(d_M - d_{PM})] - [(\delta^{18}O_M - \delta^{18}O_{PM})(d_S - d_{PM})]}{[(\delta^{18}O_W - \delta^{18}O_{PM})(d_M - d_{PM})] - [(\delta^{18}O_M - \delta^{18}O_{PM})(d_W - d_{PM})]}$$

$$C_M = \frac{[(\delta^{18}O_S - \delta^{18}O_{PM})(d_W - d_{PM})] - [(\delta^{18}O_W - \delta^{18}O_{PM})(d_S - d_{PM})]}{[(\delta^{18}O_M - \delta^{18}O_{PM})(d_W - d_{PM})] - [(\delta^{18}O_W - \delta^{18}O_{PM})(d_W - d_{PM})]}$$

When converted into percentages, C_{PM}, C_M and C_W yield a contribution of **8%**, **83%** and **9%**, respectively.

4.10.13. ^{3}H (tritium) Isotope Dating

Tritium (^{3}H) is a radiogenic and radioactive isotope of hydrogen with a half-life of 12.4 yr. It is an excellent tracer for determining timescales for the mixing and flow of waters because it is considered relatively conservative geochemically and is ideally suited for studying processes that occur on a timescale of less than 100 yr. So, for this study this unique concept has been used to determine the age of the waters so to get the knowledge about the water source of the spring. Tritium content is expressed in tritium units (TU), where 1TU equals 1 ^{3}H atom in 10^{18} atoms of hydrogen. Age is estimated by assuming:

1.TU of the recent monsoon rain is about 12TU and substituting this value from the age Equation.

2. Piston flow (non-mixing).

29 samples of the Takoli gad catchment were analyzed for tritium dating, and the concentration of tritium in the samples varied between the range of 1.5 TU to 14.2TU. According to the tritium concentration in the samples of the area, the age of groundwater is found to be distributed in 6 age brackets

(i) recent
(ii) 3-5 years
(iii) 8-10 years
(iv) 16-18 years
(v) 20-25 years
(vi) above 30 years

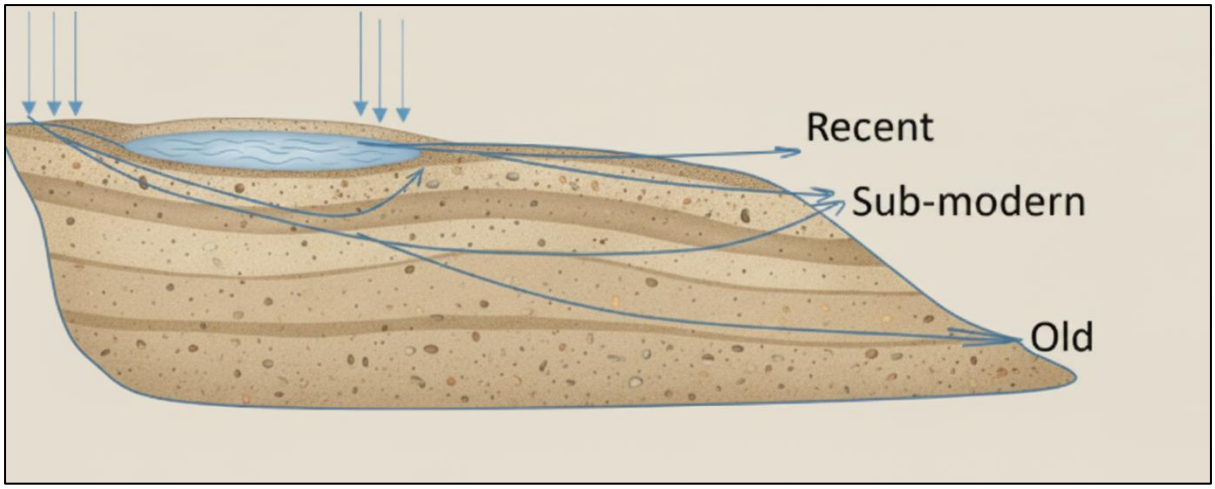


Fig. 52: Showing the mixing of different aged waters

Two major sources are feeding the springs in this area: One is recent monsoon, and another one is old groundwater; mixing of these two leads to six different age groups GW type (Fig. 53). The springs of this area are connected by multiple aquifers, mainly the mid-altitude ones.

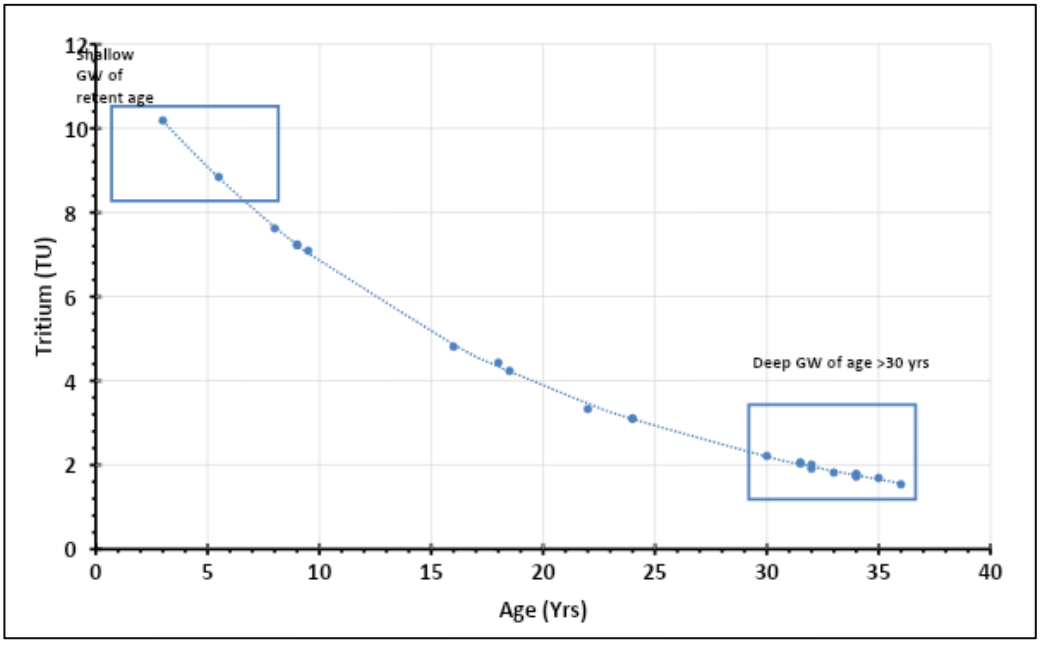


Fig. 53: Relation between tritium unit and age in years.

From the above analysis of tritium, it is observed that at low altitudes the age of the water is younger than those water sample which were collected at higher altitudes. This could be because of the less infiltration of the water, at higher altitudes as due to steeper slopes, most of the rainwater follows the natural gradient of the slopes and flow towards downstream and does not get much time to percolate through the soil layers to reach the aquifers due to which the water levels are deteriorating and the ERT data has also been evident that the ground water

levels of the higher altitude regions and the springs which have dried share the same reason of ground water level at greater depth. Which may be the reason as the water is unable to feed the springs.

5. Delineation of spring recharge elevation:

The stable oxygen and hydrogen isotopes play an important role in identifying the recharge altitudes and zones of springs within a catchment as discussed above. The identification of dominant recharge elevations that contribute to spring flow can be achieved through the comparison of the isotopic signature of spring sources with the altitudinal gradient for $\delta^{18}O$ and δD in rainfall and comparing it to Local Meteoric Water Line (LMWL). The isotopic composition of rainfall exhibits altitude-dependent variations because of temperature-dependent fractionation mechanisms occurring during the processes of condensation and precipitation. The isotopic composition of rain samples collected at different altitudes (Fig.7) along the hillslope exhibits different isotopic signatures, which contribute to the development of a LMWL.

Isotopic signature of spring water falls on LMWL which clearly indicates that, the source of spring water in meteoric water. Any deviation of spring isotopic signature from LMWL may imply the occurrence of fractionation in rainfall before joining the recharge area. Such investigations may be useful for understanding the recharge of spring by other possible sources or combination of sources. The determination of the altitude of the recharge areas of aquifers that supply water to the springs can be achieved by establishing an altitudinal gradient through the measurement of stable isotopic compositions of rainfall at various altitudes within a catchment. The approach is comparing the isotopic compositions of rainfall samples taken at different elevations along the hill slope with those of spring water. This Comparison makes it feasible to establish the altitude range where the isotopic signatures of spring water coincide with the signatures of the appropriate recharge areas in the catchment. The relationship between isotopic compositions and altitude is useful tool for identifying the elevation ranges that contribute to spring water replenishment and establishing the spatial distribution of spring recharge zones.

5.1. Principle

As moist air masses rise over mountains, they cool adiabatically, causing condensation and rainout of heavier isotopes (^{18}O and ^{2}H). Consequently, precipitation becomes isotopically

lighter (more negative $\delta^{18}O$ and δD values) with increasing altitude. This produces a **linear relationship** between isotope ratios ($\delta^{18}O$ or δD) and altitude, typically expressed as:

$$\delta^{18}O = m \times (Altitude) + c$$

where m is the isotopic lapse rate (‰ per meter) and c is the intercept.

This gradient can be derived from measured $\delta^{18}O$ (or δD) values of rainfall collected at different altitudes, or from regional isotopic lapse rates available in literature when only limited local rain data are available.

5.2. Use of Rainwater Isotopic Signature

In the present study, **rainwater samples were collected during the monsoon season(June-September)**, representing the main recharge period for the springs. Since only a single rainfall event was sampled (and not multiple rainfall episodes), the obtained $\delta^{18}O$ and δD values were used directly without the need for **volume-weighted mean** correction.
In cases where multiple rainfall events are available, a weighted average $\delta^{18}O$ and δD value (based on rainfall amount) is typically computed to represent the overall isotopic composition of monsoon precipitation.

5.3. Isotopic Comparison and Projection

For each spring, $\delta^{18}O$ and δD values were plotted against the **rainwater $\delta^{18}O$–altitude line** (constructed either from observed or regional lapse rate data). By projecting the spring water isotopic value onto this regression line, the **corresponding altitude** on the x-axis gives the **estimated recharge altitude** of that spring (Fig. 54).

From the above plot, this isotopic lapse rate obtained from rainwater data is:

$$\delta^{18}O = -0.0031 \times Altitude - 5.50$$

then for a spring having $\delta^{18}O$ = –8.66‰ (Spring Name: Pali 2nd, Spring Altitude 575 m): its estimated recharge altitude can be calculated as:

$$Altitude = \frac{(\delta^{18}O - c)}{m} = \frac{(-8.66 + 5.50)}{-0.0031} \approx 1018 \text{ m}$$

Thus, each spring's $\delta^{18}O$ (or δD) value provides a quantitative estimate of the mean elevation of the recharge area.

The representative springs and their recharge altitude are given below (Table 8) calculated by above $\delta^{18}O$-altitude relation.

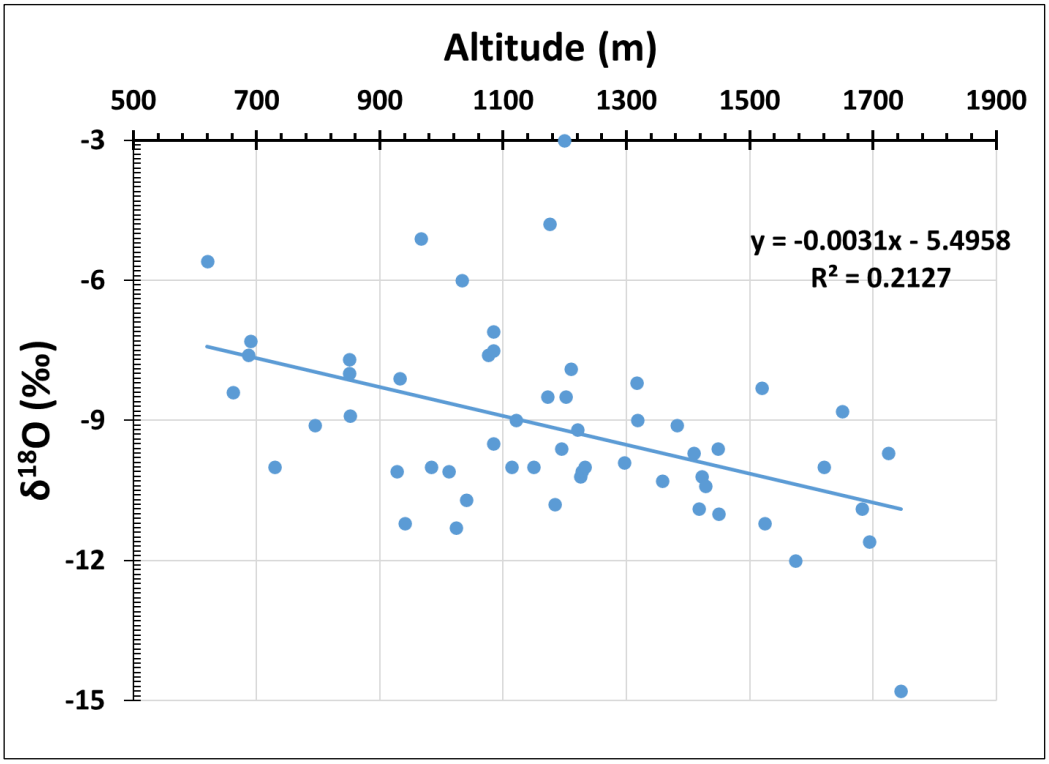


Fig. 54: $\delta^{18}O$ v/s altitude plots for the determination of recharge altitude of springs.

Table 8: Recharge Altitude of the Springs

Spring name	Latitude	Longitude	Spring Altitude(m)	Recharge altitude (m)
PALI(2nd)	78.7193	30.2553	575	1018.19
SILOLI_6(RAIGAD)	78.7321	30.2607	608	1348.55
DANGCHAURA_2	78.7204	30.2582	612	1201.61
DANGCHAURA_1	78.7193	30.2587	621	906.05
SILOLI_5	78.7254	30.2595	626	1181.23
GAHAR_1	78.7174	30.2677	630	919.03
SILOLI_4	78.7321	30.2607	660	1099.68
TAKOLI GADERA	78.7150	30.2722	676.2	1128.84
DAGAR GADERA	78.7150	30.2722	676.2	1084.19
LUSI_2	78.7014	30.2881	699	1235.81
SILOLI_2	78.7326	30.2600	700	869.52
SILOLI_1	78.7324	30.2601	739	913.55
SILOLI_3	78.7324	30.2601	739	865.48
MUNDOLI_1	78.7119	30.2640	751	920.97
URMAN_2	78.7275	30.2527	777	1189.68
JIYALA_2(POKHARI)	78.7435	30.2548	785	898.71
TAKOLI_2	78.6819	30.2999	792	931.85
MALUPANI(PAINDULA)	78.7028	30.2896	805	1102.50

TAKOLI_1	78.6791	30.3012	821	1114.11
AMROLI	78.7044	30.2920	860	945.55
JIYALA_1	78.7413	30.2546	865	952.26
URMAN_1	78.7244	30.2486	865	1127.10
DYULI_2	78.7348	30.2796	866	971.55
LUSI_1	78.7094	30.2811	899	1086.52
PADIYAR GAON_1	78.7410	30.2702	966	1071.05
DYULI_3	78.7360	30.2856	974	1010.40
SEMI SEMLA_1	78.6988	30.2972	980	1082.90
KANDOLI_3	78.6827	30.3095	998	1096.32
JAKHAND_2	78.6486	30.3304	1002	1092.18
KATAL/DOBLIYA_1	78.6939	30.3014	1004	1032.71
JAKHAND_1	78.6490	30.3293	1006	1135.97
JAKHAND_4	78.6560	30.3294	1036	1153.39
JAKHAND_5	78.7072	30.3299	1047	1122.84
JAKHAND_3	78.6537	30.3297	1066	1161.74
KAFALD_2	78.6754	30.2882	1115	1210.00
DHAULANGI+SILOD DHARA	78.6342	30.3336	1154	1332.84
GWANA_3	78.7293	30.3396	1160	1378.52
TYALINI_3	78.5218	30.3087	1177	1459.68
DHAULANGI DHARA	78.6334	30.3336	1189.19	1473.47
SILOD DHARA	78.6336	30.3164	1220.29	1258.32
THATIDAGER(NEW)_6	78.6939	30.3509	1240	1297.94
RAITASI_3(SEASONAL)	78.6833	30.3593	1328	1445.16
BANJELA CHALK	78.6451	30.2997	1380	1435.16
MACHYARI_4	78.6307	30.3215	1442.29	1579.03
KAPROLI_1	78.7426	30.2988	1492	1609.92

5.4. Interpretation

The combined use of $\delta^{18}O$, δD, and altitude provides a robust approach for identifying the recharge altitude and origin of spring waters. Considering that approximately 83% of the spring discharge is derived from monsoonal precipitation, the recharge altitude was calculated using the isotopic relationship between monsoon rainfall and spring water. Based on these calculations, the average recharge altitude of the springs is about 218 m above their respective locations, with values ranging from a minimum of 28 m to a maximum of 740 m. Interestingly, low-altitude springs exhibit higher recharge altitudes compared to those situated at higher elevations.

6. Status of springs in Study Area:

The status of springs in the study area reveals a concerning trend of declining discharge in several key locations. Springs such as MEHKHANDI-5, THATI-DAGAR-6, RAITASHI-3, SHEL-1, SHEL-3, KUND-1, MUSHANGAON-1, RAITASHI-2, BINANI-1, BAINJWARI-5, and JAKHED-1 have consistently shown reduced discharge values over consecutive observation periods and the number of spring which have become seasonal are also increasing, indicating a gradual depletion of groundwater reserves. This continuous decline suggests lower recharge rates, possibly due to reduced rainfall infiltration, land-use changes, or the degradation of recharge zones. The weakening discharge patterns point toward diminished spring sustainability, with potential long-term implications for local water availability. These observations underline the urgent need for spring-shed management practices, including catchment protection, vegetation restoration, and artificial recharge measures to revive and stabilize the hydrological response of these springs.

6.1. Completely dry spring & decrease in spring discharge:

In the study area, a total of 18 springs has been identified as permanently dry (Table 9), indicating a complete cessation of discharge throughout the observation period. These springs, once active sources of groundwater discharge, now remain inactive due to prolonged decline in water table levels, reduced recharge potential, and possible changes in catchment characteristics such as deforestation, slope modification, or land-use alteration. In contrast, 19 springs have been classified as seasonal (Table 9), exhibiting discharge only during limited periods of the year, primarily in the monsoon or immediate post-monsoon months. However, even among these seasonal springs, a notable decline in discharge has been recorded, suggesting progressive depletion of aquifer storage and diminishing recharge efficiency. This trend highlights a concerning shift in the hydrological balance of the region, emphasizing the need for immediate recharge interventions, watershed management, and conservation of spring catchment zones to restore and sustain these vital freshwater sources. A google earth image of the marked critical springs (Fig. 55) is also giver for better understanding of the locations.

Table 9: Critical/Dying springs list

Sl. No.	Spring name	Coordinates	Spring status
1.	PAINDULA 1	30.2889, 78.7123	Seasonal

2. PAINDULA 2	30.2898, 78.7119	Permanent dry
3. ARAILI 1	30.2877 ,78.7145	Permanent dry
4. ARAILI 2	30.2878 ,78.7152	Permanent dry
5. GAWANA 6	30.3327 ,78.7320	Permanent dry
6. GAWANA 8	30.3252 ,78.733	Permanent dry
7. BHALDGAON (KANCHANPURI) 1	30.2948, 78.6636	Permanent dry
8. BHALDGAON (KANCHANPURI) 2	30.2935, 78.6619	Permanent dry
9. MEHKHNADI-5	30.3232, 78.6753	Seasonal
10. JAKHI-1	30.3263 ,78.7244	Seasonal
11. BAINJWARI-4	30.3399 ,78.7159	Seasonal
12. KAPROLI-1	30.2989 ,78.7428	Seasonal
13. KAPROLI_5	30.2916, 78.7459	Seasonal
14. URMAN 3	30.2547, 78.7277	Permanent dry
15. SEL 1	30.3128 ,78.6979	Permanent dry
16. SEL TELLA 2	30.3107, 78.6882	Permanent dry
17. SEL TELLA 3	30.3107, 78.6882	Permanent dry
18. GAHAR-1	30.2463 78.7167	Permanent dry
19. TALYAMANDAL 1	30.3311, 78.6696	Permanent dry
20. RAITASHI 3	30.3592, 78.6832	Seasonal
21. BEFORE RAITASI KOTHAR MOD	30.3572, 78.6938	Seasonal
22. THATIDAGAR 6	30.3532, 78.6915	Seasonal
23. THATIDAGAR 10	30.3532, 78.6972	Seasonal
24. DANGCHAURA 2	30.2580, 78.7204	Permanent dry
25. BOARGAON A	30.2767,78.7019	Permanent dry
26. BOARGAON B	30.2767, 78.7019	Permanent dry
27. TYALINI_2	30.2976, 78.6564	Seasonal
28. TYALNI 3	30.3085,78.6420	Seasonal
29. KUND BHARPURKHAL 1	30.2914 ,78.6644	Seasonal
30. RARAGAR 2	30.3949, 78.7248	Seasonal
31. KOTHAR 1	30.3645, 78.6981	Seasonal

32. BAIRANGNA	30.3381, 78.7001	Permanent dry
33. PAKNIYA_1	30.2868, 78.7452	Permanent dry
34. KAFALD_2	30.2882, 78.6754	Seasonal
35. PIPOLA_1	30.2954 ,78.7047	Seasonal
36. BAINJWARI_4	30.3406 ,78.7159	Seasonal
37. MACHYARI_3	30.4900 ,78.6260	Seasonal
38. UNCHHAUN_3	30.2750 ,78.6674	Seasonal
39. KAFALD_2	30.2882 ,78.6754	Seasonal

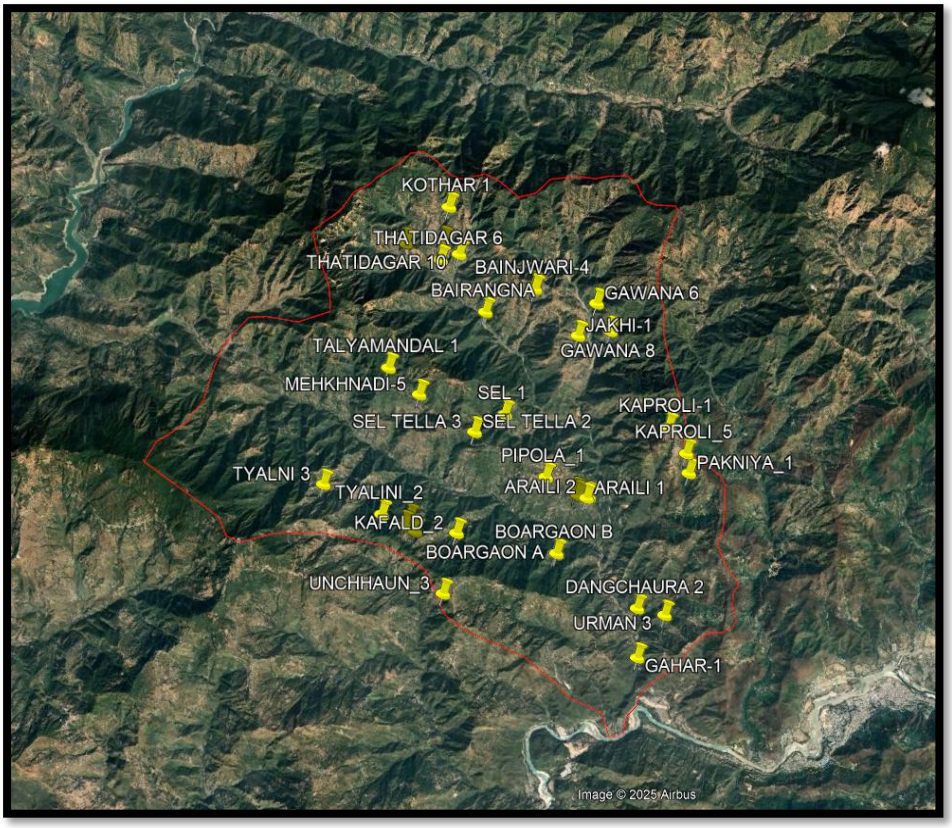


Fig.55: Critical springs places marked on Google Earth.

7. Analytical Hierarchy Process (AHP) for Resource Potential Zonation

The identification and delineation of resource potential zones within a watershed require the integration of multiple interrelated physical, hydrological, and land surface parameters. Owing to the complex nature of watershed systems, where no single factor independently governs resource availability, a multi-criteria framework becomes essential. Among various Multi-Criteria Decision Analysis (MCDA) techniques, the Analytical Hierarchy Process (AHP), proposed by Saaty (1980), has been widely adopted for resource assessment due to its

systematic structure, flexibility, and ability to incorporate both quantitative data and expert judgment. In the present study, AHP was also employed to evaluate and integrate eight key thematic parameters - rainfall, geology, soil, geomorphology, slope, drainage density, elevation, and land use/land cover (LULC)—to delineate resource potential zones of the watershed.

7.1. Conceptual Framework of AHP

AHP is based on the principle of decomposing a complex decision-making problem into a hierarchical structure consisting of goal, criteria, sub-criteria, and alternatives. In this study, the primary goal is the delineation of resource potential zones, while the eight thematic layers represent the decision criteria. Each criterion contributes differently to resource potential, depending on its control over infiltration, storage, runoff generation, and land–water interaction processes. AHP facilitates the relative weighting of these criteria through pairwise comparisons, allowing the influence of each parameter to be expressed numerically.

The method relies on pairwise comparison matrices, where each thematic parameter is evaluated against others using Saaty's fundamental scale ranging from 1 (equal importance) to 9 (extreme importance). This approach ensures that the relative importance of parameters is based on logical judgment rather than arbitrary assignment.

7.2. Selection and Importance of Thematic Parameters

The eight parameters selected in this study represent the dominant climatic, geological, geomorphological, and anthropogenic controls on resource availability within the watershed. Their relative importance was established (Table 10) based on hydrological significance, literature review, and field understanding.

7.3. Pairwise Comparison and Weight Derivation

Thematic class	Sub class	AHP weight	Relative Influence value	Scale value (0-5)
Rainfall	**992-1004.9mm**	**0.327**	**33%**	**1**
	1005-1018.3mm			**2**
	1018.4-1032.1mm			**3**
	1032.2-1045.5mm			**4**

	1045.6-1065mm			**5**
Geology	**Almora Thrust**	**0.209**	**21%**	**5**
	Phyllite			**5**
	Sand,silt & clay			**4**
	Phyllite, Quartz and Shale			**4**
	Limestone & Shale			**3**
	Basic Meta volcanics			**3**
	Quartzite			**1**
Soil	**Typic**	**0.184**	**18%**	**5**
	Dystric			**4**
Geomorphology	**River**	**0.108**	**11%**	**5**
	Younger alluvium			**5**
	Peidmont alluvial plain			**4**
	Mass wasting products			**3**
	Moderately dissected structural hills and valleys			**2**
	Road cutting - anthropogenic			**2**
	Highly dissected structural hills and valleys			**1**
Slope	**0-2 degree**	**0.07**	**7%**	**5**
	2-8 degree			**4**
	8-15 degree			**3**
	15-30 degree			**2**
	30-77.9 degree			**1**
Drainage Density	**Very low**	**0.044**	**4%**	**5**
	low			**4**
	moderate			**3**
	high			**2**
	very high			**1**
Elevation	**507-975 m**	**0.031**	**3%**	**5**
	975-1256 m			**4**
	1256-1544 m			**3**
	1544-1880 m			**2**
	1880-2497 m			**1**

LULC	**Dense forest**	**0.026**	**3%**	**5**
	Agricultural land			**5**
	Moderate/open forest			**4**
	Barren land			**1**
	Built-up/settlement			**1**

Table 10: Thematic layer weightage

Using Saaty's nine-point scale, a pairwise comparison matrix was constructed to evaluate the relative importance of each thematic parameter. The matrix was normalized by dividing each element by the sum of its column, and the average of each row was computed to derive the normalized weight for each criterion. These weights represent the relative contribution of each parameter to resource potential zonation.

To ensure the reliability of the comparison judgments, the Consistency Index (CI) and Consistency Ratio (CR) were calculated. The principal eigenvalue (λ_max) of the matrix was used to compute CI, and CR was obtained by comparing CI with the Random Index (RI) corresponding to the number of criteria. A CR value less than 0.10 indicates acceptable consistency and validates the weighting scheme. In this study, the CR value - 0.071, was found to be within the permissible limit, confirming the logical consistency of the AHP model.

7.4. Integration of Thematic Layers

Each thematic layer was reclassified into subclasses based on its influence on resource potential and assigned ranks ranging from least favorable to most favorable conditions. The final resource potential index was computed using a weighted linear combination approach, where the normalized weights derived from AHP were multiplied with the ranked raster layers. The integration of all weighted layers resulted in a composite index representing the spatial variation of resource potential across the watershed.

The final resource potential map was classified into distinct zones such as very poor, poor, moderate, good, and excellent using natural breaks (Jenks) classification. This zonation reflects the combined influence of climatic, geological, geomorphological, and land surface factors and provides a comprehensive representation of resource availability.

7.5. Significance of AHP-Based RPZ Assessment

The AHP-based approach offers a transparent, reproducible, and scientifically robust Framework for resource potential assessment. By explicitly accounting for the relative importance and interaction of multiple parameters, the method reduces subjectivity and enhances decision-making reliability. The integration of eight carefully selected thematic layers ensures that both surface and subsurface controls are adequately represented, making the resulting resource potential zonation map (Fig. 56) a valuable tool for sustainable watershed management, groundwater development, and land-use planning.

8. Spring Recharge Strategies (Nature Based Solutions)

8.1. Scientific Mapping and Monitoring

- Develop a **Spring Inventory & Monitoring System** integrating GIS layers of slope, LULC, drainage density, ERT aquifer zones, and isotopic recharge altitudes.

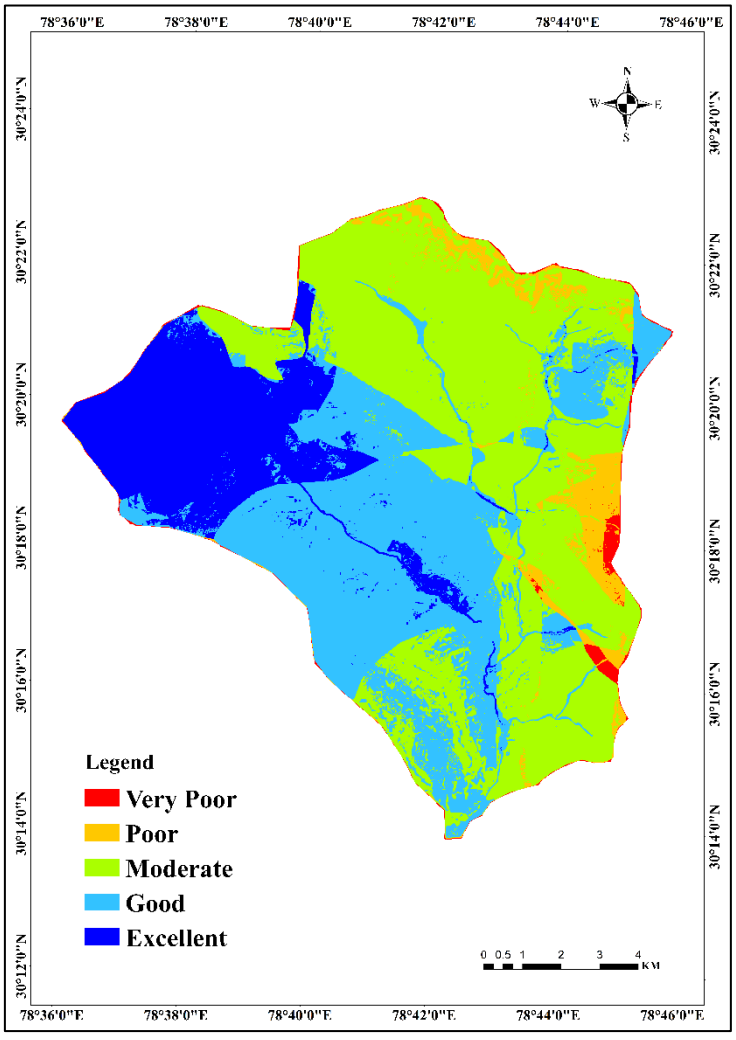


Fig. 56: Resource potential zones map of Takoli Gad

- Install automatic discharge and EC loggers at critical springs to build seasonal datasets.
- Repeat isotope and EC sampling annually to evaluate recharge response and water age.

8.2. Recharge Zone Protection and Enhancement

- Implement **afforestation with native broad-leaf species** (e.g., Quercus leucotrichophora) in upper recharge belts.
- **Ban grazing and construction** in identified infiltration corridors.
- Cleaning of the spring water flow path (cutting the unwanted grownup vegetation in the flow paths)
- Construct **staggered & Continuous contour trenches** (Fig. 57)**, recharge shafts, and percolation tanks** at ERT-indicated infiltration depths.
- Promote **rooftop rainwater harvesting** and link overflow to recharge pits near spring catchments.
- Restricting the diversion of spring water flow through pipes for personal/ agricultural uses.
- Use **bio-engineering measures** - vetiver grass, brushwood check dams (Fig. 58) for slope stabilization.



Fig.57. Continuous contour trenches



Fig.58. Brushwood check dams

8.3. Watershed-Scale Land and Water Management

- Integrate **drainage density and slope data** to design **micro-watershed recharge plans**.
- In high-runoff zones, construct **check dams and gabion structures** to slow flow and enhance percolation (Fig. 59).
- Establish **buffer zones around recharge areas** using LULC-based regulation (no road cutting or quarrying).
- Combine **remote-sensing updates** every 3–5 years to track land-cover change and its hydrological effect.

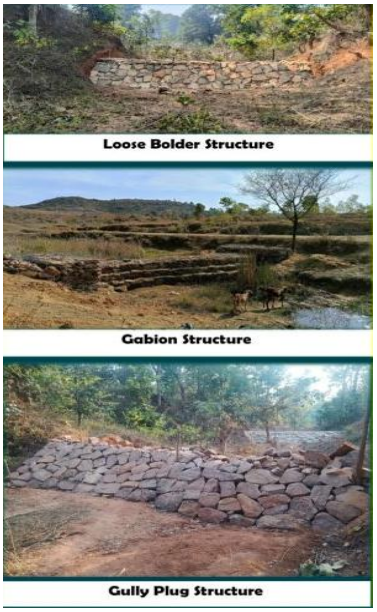


Fig.59: Spring recharge Structure

8.4. Community and Institutional Involvement

- Build **village-level Spring Committees** trained in discharge monitoring, vegetation maintenance, and soil-moisture conservation.
- Conduct **awareness campaigns** (as initiated in the Spring Management Program) focusing on traditional water conservation and ecosystem services (Fig. 60).
- Develop a **local para-hydrogeologist cadre** for continuous spring-shed mapping and intervention maintenance.



Fig.60: Awarness campaign on spring

8.5. Policy and Integration

- Incorporate the spring-shed action plan within District Water Security Plans and align with NMSHE and Jal Jeevan Mission frameworks.
- Recommend mandatory ERT-based aquifer mapping before implementing any rural water supply or construction project in hilly areas.

- Advocate for a State-level Spring Atlas integrating isotopic and geophysical data to guide future conservation investments.

8.6. Expected Outcomes

- **Scientific understanding** of each spring's hydro-geological system, enabling site-specific rejuvenation.
- **Improved discharge** through enhanced infiltration (target > 20 % increase in lean-season flow over 3 years).
- **Reduced water scarcity** and dependence on bore wells, promoting gravity-fed, low-energy water systems.
- **Ecosystem restoration**—forest regeneration, slope stability, and revived biodiversity around spring corridors.

9. SOP for Spring Recharge Area Identification and Recharge Structure

The combined use of $\delta^{18}O$, δD, and altitude provides a unique method for identifying the recharge areas and origin of spring waters. Since approximately 83% of the spring discharge is derived from monsoonal precipitation, the recharge areas were delineated using the isotopic relationship between monsoon rainfall and spring water. Based on this isotopic analysis, the average recharge altitude was estimated to be about 218 m above the spring locations, with values ranging from a minimum of 28 m to a maximum of 740 m. Interestingly, low-altitude springs are recharged from comparatively higher elevations, while high-altitude springs show recharge from relatively nearby or lower zones, indicating spatial variability in the recharge dynamics across the study area.

Considering the estimated recharge altitudes, a set of short-term and long-term management measures have been formulated to mitigate the declining discharge and progressive drying of springs in the Takoli Gad catchment. These measures are designed based on the hydrogeological and isotopic understanding of the recharge zones, aiming to enhance groundwater replenishment, improve spring sustainability, and restore the natural hydrological balance of the area.

9.1. Short-Term Measures (1–3 Years)

Goal: Immediate improvement of infiltration, storage, and discharge at the local spring-shed scale.

Table 11: Short-Term Measures for spring recharge

Focus Area	Measures	Scientific Basis

1. Spring-Outlet Protection	• Clean and de-silt spring chambers, remove debris blocking discharge. • Build small retaining walls and collection tanks to reduce evaporation and surface runoff.	Reduces hydraulic head loss and prevents contamination; keeps spring mouths active.
2. Catchment Moisture Conservation	• Construct contour trenches, staggered pits, and recharge trenches along gentle slopes identified by RS–GIS (through slope map and drainage density map). • Apply mulching and leaf-litter retention near spring zones.	Increases residence time of rainwater and enhances infiltration through topsoil and fractures.
3. Immediate Artificial Recharge	• Build percolation pits, infiltration wells, and soak trenches at ERT-identified low-resistivity (aquifer) zones. • Divert rooftop and runoff water to these pits.	Rapidly recharges shallow fractured aquifers feeding the spring.
4. Vegetative Measures	• Plant local grass species (Vetiver, Napier) and shallow-rooted shrubs near trenches. • Protect existing root-zone vegetation.	Root mats improve soil porosity and check erosion; support infiltration.
5. Flow Diversion & Check Dams	• Install small check dams, brushwood barriers, and gabion structures in nearby gullies or ephemeral streams.	Slows down runoff velocity; allows percolation into sub-surface fractures feeding springs.
6. Community Monitoring	• Start seasonal discharge, pH, and EC recording by local Spring Committees. • Use simple EC–discharge correlation to track recharge response.	Immediate dataset for evaluating intervention efficiency.

9.2. Long-Term Measures (3–10 Years)

Goal — Restore watershed-scale recharge, regulate land use, and ensure sustainable discharge.

Table 12: Long -Term Measures for spring recharge

Focus Area	Measures	Scientific Basis

1. Recharge Zone Protection (Isotopic Altitude-Based)	• Declare upper-slope forest belts (200–700 m above spring altitude) as protected recharge zones. • Restrict Road cutting, quarrying, and construction here.	$\delta^{18}O$ - δD and tritium results show recharge originates from these elevations; protection ensures sustained inflow.
2. Afforestation & Eco-Restoration	• Reforest degraded upper catchments with native broad-leaf species (Quercus leucotrichophora, Rhododendron arboreum). • Maintain mixed canopy for year-round leaf-litter and infiltration.	Dense forest improves infiltration, reduces surface runoff and evaporation losses.
3. Land-Use Regulation (RS–GIS Based)	• Integrate LULC change maps into district land-use planning. • Prevent further conversion of forest/agriculture into barren or built-up land in recharge zones.	Remote-sensing data show forest loss directly correlates with declining discharge.
4. Aquifer Recharge Infrastructure	• Build cascade series of percolation tanks, recharge shafts, and gravity-fed infiltration trenches along fracture corridors revealed by ERT. • Link micro-watersheds through contour-aligned recharge channels.	Re-connect disconnected aquifers and stabilize groundwater table.
5. Continuous Scientific Monitoring	• Annual isotope ($\delta^{18}O$, δD, ^{3}H) sampling to track recharge age and altitude. • Maintain hydro-chemical (EC, TDS, pH) and discharge databases.	Ensures adaptive management and scientific evaluation of interventions.
6. Institutional & Community Capacity	• Train local para-hydrogeologists and Spring-Shed Committees. • Integrate the action plan into Jal Jeevan Mission and NMSHE programs. • A community based action plan (Fig. 61) should be distributed as form of pamphlet or wall drawing to spread awareness.	Builds long-term sustainability through community stewardship.
7. Policy Integration	• Mandate ERT-based aquifer mapping before water-supply projects. • Develop a district "Spring Atlas" with isotopic recharge data.	Embeds science into planning and governance.

9.3. Expected Outcomes

- **Short term:** Through the proposed measures noticeable rise in spring discharge (10–30 %) and improvement in water quality can be observed within 2-3 years.
- **Long term:** Stabilized baseflow, re-established perennial springs, restored vegetation cover, and improved local water security.



Fig.61: Community/Layman Action Plan For Spring Recharge (Image develop through AI)

10. Spring management awareness program:

The Spring Management Awareness Program was organised in Takoli Gad with the objective of sensitising the local community and school students about the critical importance of spring conservation and management in the Himalayan region. Springs are the lifeline of mountain communities, providing essential water for drinking, irrigation, and domestic use. However, over the years, many springs have shown declining discharge due to factors such as deforestation, land-use changes, and reduced groundwater recharge.

During the program, our professor, along with other concerned members and field experts, interacted with school students and residents to explain how springs are formed (Fig. 62), their dependence on rainfall infiltration, and the factors that contribute to their degradation. They emphasised the need to adopt sustainable land and water management practices to ensure long-term availability of spring water. Through engaging discussions, participants were made aware of practical measures for spring rejuvenation, such as constructing recharge pits, contour trenches, percolation tanks, and promoting afforestation in the recharge zones.



Fig. 62: Interaction with students and residents during field visits and sample collection to enhance understanding of watershed management.

The event also highlighted the significance of traditional knowledge and community participation in maintaining local water sources. Locals were encouraged to take ownership of their nearby springs and actively contribute to protection efforts. The interaction with school students aimed to inspire younger generations to understand the value of natural resources and become ambassadors for water conservation. Overall, the program created a platform for meaningful dialogue between experts and the community, strengthening collective efforts toward sustainable spring management and ensuring water security for the future.

11. Specific Recommendations & Conclusions

- **Integrated Scientific Understanding of Spring Hydrology**

The project successfully demonstrated an integrated, multidisciplinary approach-combining remote sensing, Electrical Resistivity Tomography (ERT), stable and radioactive isotope analysis ($\delta^{18}O$, δD, ^{3}H), and hydro geochemistry to understand the recharge mechanisms, flow paths, and decline of spring systems in the Takoli Gad watershed. The results confirm that chemical weathering, carbonate dissolution, and rainfall recharge are the major controls on the hydrochemistry of spring water, with most samples classified as Ca-Mg-HCO_3 type.

- **Identification of Recharge Zones and Flow Dynamics**

Using isotopic ($\delta^{18}O$-δD) and ERT data, the study delineated specific recharge altitudes (~218 m above mean spring location) and confirmed that monsoonal precipitation contributes ~83% of the total recharge. Low-altitude springs were found to have recharge sources at higher elevations, proving that hillslope infiltration and lateral flow dominate recharge processes. This knowledge allows precise targeting of artificial recharge structures in identified recharge belts.

- **Geophysical Insights into Aquifer Conditions**

ERT surveys in critical and dried springs (e.g., Paindula, Talyamandal, Araili) revealed low-resistivity zones (indicative of saturated fractured formations) at depths of 4–14 m, suggesting potential shallow aquifers. Many dried springs were found to have lost hydraulic connectivity due to falling groundwater tables or blockage of fractures, emphasizing the need for recharge trenching, check dams, and vegetation recovery to improve infiltration and stabilize aquifer levels.

- **Land Use and Land Cover (LULC) Changes and Their Impact**

Comparison of 2015 and 2024 LULC data revealed a 60% decline in dense forest cover and a 50% increase in barren land, with moderate forest area expanding slightly due to reforestation

drives. These changes have directly reduced infiltration and increased surface runoff, accelerating spring depletion. Restoration of dense forests and soil conservation in barren zones are therefore essential components of long-term spring rejuvenation.

- **Morphometric and Geomorphological Controls**

The Takoli Gad watershed exhibits steep relief (relief ≈ 1990 m; drainage density 1.75 km/km²) and strong slope gradients (up to 77°), promoting high runoff and low infiltration. However, moderate-to-gentle slope zones identified through GIS analysis are ideal natural recharge areas. Morphometric parameters such as elongation ratio (0.86) and ruggedness number (3.48) indicate a structurally disturbed but moderately permeable terrain, explaining the heterogeneous distribution of spring discharge.

- **Seasonal Hydro geochemical Variations**

Across seasons, TDS ranged from 20-535 mg/L, with the highest values in winter due to prolonged residence time and fertilizer input during Rabi cropping. pH varied from slightly acidic during monsoon to alkaline in winter. These findings suggest rainwater recharge dominance in monsoon and rock–water interaction control in winter, providing evidence for short groundwater residence time and active seasonal renewal of spring water.

- **Social and Capacity-Building Impact**

Beyond scientific analysis, the project emphasized community engagement and training of local para-workers for sustainable spring-shed management. Awareness programs and participatory mapping sessions helped integrate scientific data with traditional knowledge, building a framework for community-based water governance in the Himalayas.

- **Policy and Management Recommendations**
    - Establish a standardized "Spring Rejuvenation SOP" adaptable to other Himalayan watersheds, incorporating isotope–geophysical–hydro chemical integration.
    - Prioritize recharge interventions (contour trenches, vegetative barriers, percolation pits) in gentle-slope, low-drainage-density areas.
    - Restrict construction and deforestation in identified recharge zones.
    - Integrate spring monitoring into state water policies under the Namami Gange and Jal Shakti frameworks.

- Promote dense forest regeneration and soil–moisture conservation through community and government schemes.

- **Overall Conclusions**

The study conclusively establishes that the drying of springs in Takoli Gad is driven by deforestation, land degradation, irregular rainfall, and geological disturbances that have disrupted recharge pathways. However, it also demonstrates that scientifically guided, community-based interventions can effectively reverse this decline. By mapping recharge zones, quantifying recharge altitudes, and correlating hydrogeochemical signatures, the project provides a replicable, cost-effective model for spring rejuvenation applicable across the Indian Himalayan Region.

Budgetary Details:

Items	Total fund received	Expendi-ture incurred during the year 2019-20	Expendi-ture incurred during the year 2020-21	Expendi-ture incurred during the year 2021-22	Expendi-ture incurred during the year 2022-23	Expendi-ture incurred during the year 2023-24	Expendi-ture incurred during the year 2024-25	Expendi-ture incurred during the year 2025-26	Total Expenditure up to 30.09.2025	Balance as on 30.09.2025
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Manpower	2160000	0	812160	1018782	439933	805990	0	0	3076865	(-) 916865
Travel	1500000	31199	67468	219390	350287	0	14360	257353	940057	559943
) rastructure / uipment	4000000	0	3963750	0	0	0	0	0	3963750	36250
) Experimental Charges	2640000	1230000	126130	301621	982249	0	0	0	2640000	0
Contingency	1500000	1839	101038	332069	544450	0	0	199932	1179328	320672
)Overhead Charges	1770000	990000	0	390000	390000	0	0	0	1770000	0
Total	**13570000**	**22,53,038**	**50,70,546**	**22,61,862**	**27,06,919**	**8,05,990**	**14,360**	**4,57,285**	**1,35,70,000**	**0**

Simple SOP for Spring Rejuvenation (For Layman Use)

1. How to Understand Spring Seasonality

Use only two easy-to-measure parameters:

- **Electrical Conductivity (EC)** – tells about dissolved minerals.
- **Temperature (T)** – tells about the type and timing of recharge.

Season	What You Observe	What It Means
Summer (April - June)	EC increases, Temperature rises	Less recharge, more evaporation, concentrated minerals. Spring flow reduces.
Monsoon (July - Sept)	EC decreases, Temperature drops	Fresh rainwater recharges aquifer, dilution of minerals, spring discharge increases.
Winter (Oct - Feb)	EC moderate, Temperature stable	Slow recharge from stored groundwater, steady flow.

If EC keeps rising in all seasons → recharge is weak and the spring is drying.

How to measure:

Use a simple **EC and temperature meter** (available in local markets). Take readings once every month.

2. Step-by-Step Action Plan for Spring Recharge

Step 1. Identify Recharge Area

- Usually lies **above the spring**, often **200–700 m higher** on the hill.
- Mark the forested or gently sloping area where water naturally infiltrates.

Step 2. Protect and Conserve

- Stop grazing, road cutting, or dumping in that recharge area.
- **Plant native trees and grasses** (Oak, Rhododendron, Vetiver).
- Keep leaf litter – it holds moisture.

Step 3. Water Retention Measures

Do small, simple structures along the slope:

- **Contour Trenches** – shallow horizontal ditches to slow down rainwater.



Contour Trenches

- **Percolation Pits** – 1 × 1 × 1 m holes filled with stones near spring catchment.



Percolation Pits

- **Brushwood Check Dams** – small barriers in seasonal drains using twigs or boulders.



Brushwood Check Dams

These help rainwater soak into the ground and recharge the spring.

Step 4. Clean and Protect Spring Outlet

- Remove silt and debris from the spring outlet.
- Build a small **stone wall** or tank to store clean water.
- Avoid using cement directly at the mouth (it can block natural flow).

Step 5. Community Monitoring

- Form a small village "Spring Team".
- Record **monthly EC, temperature, and flow** in a notebook.
- If EC decreases and flow increases after rain, recharge is working.

3. Summary Point Scheme

Step	Action	Expected Benefit
1	Identify recharge zone	Find source of spring water
2	Stop disturbances (grazing, road cutting)	Protect infiltration area
3	Build trenches, pits, check dams	Improve recharge
4	Reforest upper slopes	Increase infiltration
5	Clean spring mouth	Maintain discharge quality
6	Monitor EC & T monthly	Track health of spring

4. Key Message

"If temperature goes down and EC decreases after rain, the spring is healthy and recharging well. If EC keeps increasing and water flow drops, protect and recharge the upper slope immediately."

So overall, this spring reviving measures can be used for any **monsoon dominated Himalayan springs**.