ASSESSMENT OF PHYSICO-CHEMICAL PARAMETERS OF GROUNDWATER OF R. S. PURA, JAMMU, J&K

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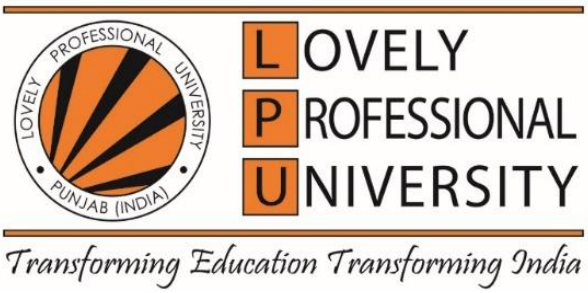

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ABBREVIATIONS

AAS	Atomic absorption spectrophotometer
ADD	Average daily dose
AI	Aggressive index
APHA	American public health association
A_T	Average exposure time
Av.	Average
BDL	Below detection limits
BIS	Bureau of indian standards
BOD	Biochemical oxygen demand
BOR	Borewells
B_W	Bodyweight
CAI- (1&2)	Chloro-alkaline indices (1&2)
CD	Contamination index
CDI	Chronic daily intake
COD	Chemical oxygen demand
Conc.	Concentration
CPCB	Central pollution control board
CR	Carcinogenic risks
CRM	Certified reference material
CSF	Cancer slope factor
C_W	Concentration of contaminant in water
DNA	Deoxyribonucleic acid
DO	Dissolved oxygen
DWQI	Drinking water quality index
EBT	Eriochrome black-T
EC	Electrical conductivity
E-coli	Escheria coli
E_D	Exposure duration
EDTA	Ethylene diamine tetra acetic acid
E_F	Exposure frequency

EWQI	Entropy water quality index
Fig.	Figure
GHP	Government handpumps
GIS	Geographic information system
GWQI	Groundwater quality index
HAV	Human acceptable limit of nitrate
HEI	Heavy metal evaluation index
HHRA	Human health risk assessment
HI	Hazard Index
HP	Handpumps
HPI	Heavy metal pollution index
HQ	Hazard quotient
I_R	Ingestion rate
IS	Indian standards
IWQI	Irrigation water quality index
J&K	Jammu and Kashmir
KI	Kelly's index
LSI	Langlier saturation index
MAR	Magnesium absorption ratio
Max.	Maximum
MH	Magnesium hazards
Min.	Minimum
NPI	Nitrate pollution index
MOA	Methyl orange alkalinity
PA	Phenolphthalein alkalinity
PCA	Principal component analysis
PCS	Principal components
PHE	Public health engineering
PI	Permeability index
POM	Post monsoon
PP	Paper page
PRM	Pre-monsoon

PS	Potential salinity
Rfd	Reference dose
RSBC	Residual sodium bicarbonate
RSC	Residual sodium carbonate
RSI	Ryznar stability index
SAR	Sodium absorption ratio
SEM	Standard error mean
SI	Stability index
SON	Standard organization of Nigeria
SPADNS	Sodium,2-(parasulfophenylazo)-1,8-dihydroxy-3,6-naphthalene disulfonate
SSP	Soluble sodium percentage
TA	Total alkalinity
TH	Total hardness
THQ	Target hazard quotient
UAE	United arab emirates
USEPA	United state environmental protection agency
USSL	United states salinity laboratory
UV	Ultra violet
Vol.	Volume
WHO	World health organization
WQI	Water quality index

UNITS

g	Grams
Kg	Kilograms
Kms	Kilometers
L	Liter
M	Molarity of solution
N	Normality of solution
mg/kg/day	Milligrams per kilograms per day
meq/L	Milliequivalents per liter
mg/L	Milligrams per liter
ml	Milliliters
ppb	Parts per billion
ppm	Parts per million
µS/cm	Micro siemens per centimeter
NTU	Nephelometer turbidity units

SYMBOLS AND FORMULAS

$AgNO_3$	Silver nitrate
As^{3+}	Arsenic ions
B	Boron
$BaSO_4$	Barium sulphate
Ca^{2+}	Calcium ions
$CaCO_3$	Calcium carbonate
Ca-Mg-Cl	Calcium-magnesium-chloride
Ca-Mg-HCO_3	Calcium-magnesium-bicarbonate
Cd^{2+}	Cadmium ions
Cl^-	Chloride ions
Co^{2+}	Cobalt ions
CO_3^{2-}	Carbonate ions
Cr^{3+}	Chromium ions
Cu^{2+}	Copper ions
F^-	Fluoride ions

Fe^{2+}	Iron ions
HCO_3^-	Bicarbonate ions
Hg^{2+}	Mercuric ions
HNO_3	Nitric acid
H_2SO_4	Sulphuric acid
I^-	Iodide ions
K^+	Potassium ions
KCl	Potassium chloride
K_2CrO_7	Potassium chromate
Mg^{2+}	Magnesium ions
$MgCO_3$	Magnesium carbonate
Mg-SO_4-Cl	Magnesium sulphate chloride
Mn^{2+}	Manganese ions
N	Nitrogen
Na^+	Sodium ions
Na%	Sodium percent
NaCl	Sodium chloride
NaOH	Sodium hydroxide
NH_4^+	Ammonium ions
NH_2OH	Hydroxylamine
Ni^{2+}	Nickel ions
NO_2^-	Nitrite
NO_3^-	Nitrate
NO_3-N	Nitrate-nitrogen
OH^-	Hydroxyl ions
Pb^{2+}	Lead ions
pH	Potential of hydrogen ions
PO_4^{3-}	Phosphate ions
Rn	Radon
Se^{2-}	Selenium ions
SO_4^{2-}	Sulphate ions
Zn^{2+}	Zinc ions

DECLARATION

(To be filled by Scholar)

I, **Somalya Dogra**, bearing Registration No. **42000475**, hereby declare that the research work embodied in the Ph.D. thesis titled "**Assessment of physico-chemical parameters of groundwater of R. S. Pura, Jammu, J&K**" submitted to **Lovely Professional University, Punjab,** is the original and Bonafide work carried out by me under the supervision of **Dr. Navdeep Singh, Assistant Professor, Department of Chemistry**, **School of Chemical Sciences and Engineering, Lovely Professional University, Punjab** and Co-supervision of **Dr. Vikas Sharma, Head of Department, Division of Soil science and Agricultural Chemistry, SKUAST-Jammu.**

I further declare that:

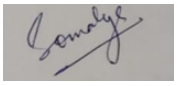
a) The work presented in this thesis is a genuine contribution to the field of research and is a result of investigations carried out by me during the period of my doctoral study.

b) The research work has been conducted in accordance with the academic and ethical standards prescribed by the university.

c) Due acknowledgements and references have been duly given wherever the work of others has been cited or used.

d) The thesis has not been submitted either partly or fully to any other university or institution for the award of any degree or diploma.

I understand that any violation of the above declarations may lead to the cancellation of my degree by the university at any stage.

Signature of PhD Scholar: 

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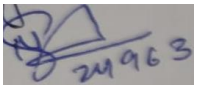
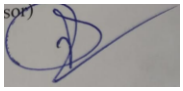
Date: 08-07-2025

CERTIFICATE

(To be filled by Supervisor)

This is to certify that the work reported in the Ph. D. thesis entitled "**Assessment of physico-chemical parameters of groundwater of R. S. Pura, Jammu, J&K**" submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the **Department of Chemistry**, **School of Chemical Sciences and Engineering**, is a research work carried out by **Somalya Dogra**, having registration no. **42000475**, is Bonafide record of her original work carried out under our supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

Signature of Supervisor: 	**Signature of Co-supervisor:** 
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ABSTRACT

Abstract: Groundwater, one of the purest forms of water, is present below the earth's surface and is required for various daily routine activities. But this precious resource is getting polluted because of various activities (natural and man-made), leading to the deterioration of groundwater quality. Continuous and long-term usage of this contaminated water can lead to severe health disorders. Hence, assessment of groundwater quality for drinking and irrigation suitability becomes necessary. Keeping all this in view, present study has been conducted in the Ranbir Singh Pura (R. S. Pura) tehsil of Jammu district, Jammu and Kashmir, Union Territory, India. The study area has been selected for research work because of its agricultural importance and the dependency of residents on the groundwater. Since this area is famous for Basmati rice production and the locals are dependent on groundwater for various activities like drinking, irrigation, domestic etc. As no other source, except rainfall, is available for satisfying their needs. So, immense pressure is there on the groundwater of the study area and is leading to the overexploitation of the groundwater. Hence, present study has been carried out with the objectives- i. To study the physico-chemical parameters of groundwater and health impacts caused on humans and on soil. ii. To check its suitability for drinking and irrigation purposes iii. To evaluate the Water Quality Index of study area using the Weighted Arithmetic Index method. Groundwater samples from different sources (handpumps, borewells, tubewells) were collected for Pre-monsoon (PRM) and Post-monsoon (POM) season of year 2022. 25 sampling sites have been selected for sample collection by following the guidelines laid by APHA (1999). Water samples were analyzed for 15 physico-chemical parameters [pH, Electrical conductivity (EC), Total dissolved solids (TDS), Total alkalinity (TA), Total hardness (TH), Temperature, Turbidity, Sodium (Na^{+}), Chloride (Cl^{-}), Potassium (K^{+}), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), Sulphate (SO_4^{2-}), Nitrate (NO_3^{-}), Fluoride (F^{-})] and 7 heavy metals [Iron (Fe^{2+}), Zinc (Zn^{2+}), Lead (Pb^{2+}), Copper (Cu^{2+}), Chromium (Cr^{3+}), Arsenic (As^{3+}), Nickel (Ni^{2+})]. Water quality index (WQI) has also been applied to classify the groundwater depending upon its drinking water suitability. To check the groundwater suitability for irrigation purpose, irrigation indices such as Irrigation water quality index (IWQI), Sodium absorption ratio (SAR), Permeability index (PI), Residual sodium carbonate (RSC), Sodium percent (Na%) and Kelly's Index (KI). Wilcox and Piper- trilinear diagrams were plotted to categorize groundwater samples for irrigation usage and to depict the dominant hydrogeochemical facies present in the groundwater of the study area. Health hazards have been evaluated using health indices, such as Heavy metal

pollution index (HPI), Heavy metal evaluation index (HEI), Carcinogenic risks (CR), Hazard quotient (HQ), in order to assess the health impacts caused by drinking contaminated water.

Results of the present study reported that pH of the samples of the study area was slightly acidic to alkaline in nature for both the seasons (Pre-monsoon and post-monsoon). Sampling site Satowali (S-14) was reported with higher levels of EC for both seasons. TDS of the groundwater samples was found within the permissible limits, except for 12% of samples where TDS was exceeding the standard limits, of BIS-2012 and WHO-2011 in both the seasons. Sampling sites Satowali (S-14), Rangpur Sadrey (S-17) were found with highest TDS concentration for PRM and POM season. Groundwater samples of the study area were reported within safe limits of BIS-2012 for TA, TH and Na^+. Only bicarbonate (HCO_3^-) ions were found to be present in the groundwater of study area while hydroxyl (OH^-) and carbonate (CO_3^{2-}) ions were found to be absent. Maximum groundwater samples (72%) had high Ca^{2+} concentration, where sampling sites namely, Khamb (S-1), Satowali (S-14) and Jassore (S-23) were found with highest Ca^{2+} concentration. All the sampling sites of the study area, for both the seasons, exceeded the permissible limits of Mg^{2+} laid by BIS-2012 and WHO-2011. High content of Ca^{2+} and Mg^{2+} in the study region indicate calcium and magnesium hardness in the groundwater and was reported due to mineral and salt dissolution, limestone hardness. K^+ concentration was found higher during Pre-monsoon season but found safe in post monsoon season. High concentration of K^+ in groundwater of study area includes application of K^+ rich fertilizers and natural factors like weathering of rocks. Chloride (Cl^-), Nitrate (NO_3^-), Fluoride (F^-), Sulphate (SO_4^{2-}) were reported within safe limits of BIS-2012 for Pre-monsoon and post-monsoon season.

Water quality index classified the groundwater of study area into various classes based on the suitability of water for drinking. For PRM season, WQI classified groundwater samples under good (36%), poor (60%) and very poor (4%) category. Only sampling site S-14 (Satowali) was reported under Very poor category (WQI- 239.35) for PRM season. For POM season, WQI classified groundwater samples under good (52%) and poor (48%) category. In the study region, higher WQI values was reported during POM, which was due to effective leaching of ions, over exploitation of groundwater and anthropogenic activities.

IWQI classified 96% and 88% samples under 'No to moderate' restriction category during Pre-monsoon (PRM) and post-monsoon (POM) season respectively, indicating water suitability for irrigation purposes. Sampling site S-14 (Satowali) was reported unfit for

agricultural use as per IWQI in both the seasons, thus restricting its use for irrigation. Results of the present study revealed that the groundwater is safe for agriculture usage as per Na%, SAR, KI and RSC water classification. According to PI classification, 68% and 40% samples have been classified as suitable/safe for irrigation during Pre-monsoon (PRM) and post-monsoon (POM) season respectively. Wilcox diagrams classified majority of groundwater samples under 'Excellent-good' category. Piper- Trilinear plots revealed that $MgCO_3$ followed by Mg-SO_4-Cl to be the prominent hydro chemical species in the groundwater of study area. It was also reported by the present study that the groundwater of the study area contains more strong acids and alkaline earth metals as compared to alkalis.

Water samples (100% and 40%) were reported beyond the safer limits of Fe^{2+} given by BIS-2012 during Pre-monsoon (PRM) and post-monsoon (POM) season respectively. Gharana (S-22) was found with highest Fe^{2+} concentration for both the seasons. For PRM season, 76% samples and for POM season, 68% samples were exceeding the BIS-2012 limits of Cu^{2+}. Satowali (S-14) and Suchetgarh (S-15) were reported with highest Cu^{2+} concentration in both the seasons. Pb^{2+} was below the detection limits at many sits at ppm level but wherever detected, it was above the safer limits set by BIS-2012 and WHO-2011. Satowali (S-14) sampling site followed by Suchetgarh (S-15) found with highest Pb^{2+} concentration in both the season. High concentration of Pb^{2+} in groundwater of study area occurs due to some non-point sources like atmospheric deposition which later on settle down on soil and lead to leaching of Pb^{2+} in the groundwater, agricultural activities such as usage of fertilizers and pesticides in excess, natural factors such as geological composition of rocks. Chromium (Cr^{3+}) concentration was exceeding the set limits at all the sampling sites of study area in both the seasons, indicating chromium contamination due to high usage of inorganic fertilizers particularly phosphatic fertilizers in the study area. Concentration of Ni^{2+} in both the seasons was below the detection limits (at ppm levels). No zinc contamination was observed for Pre-monsoon (PRM) and post-monsoon (POM) season as the concentration of Zn^{2+} was found within the permissible limits of BIS-2012. At some sampling sites, Arsenic was not detected at ppm levels but at rest of the sampling sites, it was found that 28% of samples in PRM and 36% samples in POM exceeds the permissible limits of As^{2+}as prescribed by BIS-2012 and WHO-2011 standards

According to Nitrate Pollution Index (NPI), no nitrate pollution was reported in the study area for both the seasons. Pb^{2+} and Cr^{2+} contamination was reported as per HPI. In the study area, high contamination of Cu^{2+}, Cr^{3+} and Pb^{2+} was found according to HEI. High Carcinogenic risks for Pb^{2+}, Cr^{3+} and Cu^{2+} (for women, men and children) were reported.

Children were found more susceptible to carcinogenic risks as compared to adults. Non-carcinogenic risks in the form of HQ were calculated and results revealed that the groundwater was found contaminated with high concentrations of Zn^{2+}, Fe^{2+}, Cu^{2+} and Pb^{2+} during PRM season. Overall, the study area was found contaminated with the concentration of Cu^{2+}, Cr^{3+} and Pb^{2+}. Domestic waste, agricultural activities such as excessive usage of pesticides and fertilizers and plumbing could be the causes of high concentration of these heavy metals in the study area and can lead to severe health impacts of locals such as stomach ache, liver and kidney damage, enhanced blood pressure in adults etc. PCA was also carried out to assess the dominant species in the groundwater in which first principal component (PC1) indicates EC, TDS, TA, TH, Cl^-, Mg^{2+}, Pb^{2+}, NO_3^- as the loading factor and can be concluded that these variables were totally hydro-chemical and were supposed to be originated from geogenic sources. Second Principal component (PC2) of pre-monsoon season contains Zn^{2+} and Pb^{2+} while of post-monsoon season contains K^+ and Pb^{2+} depicting the usage of agricultural fertilizers, pesticides and interference of human activities. In order to combat with the problem of pollution in the study area, some suggestions such as use of organic fertilizers instead of organic fertilizers, groundwater used for drinking must be treated before consumption, continuous monitoring and groundwater suitability assessment has been recommended.

Chapter 1

Introduction

Introduction

Water is precious natural resource needed for the living life on the Earth. It is the elixir of life and everyone living on earth need it for their day-to-day activities. It forms the important constituent of ecosystems and keeps environmental conditions healthy, alive and sustainable. From our body to the ecosystem, the uses of water are limitless. It is used for different purposes such as drinking, irrigation, domestic, hydropower generation, livestock, recreational and industrial purposes (Dogra et al. 2023; Kouser et al. 2022; Sudan S, 2018). Out of the total water present on earth's surface, 97% is classified as Saline water with very high salt content and unfit for human consumption whereas rest about 3% is fresh water which can be consumed. Fresh water includes water in lakes, rivers, ponds, streams, wells, springs and groundwater (Khadse et al. 2016, Sudan S, 2018, Kaur et al. 2019). Distribution of water on earth's surface is given in Fig. 1.

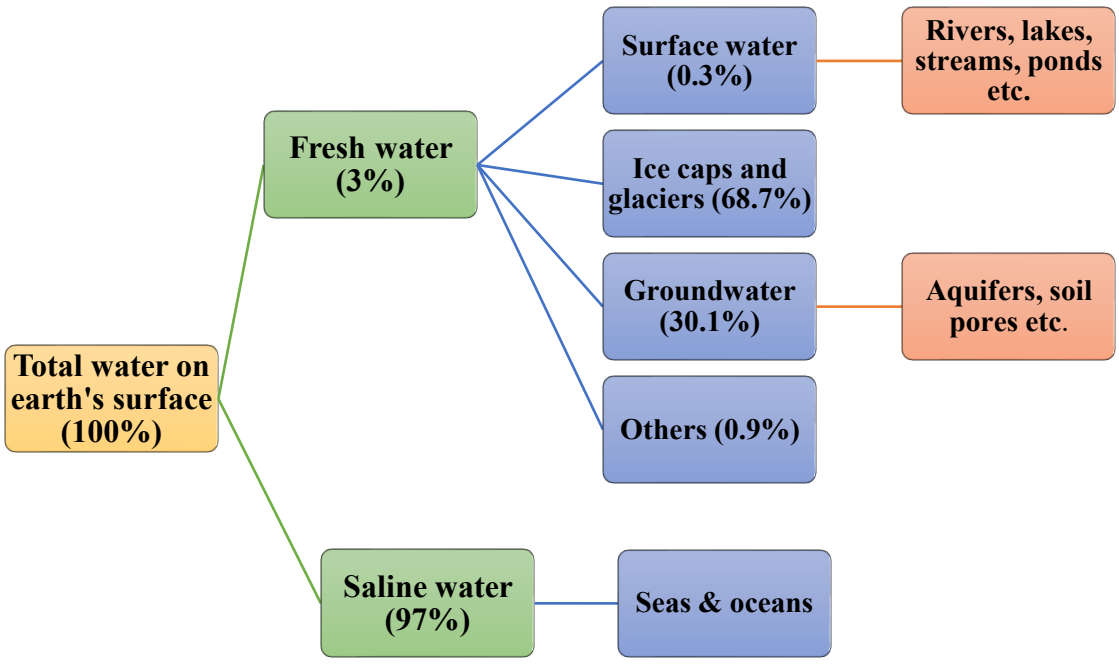

Fig. 1. Distribution of water on earth's surface (De. A. K., 2010)

1.1 Groundwater: uses and importance

Groundwater is type of water available below the earth's surface. Groundwater is one of the purest forms of water because it gets filtered in soil column through ion exchange, filtration and by the action of anaerobic bacteria (Kaur et al. 2019; Sudan S, 2018). Groundwater generally contains no suspended matter, is colourless, odourless, free from pathogenic bacteria unless contaminated by human activities. It is an important source of fresh water used for domestic, agricultural and industrial purposes in most of the rural and urban areas across the globe (Sudan S, 2018; Ahada and Suthar, 2018; Kaur et al. 2019; Li et al. 2021). Globally, groundwater is estimated to meet nearly 35%, 30%, 20% and 15% needs of water for food production, drinking, agriculture, industry and mining purposes respectively (Kouser et al. 2022; Kumari and Rai, 2020; Tegegne et al. 2023; Li et al. 2021; Adimalla et al. 2018; Sharma et al. 2021). In the entire world, groundwater consumption is highest in India i.e., approximately 250 billion m^3 per year (Gautam et al. 2023; Sharma et al. 2021; Kumar et al. 2020).

India holds 2.2% of the global land, 4% of the world's water resources and is supporting more than 16% of the world population. Groundwater is the chief water resource used for the developmental activities in India (Jasrotia et al. 2019; Yadav and Kumar, 2020). In India, nearly 89%, 9% and 2% of water is used for irrigation purposes, domestic purposes and industrial uses respectively (Ahada and Suthar, 2018). It is reported that 80% of Indian rural population and more than 50% of the urban population depends on groundwater for satisfying their different needs (Saraswat et al. 2019; Ahada and Suthar, 2018; Ramakrishaniah et al. 2019; Jain and Vaid, 2018). Groundwater accounts for about 88% of the safe drinking water in rural areas (Singh et al. 2012). According to a national sample survey, 56% households get drinking water from hand pump or tube well, 25% based on piped water and 14% from open wells (Singh et al. 2020).

Most of the human activities required ample quantities of water to satisfy the increasing demands of food grains (Sudan S, 2018). Due to increase in demand of water and lesser availability of surface water, people are shifting to groundwater resources for drinking, irrigation and other purposes (Beyene et al. 2019). Overexploitation and injudicious usage of groundwater resources are resulting in degradation of groundwater quality and lowering of groundwater level (Gautam et al. 2023). Thus, access to safe and clean drinking water is becoming the challenge and is posing issues to human health (Boateng et al. 2016; Mahaqi et al. 2018).

1.2 Groundwater contamination and ill impacts

Contamination of groundwater can be described as the accumulation of unwanted substances in groundwater of an area either by anthropogenic activities or by natural phenomenon. Natural processes, viruses and bacteria, urbanization and industrialization, uses of chemicals in industries, frequent use of fertilizers and pesticides in farming fields, animal and human waste, unplanned drainage systems, increase in pollution, population explosion, heavy metals etc. are some of the causes for the degradation of the groundwater quality (Kaur et al. 2017; Ahada and Suthar, 2018; Saraswat et al. 2019; Li et al. 2021; Tegegne et al. 2023). Due to contamination by the above factors, groundwater uses are adversely affecting the plant growth, soil fertility, animal and human health (Rao S, 2006; Singh et al. 2013). Groundwater pollution is a serious problem worldwide including India. Contaminants in groundwater are usually colourless and odourless and contamination done by these substances are generally irreversible i.e. once water gets contaminated, it is quite hard to bring it back to its original state (Chakraborti et al. 2015; Li et al. 2021; Dogra et al. 2023). Groundwater contaminants entered into the body of humans through various sources and can magnify in the human, animal and plant body through the food chain and soil (Abdelhafez et al. 2021; Alidadi et al. 2021; Mjemah and Mariki, 2021; Kaur et al. 2019; Khanoranga and Khalid, 2019; Singh et al. 2013). The ingestion of contaminants from groundwater is a serious issue in agricultural and rural areas where local people drink groundwater directly from groundwater sources.

India is developing country in which development of core industries like metals, chemicals, fertilizers, petroleum etc. and other industries such as pesticides, plastics, detergents, solvents, paints, dyes are increasing. All the disposed waste and their effluents are affecting water bodies by polluting it, thereby changing the physico-chemical properties of water such as pH, total dissolved solids (TDS), electrical conductivity (EC), total alkalinity (TA) etc. The disposal of wastes may contain heavy metals like lead, nickel, chromium etc. which may lead to heavy metal contamination of natural habitats (i.e. water, soil and air ecosystems) (Singh et al. 2013; Adimalla et al. 2018; Kaur et al. 2019; Dogra et al. 2023). Drinking groundwater contaminated with the heavy metals is causing diseases such as arsenic poisoning, iron overload disease, bronchitis and various life-threatening diseases in different areas of the World (Kouser et al. 2022; Gautam et al. 2023). Drinking contaminated water can have severe impact, on human health, which are chronic and are hard to detect (Chakraborti et al. 2015; Li et al. 2021). Kumar et al. 2020 reported that nearly 663 million people in the world is using contaminated water. In developing countries

like India, about 80% of water related diseases are either linked to unsuitable drinking water quality or poor water conditions (Khanna P, 2019; Ramakrishaniah et al. 2019). Nearly 37.7 million people have been suffering from water-borne diseases in India, out of which 1.5 million people die every year (Kumar et al. 2020). So, Physico-chemical parameters and human health risk assessment, by applying various indices, has been widely used to ascertain the ill-effects of chemical intake from groundwater among various populations (Guo et al. 2021; Gabr et al. 2020).

1.3 Role of physico-chemical parameters in assessing groundwater quality

Quality of water pertains to its physical and chemical characteristics with regard to its suitability for different purposes. Quality of ground water is affected by natural as well as man-made pollution factors/sources. Presence of pollutants in the rocks and sediments occurs naturally while human activities can also affect the properties of the groundwater due to pollution, use of farming chemicals, effluent discharges, soil erosion etc. (Jain and Vaid, 2018; Beyene et al. 2019; Gugulothu et al. 2022; Dogra et al. 2023).

Physico-chemical parameters such as pH, Hardness, Alkalinity etc. plays an important role in assessing the groundwater quality. Drinking groundwater having high or low pH can have adverse effect on the eyes, skin and mucous membrane in humans (Akter et al. 2016; Bhunia et al. 2018; Abdelhafez et al. 2021). High Electrical Conductivity (EC) occurs due to several salt and mineral concentration in groundwater leading to high salinity (Gautam et al. 2023; Kouser et al. 2022; Shil et al. 2019). Drinking water with elevated TDS levels can cause unfavourable physiological reactions, gastrointestinal irritation and can change the taste of water (Chen et al. 2019; Wagh et al. 2020). High level of alkalinity indicates higher levels of calcium carbonate ($CaCO_3$) in water which can decrease the water's acidity (Gugulothu et al. 2022). TH can cause scaling of water pipes, closure/blockage of industrial pipes and even health issues (Vasanthavigar et al. 2010; Gulgundi and Shetty, 2018; Gabr et al. 2020). Consumption of high concentration of magnesium (Mg^{2+}) and calcium (Ca^{2+}) in drinking water can lead to bladder or kidney stone, hypertension, osteoporosis, colon cancer etc. (Saleem et al. 2016; Sudan S, 2018; Wagh et al. 2020). Drinking water contaminated with high concentration of Sodium (Na^{+}) and Potassium (K^{+}) can lead to many lethal diseases namely, hypertension, kidney damages, shortness of breath, headache, heart failure etc. (Sudan S, 2018; Wagh et al. 2020; Lanjwani et al. 2020). High chloride (Cl^{-}) content in groundwater can lead to the damaging of metallic pipes, structures and also impacting the agriculture crops (Kumar et al. 2009; Vardhan et al. 2015). Small

concentration of Fluoride (F^-)in drinking water is important for dental health while its excessive concentration can lead to skeletal and dental fluorosis (Yadav and Kumar, 2020; Subramaniyan et al. 2022). Excessive concentration of nitrate (NO_3^-) in drinking water can lead to thyroid disease, hypertension, blue baby syndrome/ Methemoglobinemia in children (a condition in which baby's skin becomes blue because of decreased amount of haemoglobin in the blood) and can also lead to growth of algae and other organisms that cause undesirable taste and odour in water (Abbasnia et al. 2018(a); Wagh et al. 2020). Sulphate (SO_4^{2-}), when present in excess in water used for drinking can produce laxative effect, catharsis, dehydration and gastrointestinal irritation on humans (Wagh et al. 2020). Thus, to check the quality of the ground water, the analysis of physicochemical parameters of water plays an important role. The major groundwater parameters, which decide ground water suitability for drinking and irrigation includes pH, Electrical Conductivity (EC), TDS, Total Hardness (TH), Nitrate (NO_3^-), Calcium (Ca^{2+}), Chloride (Cl^-), Fluoride (F^-), Magnesium (Mg^{2+}), Sulphate (SO_4^{2-}), Total Alkalinity (TA), Carbonate (CO_3^{2-}), Bicarbonate (HCO_3^-), etc. (Saleem et al. 2016, Acharya et al. 2018, Mallick et al. 2018, Chen et al. 2019, Saraswat et al. 2019). Water Quality Index (WQI) determines the overall quality of ground water (Vasanthavigar et al. 2010, Ramakrishanaiah et al. 2009, Acharya et al. 2018).

In drinking water, enhanced concentration of Iron (Fe) can lead to various human health risks such as stomach problems, liver fibrosis, gastrointestinal problems, zinc absorption etc. (Palmajumdar et al. 2021; Akter et al. 2016; Khanna P, 2019; Kumar et al. 2017). Ingestion of zinc (Zn) in higher amount can cause anaemia, kidney related issues, diarrhoea, stomach & pancreatic disorders etc. (Kumar et al. 2017). If concentration of copper (Cu^{2+}) in drinking water is too low or too high, it can lead to various health impacts such as anaemia, kidney and liver damage, digestive disturbances, bitter or metallic taste, effect on central nervous system etc. (BIS-10500, 2012; Sudan S, 2018; Alidadi et al. 2019). Drinking water having high contamination of Lead (Pb^{2+}) can threaten humans with anaemia, burning in the mouth along with swelling of the gastro-intestinal tract, mental confusion, central nervous system damage and even can lead to death (Kaur et al. 2019; Raja et al. 2021; Sudan S, 2018; Alidadi et al. 2019). Hexavalent state of chromium (Cr^{6+}) can lead to lung tumours as it is cancerous, respiratory problems, ulcers, dermatitis (Sudan S, 2018; BIS- 10500 (2012); Alidadi et al. 2019). Increased level of heavy metals like Ni^{2+}, Cr^{6+}, As^{2+} in drinking water can aggregate in the body tissues and can cause health issues

such as lung cancer by nickel (Khanoranga and Khalid, 2019; Sudan S, 2018; Raja et al. 2021).

Since heavy metals can pose serious health impacts, so, their determination in groundwater is of prime importance. Thus, monitoring of water quality for the purpose of drinking will help to determine the health risks caused by the heavy metals on human health. Various Health risk assessment indices used by different researchers are Human Health Risk Assessment (HHRA), Heavy Metal Evaluation Index (HEI), Average Daily Dose (ADD)/ Chronic Daily Intake (CDI), Carcinogenic Risks (CR), Heavy Metal Pollution Index (HPI), Target Hazard Quotient (THQ) (Khanoranga and Khalid, 2019; Paneerselvam et al. 2020; Kaur et al. 2020; Abdelhafez et al. 2021; Raja et al. 2021).
Suitability of irrigation waters also needs to be evaluated as it may include some unwanted constituents. Groundwater quality as well as hydro-chemical characteristics of groundwater can be related to pollution level in an area where intense agricultural activities are going on (Acharya et al. 2018; Baloch et al. 2021). The penetration of pollutants through the unsaturated zones of soil and get entered into the groundwater, where they deteriorate the groundwater quality. Now, when this water is used for irrigation, then it can have direct impact on the permeability and fertility of soil as well as on production of crops because of ion exchange reactions between soil and groundwater (Baterseh et al. 2021; Saraswat et al. 2019). Concentration of sodium ions in groundwater is of importance of interest because of its reaction with soil to reduce the permeability, causing poor internal drainage of soil. It is evident from studies conducted by Madhav et al. 2018, Shil et al. 2019 and Chen et al. 2019 that the sodium-enriched soils do not support plantation. The irrigation water evaluation of groundwaters of different regions have been carried out by many researchers and reported that various indices are helpful in assessing irrigation water quality such as Irrigation water quality index (IWQI), Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), Sodium Percent (Na%), Permeability Index (PI), Kelley's Index (KI), etc. (Vasanthavigar et al. 2010; Singh et al. 2012; Madhav et al. 2018; Shil et al. 2019; Raheja et al. 2024). This will give an overview of chemical nature of groundwater and is helpful in assessing whether the groundwater is suitable for the health of agriculture and soil.

It has been reported by different authors that the groundwater is unsuitable for irrigation or drinking purpose when its physico-chemical parameters exceed the set standards across the different regions of the world (Ishaku J M, 2011; Bernard and Ayeni, 2012; Maglangit F, 2014; Houatmia et al. 2016; Soleimani et al. 2018; Chen et al. 2019; Loh et al. 2020;

Guo et al. 2021; Osta et al. 2022). A study conducted in Reasi district of Jammu and Kashmir reported that the carcinogenic risks caused by intake of metals through water is 7.6×10^{-6}–1.1×10^{-4} (Kaur et al. 2019). Health Risk assessment of water by Paneerselvam et al. 2020 found children to be at greater risk when equated with males and females (in Yercaud region of Tamil Nadu, India). Raja et al. 2021 reported that population of Virudhunagar locality of Tamil Nadu, India was suffering from high Pb^{2+} and Cr^{6+} health risks. The study conducted by Mohammadi et al. 2019 in Khorramabad, Iran reported high carcinogenic risks for Ni^{2+}, Cd^{2+}, Cr^{3+} and Pb^{2+} as their values were exceeding the acceptable limits i.e., 1×10^{-6} in the study area. 20 from 95 samples found with greater health risks in children on comparison with adults in Sindh, Pakistan. Carcinogenic risks from drinking water for children and adults were reported to be 1.33×10^{-4} and 7.38×10^{-5} respectively and were above the permissible safety limits of USEPA risks. These groups were found at risk due to high Hazard Index (Baloch et al. 2021). The review on these studies has served as a baseline to formulate parameters adopted and to understand the significance of water for different purposes. Studies from different parts of the world, representing Abu Dhabi (UAE), Afghanistan, Bangladesh, China, Egypt, Ethiopia, Ghana, India, Iran, Kosovo, Morocco, Nigeria, Pakistan, Philippines, Saudi Arabia, South Africa and Tunisia found that groundwater is either not fit for drinking or irrigation purposes and are posing health risks. There is a lot of literature, which lay stress on deterioration of quality of both groundwater and surface water. The supply of safe drinking water is essential for human health and well-being. However, the safety of groundwater is of main concern for various purposes (Tokatli C, 2021). The World Health Organization stated that: "sufficient, safe, and accessible water must be available to all for sustainability." Therefore, the determination of physical and chemical properties for groundwater suitability becomes mandatory for sustainable water resource security (Tegegne et al. 2023).

1.4 Research gap and study objectives

Studies conducted on groundwater quality assessment in different regions of Jammu district for irrigation and drinking purpose (Sudan S, 2018; Khanna P, 2019; Jasrotia et al. 2019), Reasi region of Jammu (Kaur et al. 2019), Kathua region of Jammu (National institute of Hydrology, Roorkie, 1996-97; Kumar et al. 2022; Kouser et al. 2022), Udhampur region of Jammu (Kumar et al. 2017; Murtaza et al. 2019), Samba region of Jammu (Khanna P, 2019) and in various regions of Kashmir (Rather and Dar, 2019). The above-mentioned studies have been carried out in whole Jammu region where additional

water supply is available but study area is selected because of high population which rely on groundwater, where groundwater is the only water source usable for drinking and various other purposes. Basmati rice is imported to different parts of the world from this area and thus having agricultural significance.

Despite having agricultural importance, rare or no work has been carried out in this area on groundwater quality monitoring and assessment. So, present study has been carried out with the aim of groundwater quality assessment for various purposes (drinking and irrigation) and heavy metals analysis for health risk assessment has also been evaluated with the help of different health indices (Paneerselvam et al. 2020; Loh et al. 2020; Baloch et al. 2021; Tokatli C, 2021). Furthermore, present study will focus on the impacts of contaminated ground water on the health of local population as well as on the soil with the help of indices. So, present study is being conducted to investigate the overall hydrochemistry of groundwater of R. S. Pura (Ranbir Singh Pura) tehsil of Jammu district regarding its use for various purposes.

The objectives of research work are as follows:

• To study the physico-chemical parameters of groundwater and health impacts caused on humans and on soil.

• To check its suitability for drinking and irrigation purposes.

• To evaluate the Water Quality Index of study area using the Weighted Arithmetic Index method.

CHAPTER 2
REVIEW OF LITERATURE

Introduction

Groundwater has an important role in activities such as drinking, irrigation and other industrial related activities. Over utilization and exploitation of groundwater, pollution, agricultural activities etc. lead to the problem of groundwater contamination. This contaminated groundwater when consumed can lead to various health related issues. Moreover, using contaminated groundwater in agricultural fields can hamper the growth of plants and effects the soil fertility. So, here comes the need to assess the groundwater quality. Researchers, across the world, carried out their work in order to assess the groundwater quality for drinking purposes, irrigation purposes, health risk assessment and are summarized as follows:

2.1 Review on assessment of groundwater quality for drinking purposes

Physico-chemical parameters such as pH, EC, TDS, TH, TA, major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), major anions (Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-) played crucial role in determining groundwater quality for drinking usage. Reviewing literature formed a baseline and helped in getting information on the parameters used and methodology applied in evaluating the groundwater quality for drinking usage. Literature from the different parts of world has been surveyed and are discussed below in detail:

1. Pappaka et al. (2024) assessed the groundwater of Pandameru river basin of Anantapur district of Andhra Pradesh, India. To assess the drinking water suitability, samples were collected from 46 locations during pre-monsoon period of March 2022 and were analysed for various physico-chemical parameters and WQI was also calculated. The results were then compared with WHO guidelines. 77% of water samples were found safe and 23% unfit for drinking as per WQI. However maximum water samples were reported under high salinity and low sodium category. Some samples were exceeding the permissible limits, therefore treatment before consumption was suggested.
2. Acharya et al. (2023) evaluated the hydrochemistry and groundwater quality of newly developed Dwarka region of New Delhi, India. Total of 150 groundwater samples were taken and were analyzed for drinking and irrigation purposes. WQI, TDS and Nitrates were major concern for evaluation. Piper trilinear and Chadha diagrams were used to understand the hydrochemistry of the groundwater of study

area. 87% of the groundwater fall under 'poor to unsuitable category' of WQI which indicate its unsuitability for drinking use. Overall, groundwater was found 'moderately suitable' for irrigation purposes.

3. Assessment of groundwater suitability for drinking, irrigation and industrial purpose in Kathua region of J&K, India has been carried out by Kouser et al. (2022). Total of 75 groundwater samples were collected and were analyzed for physico-chemical parameters, Irrigation Indices (MH, SAR, PI), CR etc. The obtained results were then compared with WHO (2017) and BIS (2012) water guidelines and found that groundwater was alkaline in nature, Ca^{2+} was dominant cation and HCO_3^- found to be the dominant anion. Groundwater of study area found suitable for drinking, irrigation and industrial purpose. Hydrochemistry of study area was affected by rock-water interaction and lithologies.
4. A study on water quality evaluation of hand pumps of Kathua district of Jammu and Kashmir, India has been conducted by Kumar et al. (2022). Water samples from different sites were collected and then samples were tested in PHE Lab, Kathua. The results so obtained were then compared with BIS standard. WQI was also calculated. The study reported that hand pumps were of good water quality and were suitable for drinking purpose. The study area already had hand pump water supply from PHE but still people used water of handpumps for drinking and other purpose because of lack of awareness. So, government should supply tap water to every household and proper testing of water of hand pumps should be done.
5. Groundwater samples from 22 locations of Indpur region of West Bengal, India to check the geo-hydrological level, has been collected and analysed for pre-monsoon (PrM) and post-monsoon (PoM) season (Palmajumder et al. 2021). Concentration of NO_3^- and Fe^{2+} was found higher during PrM than PoM because of increased leaching from soil, use of fertilizers and quick withdrawal of water. Overall, irrigation water quality was under good category and low sodium hazard. As per WQI and Schoeller diagram, quality of groundwater of study area was under good category in PrM than in PoM period.
6. Kanga et al. (2020) assessed the groundwater quality assessment using WQI in Sebru River Basin, Morocco. From 81 water quality monitoring stations, water quality data for 28 years were collected. WQI, Cl^-, NH_4^+, EC, NO_3^-, fecal coliforms were assessed. The study concluded that overall water quality was classified under medium to very bad category. Untreated industrial sewage, intensive agricultural

activities, domestic waste water and landfills were main reasons for groundwater quality degradation in study area.

7. Groundwater samples from Kadava river basin were collected and analysed, for major ions during pre-monsoon and post-monsoon seasons, for drinking water contamination in Maharashtra, India. Study found that concentration of Calcium, Magnesium, Chloride, Sulphate and Nitrate surpasses the desirable and permissible limit of BIS and WHO in both the seasons. The results indicate that geo-genic processes including silicate weathering, ion exchange, agricultural inputs and evaporation are the main controlling factors which effects groundwater chemistry of this area. Aquifers are responsible for agricultural and drinking purpose, and require certain remedial measures like water purification set up, rain water harvesting techniques, least use of chemical fertilizers and should be implemented in order to sustain water quality for future use (Wagh et al. 2020).
8. A study on groundwater quality and monitoring in Cenozoic rocks of Jammu Himalaya, India has been carried out by Jasrotia et al. (2019). From 100 dug wells and tube wells, water samples were collected and were assessed for its irrigation and drinking suitability. for drinking purpose, major cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}), major anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}) and other physico-chemical parameters were assessed. The study showed that Ca^{2+}, Na^{+} and Mg^{2+} were the major cations and HCO_3^{-} found to be major anion in study area. Groundwater of study area was reported suitable for drinking and irrigation purpose.
9. Groundwater quality assessment of Samba region of Jammu, India has been conducted by collecting water samples from dug wells, tube wells and hand pumps during pre-monsoon period. Physico-chemical parameters were assessed and statistical analysis was carried out. The results of study reported that value of EC, HCO_3^{-}, TH, Ca^{2+} and N were above permissible limits prescribed by WHO and IS:10500 at some sampling sites (Khanna P, 2019).
10. Saraswat et al. (2019) carried out a study on geochemical analysis of groundwater of Surat using statistical approach and estimated the potential quality of groundwater resources. Samples were collected from bore wells, open wells, dug wells and handpumps. In this study, ground water quality parameters like Hardness, TDS, EC, Cl^{-}, pH, SO_4^{2-} and NO_3^{-} were analysed. SAR value was also calculated**.** The results concluded that groundwater in city is not potable. High values of TH, TDS and Cl^{-}

in the study area has severe health impacts on local people. Thus, the study recommended to consume the water with proper treatment.

11. Groundwater quality assessment of Neyshabur area of Iran for drinking and irrigation purpose has been carried out by Bhunia et al. (2018). 402 water samples were collected and were analyzed for pH, SAR, EC, Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^-, SO_4^{2-}, Cl^-, TDS and TH from 2010-2013 and then results were compared with WHO standards. Groundwater quality of study area was found to be very hard and slightly alkaline in nature. Most of the water samples found suitable for drinking and irrigation purposes.
12. 67 groundwater samples from urban Bengaluru, India has been collected and analyzed for its quality assessment and were analyzed for 14 water quality parameters during pre- and post- monsoon period. WQI and multivariate statistical techniques were also applied. Half of the water samples found unsuitable as per WQI and thus need some treatment before consumption. Maximum parameters exceed the permissible limits of BIS-10500. Anthropogenic activities, ion-exchange processes in water and rock-water interaction in aquifer were main causes of groundwater contamination in study area (Gulgundi and Shetty, 2018).
13. Mallick et al. (2018) did groundwater investigation and used multivariate statistical analysis along with geochemical modelling, conventional plots and hydrogeochemical process of aseer area of Saudi Arabia. 62 groundwater samples were collected and analyzed for pH, EC, TDS, Ca^{2+}, Mg^{2+}, HCO_3^-, TA, TH, K^+, Cl^-, SO_4^{2-}, NO_3^- and F^-. Correlation analysis was also performed. It was found that the groundwater of this area is dominated by Calcite and Dolomite concentrations. High alkalinity is found to be a major concern in this area. So, proper water management should be adopted to control further degradation of groundwater of this area.
14. Khan et al. (2017) implemented Geographic Information System and Water Quality Index to assess the ground water quality for drinking purpose in Raipur city of Chhattisgarh, India. 34 groundwater samples were collected as prescribed by APHA (1995) and were analyzed for 8 water quality parameters (Cl, pH, F^-, Ca^{2+}, Mg^{2+}, Al^{3+}, TH, NO_3^-). Study found that ground water of some areas of city is not suitable because of high amount of magnesium, nitrate and calcium as prescribed by BIS (2009). It is concluded that 76% of the water sample is categorized under good, very good and excellent category while rest of the sample is under poor, very poor and unfit category of water quality.

15. Matta et al. (2017) monitored and assessed the groundwater quality of Haridwar district of Uttarakhand, India. Five sampling sites were selected and were assessed for pH, temperature, EC, DO, TDS, BOD, COD, TH, Alkalinity, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ and then the obtained results were compared with BIS and WHO standard. Values were found within permissible limits and were fit for drinking and other domestic purposes. Accumulation of domestic solid waste, sewage waste water and uses of fertilizers in agricultural lands were observed during this study, which could affect the groundwater quality of study area. So, solid waste management practices were recommended by this study.
16. A cross-sectional study for determining drinking water quality of Bangladesh. A total of 960 household samples were randomly selected and were tested for salinity, pH, WQI, As^{3+}, Mn^{2+} and Fe^{2+}. Study revealed that drinking water was slightly alkaline and salinity was also high. Water quality of majority of households found to be unsuitable for drinking because of high concentration of As^{3+} and Mn^{2+}. Children were found vulnerable to high Mn^{2+} concentration due to their low protective mechanisms. So, awareness among people was suggested to improve water quality and health of people (Akter et al. 2016).
17. The effect of industrial waste on groundwater quality in vicinity of dumping site and near the Basantar river in Samba town of J&K, India was conducted by Aslam and Raina (2016). Water samples were collected from and near the river in five months. The study found that the pollution level is higher in the month of August as compared to summer months. It is found that the groundwater pollution near the industrial area was more as compared to area away from industrial area. High content of Cl^-, SO_4^{2-}, TDS in water make it unsuitable for use. It is suggested that the water should be well treated and tested before its usage and the wells from where water is being used should be digged at greater depths or should be digged away from the dumping sites.
18. Boateng et al. (2016) assessed the groundwater quality by using statical techniques and by applying WQI in Ejisu-Juaben Municipality area of Ghana. Total of 19 groundwater samples were collected and were analyzed for major anions and cations. Results showed that groundwater of the study area was slightly acidic and all physico-chemical parameters except phosphate were within permissible limits of WHO. Weathering, anthropogenic activities and leaching found to be the major factors influencing groundwater quality. Maximum samples fall under excellent

water quality as per WQI and reported that groundwater is suitable for drinking and other domestic uses.

19. A case study on the groundwater of Greater Noida area of Uttar Pradesh, India has been done by Saleem et al. (2016). To carried out the study, ground water samples were taken from 10 different locations and were analyzed for various water quality parameters. WQI was also calculated. Water samples were collected from General hand pumps (HP), Government hand pumps (GHP), Bore wells (BOR) and preserved as per the standards prescribed in APHA-1999. The results so obtained were compared with the BIS- 2012 and WHO- 2012. It is found that the industrial effluents are directly discharged into natural water bodies without any treatment which makes the groundwater unfit for human consumption. Study concluded that 10% of the water samples falls under moderately poor category while rest 90% falls under good water quality. Study recommended to treat water before usage.
20. Investigation of the physicochemical properties of groundwater of Thirupathur region of Tamil Nadu, India has been carried out by Kumar et al. (2013). Study aimed to identify the sources of contamination and to comprehend the water quality of this area. Samples were collected during pre-monsoon and post-monsoon period from 8 bore well sites. HCO_3^-, Ca^{2+}, Na^+ and Cl^- found to be dominated ions in the ground water of this area. Dominance of groundwater interaction was showed by Gibb's plot. Fluoride concentration was found to be highest at different locations. Major source of Fluoride in ground water is dissolution of this mineral present in geological formations.
21. Assessment of groundwater quality of Visakhapatnam city was done by using WQI Rao and Nageshwararao (2013). Water samples from 50 sampling stations were taken and were assessed for 11 physico-chemical parameters. Out of 50 sampling stations, 8 stations have excellent water quality and 4 sampling stations have poor water quality in all seasons. Study found that the poor quality of water is due to high concentration of NO_3^-, TDS and Cl^- in water. It is found that WQI value ranges from 28- 267. Only 2 stations have high concentration of WQI and is because of Hardness, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^- and TDS. So, the water of this area found to be non-useful for human consumption.
22. Bernard and Ayeni (2012) collected groundwater samples from 20 locations of local government area, Bichi, Nigeria and then tested these samples for pH, Temperature, Turbidity, Cl^-, Fe^{2+}, Mg^{2+}, Ca^{2+}, TA, TH, TDS, EC and NO_3^- and then obtained values

were compared with WHO and Standard Organization of Nigeria (SON). The results showed that all the chosen parameters analyzed were within the permissible limits of WHO and SON. It is found that the industrial effluents and municipal waste are directly discharged into water bodies which is responsible for the pollution of this valuable resource. The local people were consuming water without any prior treatment. So, constant monitoring and proper use of agricultural and human activities in this area is suggested.

23. Groundwater samples of Jimeta-Yola area of Nigeria were collected from boreholes and dug wells during dry and rainy season. Physico-chemical parameters and WQI were analyzed and values were then compared with WHO standards. The study found that the water quality is good in dry season whereas poor water quality was observed during rainy seasons. Sources of contamination includes household solid waste, waste water and sewage effluents. So, water consumption with proper treatment has been suggested (Ishaku J.M, 2011)
24. Reza and Singh (2010) assessed the water quality of Angul- Talcher region of Orissa, India. For study, 24 water samples were collected from open wells and tube wells during post monsoon and summer season. WQI was calculated and found that groundwater samples collected in both seasons were in good category range. In post monsoon period, water quality is lower as compared to summer season. Human activities in mining areas found to be major source of groundwater contamination during post monsoon season. High concentration of NO_3^-, Ca^{2+}, F^-, Mg^{2+}, hardness causes high value of WQI in some areas. It is concluded that both natural and anthropogenic sources are contaminating the groundwater of study area.
25. Prakash and Somashekhar (2006) collected 1026 groundwater samples from Anekal Taluk area of Bangalore, India and were tested for various physico-chemical and biological parameters. It was found that turbidity, calcium and fluoride concentration exceed the permissible limits of BIS. Also, groundwater of this area found to have bacteriological influence. Study concluded that out of 1026 samples, 836 samples found unsuitable for drinking as per BIS standards.

Table 1: Summary of literature review on different parameters and indices used for assessing groundwater quality for drinking purposes.

S. No.	References	Study area (Source of water)	Parameters and indices used	Results (All values in mg/L except for pH & EC (µS/cm))	Research Findings
1.	Pappaka et al. (2024)	Anantpur district of Andhra Pradesh, India (borewells and handpumps)	pH, Total dissolved solids (TDS), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Electrical conductivity (EC), Total alkalinity (TA), Nitrates (NO_3^-), Salinity, Sulphate (SO_4^{2-}), Fluoride (F^-), Chlorides (Cl^-), Sodium (Na^+), Potassium (K^+), Water	pH (7.4-8.3), EC (870-3580), TDS (435-1790), Ca^{2+} (59-258), Mg^{2+} (9-167), Na^+ (76-186), K^+ (1-27), Cl^- (89-284)	• WQI reported 77% water samples under safe and 23% under unfit category. • High salinity and low sodium content was found. • Treatment before consumption was suggested.

			quality Index (WQI)		
2.	Acharya et al. (2023)	Dwarka region, New-Delhi, India (Groundwater)	pH, TDS, Ca^{2+}, Mg^{2+}, TA, NO_3^-, SO_4^{2-}, F^-, Cl^-, Na^+, K^+, WQI	pH (6.51-8.50), EC (340-17680), TDS (151.4-8880), Ca^{2+} (23.8-953.9), Mg^{2+} (9.75-546.74), SO_4^{2-} (0-424.15), F^- (0-1.9), Cl^- (44.08-5325), Na^+ (8.19-882), K^+ (1-89)	• 44% samples affected from NO_3^- • WQI ranged from 44.93-844.01. 87% and 13% of samples found under poor to unsuitable and good to excellent category respectively.
3.	Kouser et al. (2022)	Kathua, Jammu, India (Tube wells and dug wells)	pH, TDS, Total hardness (TH), EC, SO_4^{2-}, Cl^-, NO_3^-, F^-, Ca^{2+}, Mg^{2+}, K^+, HCO_3^-,	pH (6.45-7.73), EC (80-1500), TDS (51.46-964.8), Ca^{2+} (9-	• Ca^{2+} and HCO_3^- found to be dominant cation and anion respectively.

			Groundwater quality index (GWQI)	140), Mg^{2+} (0.84-283.08), F^- (0-2), Cl^- (4.99-173.90), Na^+ (1.59-238.27), K^+ (0.68-392.7), GWQI (30.28-318.01)	• Low pH and higher HCO_3^- values indicate chemical weathering. • Groundwater was reported fit for drinking at all sites except one.
4.	Kumar et al. (2022)	Kathua tehsil of UT Jammu and Kashmir, India (handpumps)	pH, EC, Turbidity, Cl^-, NO_3^-, F^-, Ca^{2+}, Mg^{2+}, WQI	Cl^-(200-250), pH (7.41-7.95), F^- (0.4-1.0), Ca^{2+} (62.33-100), Mg^{2+} (24.11-30), TH (184.4-200), WQI (10.87-94.47)	• WQI indicated 'excellent-good' and 'good-poor' water quality. • All water quality parameters water under safe values of BIS-2012.
5.	Palamajumdar et al. (2021)	Indpur block, Bankura district,	pH, EC, TH, TDS, TA,	For PRM, NO_3^- (2.2-	• More than 80% of varied

		West Bengal, India (wells)	Fe^{2+}, SO_4^{2-}, Ca^{2+}, Cl^-, NO_3^-, Mg^{2+}, Na^+, K^+, HCO_3^-, WQI	6.09), pH (5.8-7.0), TH (109-720), TDS (136-1843) For POM, NO_3^- (27.2-620.6), pH (6.3-7.0), TH (70-1596), TDS (165-1849)	from 'poor to good' category of WQI. • Water quality was found good in post-monsoon (PRM) season as compared to pre-monsoon (POM). • Higher values of NO_3^-, Fe^{2+}, HCO_3^- and TH were reported.
6.	Kanga et al. (2020)	Sebu River basin in North west Morocco (groundwater quality monitoring stations)	EC, Cl^-, NO_3^-, NH_4^+, WQI	EC (0-94.91), Cl^-(11.7-99.44), NO_3^- (0-97.53), NH_4^+ (80.35-98.83)	• Groundwater quality was classified as very degraded for period (1989-2017). • Cl^- and NO_3^- were major pollutants of groundwater of study area.
7.	Wagh et al. (2020)	Kadava river basin,	pH, TH, Ca^{2+}, Na^+, TDS, SO_4^{2-},	pH (7.8-9), EC (810-	• High NO_3^- content for both PRM and

		Maharashtra, India (wells)	Mg^{2+}, EC, Cl^-, NO_3^-, HCO_3^-, K^+, F^-	6180), Ca^{2+} (13.63-98.07), Cl^- (31.24-1085.8), Na^+ (36.2-501.4), K^+ (0.3-8.3), NO_3^- (12.94-69.76), TH (131.95-1028.92)	POM season was found. • pH, TDS, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-} ions exceeds the BIS threshold limits.
8.	Jasrotia et al. (2019)	Foothills of Jammu Himalaya, India (dug wells & tubewells)	pH, TA, Ca^{2+}, EC, Mg^{2+}, Na^+, TH, K^+, CO_3^{2-}, SO_4^{2-}, Cl^-, NO_3^-, F^-, TDS, HCO_3^-, NO_3^-	Mean values for pH (7.35), EC (504), TDS (323.66), Ca^{2+} (64.32), Mg^{2+} (13.46), Cl^- (24.6), Na^+ (16.66), K^+ (1.87)	• Groundwater of study area was found alkaline with soft to hard in nature. • Ca^{2+} and HCO_3^- was reported to be the major cations and anions respectively. • CO_3^{2-}, SO_4^{2-}, Cl^- concentration

					was found within limits and moderately hard water was found.
9.	Khanna P (2019)	Samba region of Jammu, J&K, India (handpumps and dug wells)	pH, TH, EC, Mg^{2+}, Ca^{2+}, K^{+}, Na^{+}, Fe^{2+}, SO_4^{2-}, CO_3^{2-}, NO_3^{-}, Cl^{-}, HCO_3^{-}, F^{-}	pH (6.92-8.2), EC (290-1290), Ca^{2+} (40-160), Mg^{2+} (7-39), SO_4^{2-} (6-331), F^{-} (0.01-0.62), Cl^{-} (10-180), Na^{+} (17-190), K^{+} (1.1-8.6), NO_3^{-} (2.45-81)	• EC, TH, Ca^{2+}, NO_3^{-} and HCO_3^{-} were found above permissible limits of BIS. • Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Fe^{2+} and F^{-} were within permissible limits of BIS.
10.	Saraswat et al. (2019)	Surat City, Gujarat, India (borewells, dug wells, open wells and handpumps)	pH, EC, SO_4^{2-}, Fe^{2+}, Cl^{-}, F^{-}, PO_4^{3-}, TH, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cr^{2+}	pH (6.7-7.9), EC (1156.83-3478.12), TDS (845.55-1935.13), Mg^{2+} (110-495),	• High Mg^{2+} content than Ca^{2+} indicate carbonate weathering. • Mg^{2+} and Cl^{-} found to be the dominant cations and

				Ca^{2+} (65-340), SO_4^{2-} (0-424.15), F^- (Below detection limits), Cl^- (62.04-1717.85)	anions respectively. • High concentration of TH, Cl^- and TDS was reported and its high consumption can cause severe health hazard in near future.
11.	Bhunia et al. (2018)	Neyshabur region of Iran (Borewells)	Cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) Anions (SO_4^{2-}, Cl^-, HCO_3^-) pH, EC, hardness, TDS	EC (322-16740), TDS (252-9324), Ca^{2+} (1-35), Mg^{2+} (2-25), SO_4^{2-} (0.7-41.6), Cl^- (0.3-108), Na^+ (1-80), K^+ (2-27)	• Water was found hard and slightly alkaline in nature. • 90% of samples exceeds the acceptable limits of WHO-2011.
12.	Gulgundi and Shetty (2018)	Urban Bengaluru city of India (borewells)	pH, Ca^{2+}, EC, Mg^{2+}, NO_3^-, Na^+, TDS, K^+, SO_4^{2-}, Fe^{2+},	pH (6.07-8.13), EC (240-4230), TH (48-	• High conc. of EC and TDS indicates higher salt content.

			Cl^-, HCO_3^-, F^-, TH, WQI	1784), SO_4^{2-} (3-187), Cl^- (19-607), NO_3^- (2-252)	• HCO_3^- was the dominant anion. • WQI indicated that 50% of water samples unfit for drinking.
13.	Mallick et al. (2018)	Aseer region of Saudi Arabia (groundwater samples)	pH, EC, TDS, Fe^{2+}, Major Cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) Anions (SO_4^{2-}, Cl^-, NO_3^-, HCO_3^-, F^-)	pH (5.6-9.2), EC (285-3796), Ca^{2+} (48.8-540), Mg^{2+} (2.9-214), Cl^- (12-825), Na^+ (3.5-72.8), K^+ (0-9.6)	• High conc. of Ca^{2+} and HCO_3^- were reported indicating more hardness. • High alkalinity along with Ca^{2+}, Cl^- & NO_3^- were reported. • High conc. of HCO_3^- indicated carbonate weathering in the study area.
14.	Khan et al. (2017)	Raipur city, Chhattisgarh, India (groundwater samples)	WQI, pH, Mg^{2+}, Cl^-, F^-, Ca^{2+}, alkalinity,	Ca^{2+} (48.8-540), Mg^{2+} (2.9-214),	• WQI classified water as good (76%) and

			hardness, NO_3^-	NO_3^- (25-119), Cl^- (12-825)	poor-unfit (24%). • High conc. of Ca^{2+}, Mg^{2+} and NO_3^--make water unfit for drinking.
15.	Matta et al. (2017)	Rural areas of Haridwar district of Uttarakhand, India (handpumps)	pH, Cl^-, BOD, temperature, TDS, Ca^{2+}, DO, TH, TA, K^+, Mg^{2+}, EC, Na^+	pH (6.3-7.0), EC (482-599), TDS (287-384.5), Ca^{2+} (185-231), Mg^{2+} (84-135), Cl^- (220-378), Na^+ (6.30-21.88), K^+ (1.35-2.78)	• High Cl^-, Ca^{2+} and Mg^{2+} content was found. • Use of fertilizers, domestic solid waste, sewage waste water affects study area's water quality.
16.	Akter et al. (2016)	Rural Bangladesh (drinking water sources)	pH, salinity, iron (Fe^{2+}), manganese (Mn^{2+}), arsenic (As^{3+}), WQI	Average pH value 7.4, Mn^{2+} (0.1-5.5)	• pH was slightly alkaline • Fe^{2+}, Mn^{2+} and As^{3+} concentration exceeds the

					WHO and Bangladesh drinking water standards. • WQI classified water as good (33%) and poor (67%).
17.	Aslam and Raina (2016)	Samba district of Jammu and Kahmir, India (groundwater)	pH, TDS, EC, TA, TH, Cl^-, NO_3^-, SO_4^{2-}, Fe, BOD, COD, E-coli bacteria	pH (7.42-9.6), EC (700-3050), TH (208-700), SO_4^{2-} (45-420), Cl^- (155.21-593.23), NO_3^- (2.59-12.3), TA (190-650), TDS (200-1050)	• High content of Cl^-, alkalinity, TDS- making water unsuitable for drinking. • Cl^-, Fe, TA and TH exceeds at all sites. • No NO_3^- contamination was reported.
18.	Boateng et al. (2016)	Ejisu-Juaben municipality area of Ghana, South-Africa (open wells)	pH, TDS, TA, Turbidity, EC, Ca^{2+}, TH, Cl^-,	pH (3.99-7.20), EC (7.32-100.56), TDS (8-	• Low EC content was reported due to less

			NO_3^-, Mg^{2+}, SO_4^{2-}, NH_4^+, nitrites, PO_4^{3-}, WQI	125), Ca^{2+} (12-56), Mg^{2+} (1.20-8), SO_4^{2-} (3-30), Cl^- (28.40-227.20), NO_3^- (0.08-0.31), TH (18-90)	dissolved ions concentration. • Except PO_4^{3-}, all physico-chemical parameters were within the WHO permissible limits. • Ca-Cl was reported to be dominant specie. • WQI classified water under excellent category.
19.	Saleem et al. (2016)	Greater Noida, Uttar Pradesh, India (handpumps and borewells)	Ca^{2+}, Mg^{2+}, TH, Cl^-, NO_3^-, SO_4^{2-}, F^-, TDS, alkalinity, WQI	TDS (351-701), Ca^{2+} (11-88), Mg^{2+} (6-37), SO_4^{2-} (2-15), F^- (0-0.1), Cl^- (16-170), TH (52-295), NO_3^- (1-9)	• WQI ranged from 16.49-64.65 depicting 90% samples under good to excellent category while 10% under moderately poor category.

					• All water quality parameters were reported under safe limits of BIS-10500.
20.	Kumar et al. (2013)	Thirupathur region of Tamil Nadu, India (borewells)	pH, EC, TDS, Ca^{2+}, SO_4^{2-}, Mg^{2+}, Na^+, HCO_3^-, K^+, Cl^-, NO_3^-, CO_3^{2-}, F^-	pH (8.1-8.8), EC (340-17680), TH (0-65), Na^+ (179-308), K^+ (4-30), NO_3^- (2-9), SO_4^{2-} (73-175)	• HCO_3^-, Ca^{2+}, Na^+ and Cl^- were found to be the dominant ions. • F^- conc. was highest at different locations. • Samples were alkaline in nature.
21.	Rao and Nageshwararao (2013)	Vishakhapatnam, India (borewells, open wells, reservoirs)	pH, TDS, DO, TA, CO_3^{2-}, EC, Ca^{2+}, NO_3^-, TH, HCO_3^-, Mg^{2+}, Cl^-, WQI	WQI (28-267), average values of HCO_3^- (1.616), CO_3^{2-} (1.604), Cl^- (1.902)	• WQI was calculated for PRM, POM and Monsoon season. • 82% of PRM, 84% of POM and 78% of Monsoon samples were found under excellent to

					good category of WQI. • 18% of PRM, 16% of POM and 20% of Monsoon samples were under poor to very poor category of WQI.
22.	Bernard and Ayeni (2012)	Bichi area of Kano state of Nigeria (drinking ground water)	EC, pH, turbidity, colour, temperature, TA, TH, TDS, Ca^{2+}, Mg^{2+}, Cl^{-}, NO_3^{-}, Fe^{2+}	pH (6.3-8.2), EC (126-143), Ca^{2+} (24.2-30.3), Mg^{2+} (2.0-4.67), SO_4^{2-} (6-331), Cl^{-} (7.10-8.45), NO_3^{-} (0.52-1.03), TDS (790-867), Fe^{2+} (0.00-0.05)	• Comparison of results with WHO and water Standards of Nigeria (SON). • Except Fe^{2+} (mean value of 0.05), all the parameters were found within permissible limits.

23.	Ishaku J.M, (2011)	Jimeta Yola area of Northeast Nigeria (hand dug wells, bore holes, leachates)	EC, Ca^{2+}, Cl^-, NO_3^-, Mg^{2+}, Fe^{2+}, DO, WQI, TDS, TH, pH, COD, Cr (VI), SO_4^{2-}, HCO_3^-	EC (80-1990), pH (6-8.50), Ca^{2+} (1-300.50), Mg^{2+} (0.20-98), Cl^- (2.40-1730), NO_3^- (3.1-238.8), TH (5-640), Na^+ (1-240), K^+ (1-64)	• Conc. of EC, NO_3^-, Cl^-, DO was reported to be higher in dry season. • WQI for dry season (96.4) indicated good water while in rainy season (138.5) indicated poor water. • Overall, water was reported unfit for human drinking.
24.	Reza and Singh (2010)	Angul- Talcher region of Orissa, India (open and tube wells)	WQI, pH, F^-, NO_3^-, Ca^{2+}, Mg^{2+}, turbidity, TDS, TH, Cl^-, Fe^{2+}	WQI value ranged from 14-57 in PRM while 19-67 in POM.	• Higher values of F^-, NO_3^-, Ca^{2+}, Mg^{2+}, TH was reported. • WQI classified groundwater as moderately suitable for drinking.

25.	Prakash and Somashekhar (2006)	Anekal Taluk, Bangalore urban district, India (groundwater samples)	pH, color, turbidity, EC, TDS, TA, TH, Cl^-, F^-, Fe^{2+}, NO_3^-, Ca^{2+}, SO_4^{2-}, E-coli	pH (5.51-9.93), TDS (14-70770), Alkalinity (20-710), TH (20-4600), Cl^- (9.81-59.82), F^- (0-1.6), NO_3^- (0.01-6.72), SO_4^{2-} (6-1678.2)	• Slightly alkaline water was found. • High conc. of EC, TDS, E-coli, Ca^{2+}, F^-, Fe^{2+} were found.

2.2 Review on assessment of groundwater quality for Irrigation purposes

Present study has been conducted to investigate the impacts of contaminated groundwater for irrigation usage. The literature surveyed helped to outline a plan for future research and got the information on the parameters/indices used in assessing the groundwater quality. The review of literature involves the examination of past studies done and the methodology used to carry out the present research work. Investigation of review papers from different parts of India and the World on the irrigation water quality classification has been done and are as follows:

1. Raheja et al. (2024) conducted a holistic study on groundwater suitability for irrigation in Rohtak region of Haryana (India). Entropy Water Quality Index (EWQI) was calculated to assess drinking water characteristics while SAR, MAR, KI, PI, Na% were calculated to assess the irrigation water quality. Gibb's plot and US Salinity diagrams were plotted. Total of 47 sites have been selected and samples were analysed for pre-monsoon and post-monsoon season. Study reported that maximum water samples were unsuitable for irrigation purpose. US Salinity diagrams verified that maximum samples

have salinity hazards and high sodium levels in groundwater. As per Gibb's diagram, most of the ions occurs due to carbonate and silicate weathering through ion- exchange and rock-water interaction phenomenon in the groundwater. According to EWQI, groundwater was having medium to poor drinking water quality in both pre-monsoon and post-monsoon season.

2. Ibrahim et al. (2023) determined the groundwater quality assessment for irrigation water suitability in Oasis (El Kharga) of Egypt. Various Irrigation water quality indices (IWQI) were applied and physico-chemical parameters were also assessed. Study reported groundwater of study region under 'good to safe' category for irrigation purposes. IWQI classified 67.85% of the samples under 'no restriction' category. Groundwater of the study area was found under 'safe' category according to KI, PI, SAR, SSP and RSC.
3. Tegegne et al. (2023) assessed the groundwater quality of Upper Blue Nile Basin of Ethiopia. To determine the groundwater quality and to check its suitability, 78 samples were chosen from 39 locations during wet and dry seasons. Physico-chemical parameters such as EC, pH, TDS, SO_4^{2-}, PO_4^{3-}, CO_3^{2-}, NO_3^--N etc. were evaluated and irrigation indices (Na%, SAR, KI, RSC, PI, IWQI, MAR) were also calculated. The results showed that the study region possess good quality drinking water in rural area while of medium quality in urban area. 85% of the samples found suitable for drinking and irrigation usage. Excessive application of fertilizers and improper waste water disposal needs to be monitored on regular basis. Once the groundwater becomes contaminated, it is difficult to treat. Therefore, monitoring on regular basis was suggested.
4. Jude et al. (2023) carried out hydrogeochemical monitoring of groundwater and surface water quality of East of Mount Cameroon and West of the Penda Mboko River, for drinking and irrigation. Fifty samples were collected from boreholes, hand dug wells, springs and rivers. Physicochemical parameters, Drinking Water Quality Index (DWQI), Piper plot, Gibbs plots & Wilcox diagram were analysed. TDS, pH, EC and TH samples were within the permissible limit of WHO standards. According to DWQI 58% of the samples fell in excellent water quality category while 26% of samples revealed good water quality for drinking purposes. Piper plot results revealed that, Ca-Cl type is the dominant hydro-chemical facies. All samples were found in the rock dominance zone in Gibbs plots. The Wilcox diagram showed that 26% of the groundwater samples fell in the field of excellent and 74 % of the groundwater samples

fell under the field of good to permissible for irrigational purposes. Study showed that maximum groundwater samples were suitable for irrigational purposes based on RSC and SSP. The Pearson correlation revealed that the majority of the parameters were positively correlated with each other.

5. Tajwar et al. (2023) carried out hydro-chemical and water quality assessment of groundwater of Hatiya island of Bangladesh. Contamination due to natural and anthropogenic sources were found. This contamination poses ill effects on the health of humans. PCA, Pearson's correlation and hierarchical cluster analysis indicated presence of geogenic influences in groundwater. According to WQI, 40% of the groundwater samples suitable for human consumption, whereas the other 60% unfit for drinking. Irrigation water quality analysis found 54% of the groundwater samples under excellent or good condition and rest 46% samples unsuitable.
6. Ajmal et al. (2022) collected 38 groundwater samples from different locations of Hyderabad region in Sindh Province of Pakistan, to assess the suitability for irrigation and drinking purpose. 13 physico- chemical parameters, WQI, SAR, KI, MR, RSC, SSP, PI were also calculated and the results were then compared with WHO drinking water standards. High concentration of Cl^-, EC, TH and TDS were reported. Water was found unsuitable for drinking according to WQI. According to irrigation indices, maximum groundwater of study region was found suitable for irrigation usage.
7. Ayyandurai et al. (2022) assessed the suitability for irrigation in coastal part of Cuddalore district of Tamil Nadu, India. For this study, 132 water samples were gathered during pre-monsoon (PRM) of year 2017 and post-monsoon (POM) of year 2018. SAR, RSC, SSP, KI, PI, MAR, PS and TDS were calculated. Values of SAR, RSC, PI and MAR showed that maximum groundwater samples were fit for irrigation purpose whereas PI, TDS, SSP and KI values represent doubtful to unsuitable category for irrigation use. 35% of water samples found to be unsuitable in PRM and POM period, according to Wilcox classification. High concentration of Na^+, Ca^{2+}, Cl^- and HCO_3^- were found and were because of anthropogenic activities such as sewage intrusion which further degrades the quality of groundwater. Certain measures like reusing of waste water, recycling of water in industrial processes were recommended.
8. Gugulothu et al. (2022) conducted a study in agricultural region of Telangana, South India, to evaluate the geochemistry and groundwater quality for drinking and irrigation purpose. For carrying out the study, 100 groundwater samples were collected and were estimated for pH, EC, TDS, Cl^-, SO_4^{2-}, NO_3^{2-}, SAR, RSC, MR, KI, etc. It was reported

that groundwater of study area was mostly alkaline with occurrence of Na^+ and HCO_3^- ions. Maximum samples were unfit for agricultural usage. So, site specific management practices were suggested to improve the groundwater quality for crop production and also for better living conditions of the people residing in study area.

9. Sarkar et al. (2022) conducted a study in Malda district of West Bengal and collected 83 groundwater samples from wells were collected and were analyzed for irrigation purposes. Magnesium Adsorption Ratio (MAR), Chloro-Alkaline Index (CAI-I), SAR, Na%, PI and KI were calculated to assess irrigation water quality of this area. High values of some indices such as MAR, PI, CAI-I and KI indicates that water is not suitable for irrigation use. It is found that about 88% of wells were under excellent category of irrigation as per SAR values whereas 48% of wells were under doubtful category of irrigation as per Na% calculations. According to USSL diagrams, 31% of wells found to have high salinity and low alkalinity. Wilcox Diagram showed that about one-third of wells fall under doubtful category of irrigation. So, eco-friendly agricultural models and practices were suggested.
10. Subramaniyan et al. (2022) carried out a detailed investigation on the groundwater quality of Perambalur district of Tamil Nadu, India. Total 436 groundwater samples were chosen for assessing its suitability for irrigation purposes. Then the obtained values were compared with BIS-2012 and WHO-2011 standard. Maximum groundwater samples were found suitable for irrigation purpose except a few. Children were found more prone to high Fluoride intake from groundwater when compared to infant and adults. So, sustainable management of groundwater was required in this area.
11. Zafar et al. (2022) monitored the status of groundwater of Patna region of Bihar, India. The study checked the seasonal variation in physico-chemical characteristics and irrigation suitability. For drinking water suitability, parameters such as pH, EC, TDS, HCO_3^-, Cl^-, Mg^{2+}, Na^+ etc. were assessed and for irrigation suitability SAR, Na%, RSC, MH, PI and PS were calculated. The study found that groundwater of this area was slightly alkaline in nature and fall under hard to very hard category in all seasons. Groundwater was found suitable for irrigation purpose but showing variations in different seasons for drinking. Thus, study recommended local authorities to monitor groundwater and agricultural activities of this area regularly.
12. Batarseh et al. (2021) assessed the groundwater quality of Abu Dhabi region of UAE. Groundwater quality assessment was done by calculating PI, SAR, Na%, EC, Cl^- and IWQI, then the data was visualized using GIS zoning maps. It is found that out of 145

wells, 96% of wells found to be in severe restriction category of irrigation while 4% of wells fall in low to moderate restriction category of irrigation. Wilcox diagram showed that in few areas of Abu Dhabi, water with low salinity and low sodium hazard was found. So, set up of real time monitoring system for sustainable development of groundwater, building of risk management module in agricultural sector were suggested.

13. Sharma et al. (2021) assessed the water quality of Dera Bassi town of Punjab, India for drinking and irrigation purpose. Various groundwater samples were collected and were assessed for different physico-chemical parameters. Then the results were compared with BIS-2012 and WHO-2006 standards. The study revealed that pH, F^-, Cl^-, NO_3^- and SO_4^2, values were below the acceptable limits while values of TDS, TH, Alkalinity, Ca^{2+} and Mg^{2+} exceeds the acceptable limits. 96% of water samples fall under hard water category. Ca^{2+} and Cl^- were found to be dominant cation & anion respectively. According to Irrigation Indices, maximum groundwater samples were fit for irrigation. Majority of water samples fall under high salinity and low SAR category as per USSL diagrams.
14. Kumari and Rai (2020) evaluated the hydrogeochemistry of groundwater of southern Haryana, India. Physico-chemical parameters were assessed for 64 samples and then results were compared with BIS standards. WQI and Irrigation water quality parameters were also calculated. Study showed that Ca^{2+}, Cl^- and NO_3^- were above the permissible limits of BIS. However, overall quality of groundwater was found suitable for drinking except a few. According to SAR, RSC and PI, water samples fall under excellent category of irrigation. Suggestions were made to monitor the water quality on micro level and proper water management practices.
15. Rawy et al. (2019) assessed the groundwater quality in Qena Governorate area of Egypt. This study uses GIS, factor analysis and hydrochemistry to check groundwater suitability for agricultural activities. On the basis of SAR, RSC, MH and KI suitability for irrigation was assessed. Overall irrigation water quality of this area is of excellent to good category. Most of the groundwater samples were below the maximum permissible limits set by WHO and Egyptian Water Standards. Only 62% of groundwater is suitable for drinking because of low salinity and also not suitable for domestic purpose due to high level of hardness in study area. The study concluded that GIS, hydrochemical analysis and statistical factor analysis in integration helps in identifying the controlling factors of groundwater of study area.

16. Shil et al. (2019) carried out a study to analyze the stability of Mahananda river water for drinking, agriculture, and industrial use. Water samples were collected in pre-monsoon and post monsoon period from 14 sampling stations. After collecting samples, they were analyzed for various parameters. For checking drinking quality of water, WQI and Pearson's Correlation was found for irrigation use, SAR, NA%, RSC, RSBC, Magnesium Hazard, Permeability Index, Kelly's Index and Potential Salinity were calculated. Aggressive Index (AI), Langlier Saturation Index (LSI), Stability Index (SI) or Ryznar stability Index (RSI) to check its use for industries. The study found that the quality of river water is moderate to good while having exception at few sampling stations. pH values were within normal range. Low sodium type water and medium salinity of the river water was concluded. The water is found suitable for irrigation purpose, agricultural purpose but not for industrial purpose.
17. Abbasnia et al. (2018) evaluated groundwater quality and its suitability for irrigation purpose of Chabahar City, Sistan and Baluchistan province of Iran. 40 open dug wells were selected for sample collection and were investigated for various parameters such as Cl^-, Na^+, SAR, EC, pH, TDS, HCO_3^- and Irrigation Water Quality Index (IWQI). Study found the groundwater suitable for irrigation usage. As per IWQI, 40% of water samples were classified under excellent category and rest under good category of irrigation waters.
18. Chaudhary and Satheeshkumar (2018) assessed the quality of groundwater of arid northeast part of Rajasthan, India. To evaluate the irrigation water quality, 300 water samples were taken and were analyzed for SAR, Na%, RSC, KI, PI, PS, RSBC, MH & Mg/Ca ratio. As per SAR calculations, majority of water samples were found to be excellent to good category. According to USSL Diagram, most water samples fall in category of very high salinity and low alkalinity hazard. The study suggested the wise use of fertilizers in the field and mixing of canal water with groundwater to be a safe alternative for irrigation and drinking purpose.
19. Rawat et al. (2018) determined the irrigation groundwater suitability of 44 wells of Kanchipuram district of Tamil Nadu, India. Sampling activity was repeated for 9 years i.e., 2005-2013. SAR, SSP, RSC, KI, PI, CAI1 and CAI2, PS, MH, TDS & TH were calculated and found that groundwater of this area was falling under moderate to unsuitable category of irrigation water, which was affecting the crops and its production. So, regular monitoring of irrigation water quality and groundwater

pollution, artificial recharge structures and rainwater harvesting structures were suggested to improve the groundwater quality.

20. Gagandeep et al. (2016) evaluated the quality of groundwater for irrigation purpose in Hodal block of Palwal district of Haryana, India. Sixty-six groundwater samples were analysed for CO_3^{2-}, EC, Ca^{2+}, Mg^{2+}, HCO_3^-, Na^+, K^+, Cl^-, SO_4^{2-}, SAR and RSC. The study found that 16.7% of water samples were of good quality. More than 60% of samples were of saline nature. No sample was in alkaline category. Dissolution of carbonic acid in the aquifers and carbonate weathering found to be the major causes of CO_3^{2-} and HCO_3^- ions in groundwater of this area.
21. Kumar et al. (2015) conducted a study to assess the hydro-geochemistry and groundwater quality of Anna Nagar area of Chennai, Tamil Nadu, India. 24 bore wells samples were collected and were tested for various Pysico-chemical parameters like pH, EC, Cl^-, SO_4^{2-}, WQI etc. and found majority of samples falling under excellent to good category. Water of study area is of fresh to Brackish type and is moderately high to hard, groundwater is of Na-Cl and mixed Ca-Mg-Cl type as per Piper trilinear diagram. Because of increase in population and more demand of water resources, study area is under stress. Designing of new rain water harvesting structures and artificial recharge methods were suggested.
22. Ravikumar et al. (2015) carried out a research study on usage of Piper and Durov plots to illustrate the hydro-geochemical characteristics of groundwater of SRLIS river basin, Karnataka, India. 24 water samples were taken and were assessed for WQI, Na% and SAR values. The study found that water is slightly acidic to alkaline which is preferred for drinking. Piper trilinear diagrams showed the dominance of acidic anions over alkali and strong acidic anions over weak acidic anions. Majority of samples belong to mixed water types where water types cannot be identified as neither cations nor anions are dominant. Study concluded that simple mineral dissolution or mixing process is mainly responsible for variation in hydro-geochemistry of groundwater in study area.
23. Singha D (2013) studied drinking and irrigation quality of groundwater of Idukki district of Kerala, India. Various calculations like pH, SAR, TDS, EC, Na%, SSP, PI, KI etc. on the groundwater samples was done. On the basis of the physico-chemical parameters, irrigation water quality indices and parameters and WQI, groundwater of the study area was found suitable both for irrigation and drinking purposes. Groundwater chemistry of the study area was controlled by rock dominance and lithology.

24. Sadashivaiah et al. (2008) carried out groundwater quality assessment of Tumkur Taluk area of Karnataka, India, to check its applicability for irrigation purpose. During post-monsoon period, 279 water samples were taken and 269 water samples were gathered during pre-monsoon period from different locations. Water samples were collected in accordance to APHA 1994 guidelines. SAR Values, Na%, RSC and Salinity Hazard were calculated to assess water usage for irrigation. Piper Tri-linear diagrams were also used for analysing groundwater chemistry in a better way. Study found that the Ca-Mg-HCO_3 type of water predominates in both the seasons and concluded that the most of the water samples of this area falls under suitable range for irrigation purpose.
25. Rao N. S (2006) did the comparison study of groundwater quality in Guntur region of Andhra Pradesh, India. In this study, 40 wells were chosen in May and November during 1999- 2001 and 240 water samples were analysed for pH, TDS, TA, Ca^{2+}, SO_4^{2-}, HCO_3^-, Mg^{2+}, NO_3^-, Cl^- and F^-. USSL diagram suggested that groundwater samples were fit for irrigation in post monsoon period as compared to that in pre monsoon. When results were compared with drinking water standards, water samples were found unfit for drinking purpose especially in post monsoon season. A proper management plan for better groundwater quality was suggested for proper plant growth and for maintaining human health for sustainable development.

Table 2: Summary of literature review on different parameters and indices used to assess groundwater quality for irrigation purposes.

S. No.	References	Study area (source of water)	Indices and plots/diagrams used	Results	Important Findings
1.	Raheja et al. (2024)	Rohtak district of Haryana, India (handpumps and domestic tube wells)	Sodium absorption ratio (SAR), Magnesium absorption ratio (MAR), Kelly's index (KI), Permeability	SAR (25.8-50.5), MAR (54-86), KI (1.02-4.25), PI (4-15.2), Na% (59.4-88.8)	• Salinity hazards and high sodium levels was reported as per USSL plots. • Silicate and carbonate

			Index (PI), Percent sodium (Na%), USSL diagrams, Gibb's plot		weathering governed groundwater hydrochemistry. • Groundwater was found unfit for irrigation usage.
2.	Ibrahim et al. (2023)	El Kharga Oasis, Egypt (wells)	Irrigation water quality Index (IWQI), Potential Salinity (PS), SAR, Residual sodium carbonate (RSC), Na%, KI	IWQI (29.61-99.5), SAR (0.12-8.30), %Na (3.80-66.39), KI (0.04-1.98), PS (-0.85 to 12.11), RSC (-9.96 to 2.61)	• 79% samples were found under 'under 'no to low' restriction' category of IWQI. • Most of the samples found safe according to SAR, Na%, RSC.
3.	Tegegne et al. (2023)	Gunabay watershed of upper Blue Nile basin, Ethiopia (shallow and deep wells)	SAR, PS, RSC, %Na, MAR, KI, IWQI, PI, Wilcox diagrams, Piper trilinear diagrams	MAR (0-68.43), KI (0.08-11.34)	• >77% samples were found suitable as per IWQI, MAR & KI. • >50% of samples were under 'excellent-good'

					category of irrigation water as per SAR, %Na, PS and RSC.
4.	Jude et al. (2023)	Southwest region of Cameroon, Africa (dug wells and boreholes)	Wilcox diagrams, piper-trilinear plots, Chloro-alkaline indices (CAI 1 & CAI 2), KI, % Na, PI, SAR, MAR	KI (<1), %Na (22.24-370.10), MH (21.51-45.09), RSC (<1.5)	• 100% samples found safe according to Na%, KI, RSC, MAR. • 50% samples were unsuitable as per PI.
5.	Tajwar et al. (2023)	Hatiya Island, Southeastern Coastal region, Bangladesh (tubewells)	TDS, SAR, Na%, RSC, EC, piper trilinear diagrams, USSL diagrams, Gibb's plot, wilcox diagram	EC (412-14930 µS/cm), TDS (272-9854 mg/L)	• Approx. 50% of samples were found unsuitable/ having moderate-severe hazards as per EC, RSC, TDS. • Na% classified 50% samples under safe category.

6.	Ajmal et al. (2022)	Hyderabad district of Pakistan (handpumps, electric motors, tubewells)	Na%, SAR, RSC, MH, PI, KI	KI (0.4-6.5), PI (48.4-669.6), MH (20-60), Na% (38.9-87), SAR (5-50), RSC (-428 to -23.2)	• Maximum samples 'safe' as per KI. • >75% samples were under 'moderate to good' category as per Na%, MH, KI, SAR.
7.	Ayyandurai et al. (2022)	Cuddalore district of Tamil Nadu, India (handpumps)	Wilcox diagram, CAI 1 & 2, Na%, MAR, SAR, PI, KI	SAR (1.1-19.19), RSC (-18.36 to -3.3), Na% (21.82-78.38), KI (0.24-3.49), PI (34.83-82.9), MAR (10.69-53.88), CAI 1 (-0.46 to 0.54), CAI 2 (-0.30 to 2.53)	• Wilcox diagram classified 35% samples under suitable category. • Maximum samples classified as safe (SAR, RSC, Na%, KI, PI, MAR).
8.	Gugulothu et al. (2022)	Telangana, South India (groundwater samples)	CAI 1 & 2, RSC, MAR, SAR, Wilcox diagram, KI, EC	EC (88-1600µS/cm), SAR (0.13-6.71), RSC (-4.22 to 8.01), MAR (4.86-81.10), KI	• Classification of groundwater under poor/unsuitable category as per SAR,

				(0.06- 8.09), CAI 1 (-3.64 to 0.94), CAI 2 (-0.78 to 3.36)	RSC, MI and KI).
9.	Sarkar et al. (2022)	Malda district of West Bengal (wells)	Piper trilinear plots, SAR, Na%, MAR, PI, USSL diagrams, Wilcox	SAR (0.19-26.68), Na% (5.61-92.83), PI (19.14-59.78), KI (0.23-7.56)	• Wilcox diagram indicated 35% wells under unsuitable category of irrigation. • Piper diagrams revealed NaCl and HCO_3^- to be the dominant ions.
10.	Subramaniyan et al. (2022)	Southern Peninsula, India (groundwater samples)	Na%, SAR, RSC, EC, KI, MAR, PI, USSL, Wilcox	Na% (7-89), RSC (-10.4 to 6.7), KI (0.1-7.5), PI (21.2-124.3), MH (13.4- 48.8)	• PI and EC classified irrigation water as unsuitable. • Na%, SAR, RSC, KI, MH classified irrigation water as suitable.

					• 93% samples classified as suitable for irrigation.
11.	Zafar et al. (2022)	Patna, Bihar, India (groundwater samples)	SAR, Na%, RSBC, MR, PI, USSL diagrams, Doneen's plot	SAR (0.71-1.93), Na% (21.85-48.5), RSBC (-5.06), MR (6.68-37.26), PI (41.11-81.34)	• USSL diagrams indicated presence of medium-low salinity with low Na content. • Doneen's plot revealed that 98.3% samples have maximum permeability.
12.	Baterseh et al. (2021)	Abu Dhabi, Emirate, UAE (wells)	IWQI, SAR, Na%, PI, EC, Wilcox and USSL diagrams	Na% (32.27-92.71), EC (968-62000µs/cm), SAR (15.4-54.8)	• IWQI classified 96% samples under 'high – severe' restriction category. • Wilcox diagram indicated low salinity and low Na hazard

					while 78.6% samples under highest salinity and SAR class as per USSL plots.
13.	Sharma et al. (2021)	Dera Bassi tehsil of Punjab, India (Borewells and handpumps)	SAR, PI, RSC, Na%, USSL diagrams, Gibb's plot	SAR (0.08-1.99), PI (43.4-80.07), RSC (1.25-2.5), Na% (3.08-45.86),	• USSL diagrams classified max. groundwater samples under high salinity-low SAR class. • Rock dominance was reported as per Gibb's plot.
14.	Kumari and Rai (2020)	Haryana, India (Dug wells)	SAR, Na%, KI, MH, RSC, IWQI, USSL, Piper trilinear diagrams	SAR (1.64-27.71), Na% (26.3-72.88), KI (0.35-24.36), MH (11.91-94.36), RSC (-127 to 12.58), IWQI (-	• USSL classified groundwater samples under low to high salinity hazards. • Study area was found dominated by alkaline and

				3284.45 to 895)	strong acids as per Piper trilinear diagrams.
15.	Rawy et al. (2019)	Qena governorate area of Egypt (boreholes)	SAR, PI, MH, EC, RSC, KI, Piper-trilinear plots, Gibb's diagrams	EC (334-6045 µs/cm), SAR (0.5-14.4), RSC (-28.5 to 4.4), KI (0.1-9.5), PI (20.8-113.2), MH (10-97)	• Maximum samples found safe for irrigation usage (Na%, EC, SAR, KI, PI). • Few samples were reported to be unsuitable as per MH and RSC.
16.	Shil et al. (2019)	West Bengal, India (groundwater samples)	SAR, Na%, RSC, PI, KI, USSL diagrams	SAR (0.22-1.58), Na% (0.12-0.47), RSC (-0.53 to 1.03), KI (0.15-0.93), PI (65.97-100.23)	• USSL classified groundwater under low Na type and found fit for irrigation usage. • As per KI, PI and Na%, groundwater was found

					safe for irrigation usage.
17.	Abbassnia et al. (2018)	Chabahar, Sistan, Baluchistan, Iran (open dug wells)	SAR, IWQI	-	• 60% samples were reported under good-excellent category of IWQI.
18.	Chaudhary and Satheeshkumar (2018)	Arid areas of Rajasthan, India (handpumps)	SAR, Na%, RSC, RSBC, KI, PS, MH, PI, USSL diagrams, Piper-trilinear plots and Wilcox diagrams	PS (1.71-17.48), KI (0.12-2.09), RSC (-3.62 to 7.46), PI (22.62-83.72)	• USSL plots indicated high salinity and low alkalinity hazards. • Evaporation - crystallization effected the groundwater chemistry as per Gibb's plot.

19.	Rawat et al. (2018)	Kanchipuram district of Tamil Nadu, India (boreholes)	Na%, RSC, SAR, KI, PI, CAI-1&2, PS, MH, TDS, TH	SAR (0.25-69.09), RSC (-0.10 to 6.87), Na% (3.27-87.59), KI (0.03-6.60), PI (12.1-93.2), MH (4.46-92.98), TH (385.21-356.02 mg/L)), TDS (450-2000 mg/L), CAI-1 (0.02-0.04), CAI-2 (0.19-0.27)	• Irrigation indices classified maximum groundwater samples under 'moderate-unsuitable' category of irrigation water classification.
20.	Gagandeep et al. (2016)	Hodal block of Palwal district, Haryana, India (wells)	SAR, EC, RSC, Na^+, Cl^-	EC (8-12ds/m), SAR (5.66-19.94), RSC (0-4.70), Cl^- (7.14-89.77mg/L), Na^+(6.8-78.01mg/L)	• Carbonate weathering governed the hydrochemistry of groundwater. • Increasing trend of Na^+ and Cl^- ions were reported.

21.	Kumar et al. (2015)	Anna Nagar, Chennai City, Tamil Nadu, India (borewells)	EC, Cl^-, Gibb's plot, Piper trilinear plots	EC (580-7250 µS/cm), Cl^- (115.21-2011.8 mg/L)	• Evaporation and rock-water interaction domination as per Gibb's plot. • Na-Cl and mixed Ca-Mg-Cl type groundwater was reported according to Piper trilinear plots.
22.	Ravikumar et al. (2015)	Karnataka, India (tubewells)	SAR, Na%, CAI-1& 2, Durov plots, Piper plots	CAI-1 (-0.02 to 0.85), CAI-2 (-0.084 to 1.931), SAR (0.41-2.78), Na% (7.3-42.4)	• Ca-Mg-Cl-SO_4 water type dominance was reported as per Piper plots. • Durov diagrams indicated that mineral dissolution responsible for hydrochemistry of

					groundwater of study area.
23.	Singha D (2017)	Idukki district of Kerala, India (dugwells)	Salinity Index, TH, SAR, Na%, PI, SSP, MH, USSL and Piper trilinear diagrams	SAR (0.65-7.07), Na% (10.05-39.36), Salinity index (56-298), MH (8.84-42.86), SSP (12.45-47.05)	• Groundwater was found suitable for irrigation according to Gibb's and Wilcox diagrams. • Gibb's plot indicated that rock dominance controlled the groundwater chemistry.
24.	Sadashivaiah et al. (2008)	Tumkur taluk, Karnataka, India (groundwater samples)	SAR, RSC, Na%, USSL, Piper plots, Wilcox diagrams	Na% (3.34-61.46), RSC (0.47-1.55), SAR (0.11-3.54)	• Ca-Mg-HCO_3 type dominated the groundwater. • Maximum water samples reported suitable for irrigation

					(SAR, Na%, RSC).
25.	Rao N S (2006)	Guntur district, Andhra Pradesh, India (wells)	USSL diagrams, Wilcox, Gibb's plot, RSC, SAR, Na%	SAR (2-14), Na% (13-87), USSL (5-18%) - good category	• Maximum samples found to be unfit for irrigation (Wilcox, USSL, Na%). • High rock-water interaction was reported. • Groundwater samples belong to non-carbonate alkali type group as per Gibb's plot.

2.3 Review on groundwater quality for health risk assessment

Heavy metals contribute a lot in groundwater contamination. They have the ability to cause various health issues including nervous system disorders, kidney damage, liver damage and cancer as well. So, assessment of heavy metals in groundwater by applying health indices become necessary. Based on literature reviewed, health indices such as Heavy Metal Pollution Index (HPI), Human health risk assessment (HHRA), Hazard quotient (HQ) etc. were applied to assess the quality of groundwater. Research studies conducted in different areas of the world helped to get the information regarding the indices used and are discussed as under:

1. Dhakshinamoorthy et al. (2025) did the comprehensive evaluation of groundwater quality in Mayiladuthurai district of Tamil Nadu, India. Ten samples were collected from borewells and handpumps and were analysed for parameters including pH, EC, TDS, Iron (Fe^{2+}), Nitrate (NO_3^-), several major cations and anions. On comparing the result findings with the WHO and BIS drinking water standards, it was found that few parameters were exceeding their permissible limits, which includes, Fe^{2+} (up to 1.0 mg/l in 40% of samples), Na^+ (11.8-288 mg/l), TDS (30% of samples), NO_3^- (up to 31 mg/l), Total hardness (160-340 mg/l). Study reported both geogenic and anthropogenic influences followed by impact of agricultural runoff, domestic discharge and local lithology on groundwater quality and emphasized the urgent requirement for regular monitoring and localized treatment interventions to ensure safe and sustainable water use.
2. Acharya et al. (2023) evaluated the hydrochemistry of Dwarka area of New Delhi, India. Total of 150 samples from groundwater were taken and were analysed for drinking and irrigation usage. Chromium (Cr), Copper (Cu), Nickel (Ni), SO_4^{2-}, NO_3^-, F^-, WQI, TDS and Nitrates were major concern for evaluation. Piper trilinear along with Chadha diagrams were plotted to get the view of groundwater hydrochemistry of study region. 87% of the groundwater fall under 'poor to unsuitable category' of WQI which indicate its unsuitability for drinking use. Overall, groundwater was reported as 'moderately suitable' for irrigation. Maximum samples were reported to be safe under SO_4^{2-}, F^- and unsafe for NO_3^-.
3. Raja et al. (2021) assessed the health risks posed by metals in water of Virudhunagar town of Tamil Nadu, India. 8 heavy metals viz., Cr (VI), Cd^{2+}, Co^{2+}, Cu^{2+}, Mn^{2+}, Ni^{2+}, Pb^{2+} and Zn^{2+} were assessed. 20 groundwater samples were collected and were analysed for these heavy metals. Health indices such as Heavy metal evaluation Index (HEI), degree of contamination, HPI, Carcinogenic Risks (CR) and non-carcinogenic risks were calculated. The calculated CR values for Pb^{2+}, Ni^{2+} and Cd^{2+} exceed the safe limits (10^{-6} to 10^{-4}). The noncarcinogenic risk exceeds the acceptable limit for Pb^{2+} and Cr (VI). The higher carcinogenic and noncarcinogenic risk values proved that the study area has health risks due to Pb^{2+}, Cd^{2+}, Ni^{2+} and Cr (VI). Also, factor analysis and cluster analysis revealed that the wastage dumpsites and the industrial impact are the major sources for heavy metal contamination in groundwater of the study area.

4. Abdelhafez et al. (2021) evaluated underground water quality of New Valley Governorate area of Egypt. To check its suitability for irrigation and drinking purpose, 30 well water samples were assessed for various physico-chemical parameters such as major cations and anions, heavy metals and irrigation water quality indices. Groundwater of study area was reported safe for drinking and irrigation except in few areas. Water quality of study area was found to be 'Na' free risk in terms of SAR. Fe^{2+} and Pb^{2+} found to be main contaminants in study area and may have adverse effect on children. Groundwater of this area must be pre-treated to control the threats caused by drinking contaminated water.
5. Guo et al. (2021) evaluated the groundwater suitability for irrigation and drinking purpose of North China plain. Deep and shallow groundwater samples were chosen. WQI along with other groundwater quality and irrigation water quality parameters were calculated for 59 groundwater samples. Water samples were analysed for HHRA and non-carcinogenic risks/ Hazard quotient (HQ) for children, men and women via dermal and ingestion route. The study revealed that groundwater was suitable for irrigation but not for drinking purpose. Health risk due to groundwater contamination with high concentration of Fluoride and Iodine was reported higher in children. Effective measures such as groundwater management, groundwater quality investigation and monitoring etc. can be implied to improve the groundwater quality of study area.
6. Health risk assessment of toxic metals in groundwater components of Ergene River basin of Turkey has been done by Tokatli C (2021). 66 groundwater samples were analysed for As^{3+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, Pb^{2+}. HPI and HEI were also calculated. Pb^{2+}, Cd^{2+} and As^{3+} were highly toxic components reported in groundwater of study area. Cancer risk for As^{3+} in 50% of samples were reported.
7. 97 groundwater samples were collected from shallow aquifers of Sarkand, Sindh, Pakistan. Analysis for heavy metals (Fe^{2+}, As^{3+}) was done and calculated HHRA, CR, HQ (Baloch et al. 2021). It was reported that all samples were found suitable for health rate assessment in adults while 20% samples were exceeding the limits in case of children. Study concluded that out of 95 groundwater samples, only 20 samples were having As^{3+} and Fe^{2+} carcinogenic risks.
8. Lorestani et al. (2020) assessed the heavy metal concentration in groundwater of Hamedan-Bahar plain of western Iran. 9 heavy metals (As^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Cr (VI), Cu^{2+}, Fe^{2+}, Mn^{2+}, Zn^{2+}) were assessed. Pollution indicators and health assessments were evaluated to find out the contamination of groundwater with heavy metals. 'Pb^{2+}' and

'Ni^{2+}' were posing great threat. Average HPI and HEI values were 815.5 and 89.1 respectively, representing high risk for aquatic life but no risk of cancer was reported.

9. Groundwater analysis was conducted to check irrigation and drinking groundwater suitability with focus on nitrate pollution in Tamil Nadu, India (Paneerselvam et al. 2020). From 67 sample locations, sampling was carried out for post-monsoon season. Major cations and anions were assessed, WQI, Irrigation Water Quality Indices, Nitrate Pollution Index (NPI) were calculated. Health risk assessment on human health was carried out to know the impact of ingesting contaminated groundwater. NPI results reported that 15 locations should be monitored at regular intervals due to human activities, fertilizers and sewage intrusion found to be main causes of nitrate pollution in study area. Also, groundwater was found fit for irrigation usage while 28.35% of samples need treatment before drinking. Study found children to be at higher risk than adults in study area. Fully covered septic tanks were recommended, usage of natural fertilizers and proper sewage drainage system were suggested to improve the groundwater quality of study region.
10. Assessment of heavy metal contamination in Nalagarh area of Himachal Pradesh, India was carried out by Rajkumar et al. (2020). From 15 different sampling sites, groundwater samples were collected and were analyzed for heavy metals (Cr (VI), Cu^{2+}, Fe^{2+}, Mn^{2+}, Zn^{2+}, As^{3+}, Ni^{2+}, Pb^{2+}) and HPI, HEI, Contamination index (C_d) were also calculated. It was reported that Cr (VI), Cu^{2+}, Fe^{2+}, Mn^{2+} and Zn^{2+} originated from lithogenic sources while As, Cd, Ni and Pb originated from anthropogenic sources.
11. Lanjwani et al. (2020) assessed drinking and irrigation suitability of Shahdadkot district of Sindh. Water samples from 38 sites were collected and assessed for different parameters as well as for heavy metals (Ni^{2+}, Pb^{2+}, Mn^{2+}, Cd^{2+}, Cr^{3+}, Co^{2+}, Cu^{2+}, As^{3+}). For drinking purpose, EC, Na^{+}, TDS, K^{+}, Ca^{2+}, TA, Mg^{2+}, Cl^{-}, NO_3^{-}, TH, SO_4^{2-} were determined while for irrigation purpose, SAR, PI, CAI1, KI, RSC, Na% were calculated. The results were then compared with WHO drinking water standards. Values of EC and TDS were found 58% higher than WHO limits. It was also reported that concentration of F^{-} and NO_3^{-} were also above the permissible limits of WHO. 58% of water samples were unsuitable for drinking but could be used for irrigation purposes. High concentration of Ni^{2+}, Cr^{3+}, Pb^{2+} and Cd^{2+} was reported due to drainage wastewater and geological nature of area.
12. Loh et al. (2020) assessed the hydrochemistry and groundwater quality in Voltanian and basement aquifers of Northern Ghana. 112 groundwater samples were tested for its

drinking, domestic & irrigation use by analyzing various water quality parameters and heavy metals (Fe^{2+}, Mn^{2+}, As^{3+}, F^-, SO_4^{2-}, PO_4^{2-}, NO_3^-) assessment. Study found that dissolution of silicate minerals, agrochemicals and domestic waste to be the main cause of groundwater contamination in this area. According to WQI, 94% of samples found to be of excellent quality and is suitable for drinking and domestic use. Water was reported unsuitable due to elevated levels of F^-, As^{3+} and Fe^{2+} and may resulted from leaching of such ions to the groundwater.

13. Beyene et al. (2019) evaluated groundwater suitability in Jimma Zone of Oromia, Ethiopia. For sampling purpose, thirty-two groundwater samples were collected from boreholes of 7 districts of Jimma Zone and were assessed for various physico-chemical parameters such as Fe^{2+}, F^-, SO_4^{2-}, NO_3^-. High concentration of Na^+ and F^- was found in groundwater of study area, which made it unfit for drinking and irrigation purpose. However, 68.8% of groundwater samples fall under good category of irrigation. High conc. of F- were reported in which ~47% samples exceeded the limits. So, defluorination of groundwater was mandatory to use for drinking water.
14. Kaur et al. (2019) quantitatively assessed the human health exposure of heavy metals contamination from groundwater and soil in Reasi district of J&K. This study has been conducted in two age groups via three routes i.e., dermal, inhalation and ingestion. Heavy metal's (Pb^{2+}, Cd^{2+}, Cr^{3+}, Cu^{2+} and Zn^{2+}) concentration was detected using microwave plasma atomic emission spectrometer. It was observed that concentration of heavy metals in groundwater was within the permissible limits except Pb^{2+} and Cr^{3+}. However, the carcinogenic risks have been found within the prescribed limits set by United State Environmental Protection Agency (USEPA). Vehicular emissions, traffic and industrial sources could be the cause of heavy metals in groundwater. The study concluded that the overall risk is higher in children than adults which may be because of hand to mouth activities.
15. In northeast Iran, health risk assessment of Pb^{2+}, Cr(VI), As^{3+}, Ni^{2+} and Hg^{2+} through ingestion and dermal routes was done by Alidadi et al. (2019). 140 samples were chosen and health risks (HQ, HI and CR) were evaluated. Results of this study showed that HI for children were higher than safety limits. CR values for adult and children were reported to be 7.38×10^{-5} and 1.33×10^{-4} respectively. Thus, proper water treatment programs and control measures should be imposed to prevent locals from health risks.
16. Khanoranga and Khalid (2019) assessed groundwater for irrigation and drinking purpose in 3 districts of Balochistan province of Pakistan by applying WQI and

Multivariate statistical approaches. 30 groundwater samples were collected and were analyzed for major anions (NO_3^-, SO_4^{2-}, Cl^-, HCO_3^-), physico-chemical parameters (TDS, pH, EC), Heavy metals (Cd^{2+}, Zn^{2+}, Ni^{2+}, Pb^{2+}, Mn^{2+}, As^{3+}) and Metals (Na^+, K^+, Ca^{2+}, Mg^{2+}) and the results were compared with WHO standards. The results of study showed that majority of water samples were beyond permissible limits of WHO with few exceptions. Na^+ and HCO_3^{2-} were dominant cation & anion respectively. According to WQI, water was found unsuitable for drinking. Except Cu^{2+}, Zn^{2+} and Mn^{2+}, all heavy metals exceed WHO 2011 permissible limits. So, remedial measures to safeguard local people health were recommended by the authors.

17. Saraswat et al. (2019) conducted a study on geochemical analysis of groundwater of Surat to estimate the quality of groundwater resources. Samples were chosen from bore wells, open wells, dug wells and handpumps. In this study, ground water quality parameters like Hardness, TDS, Fe^{2+}, Cr^{3+}, PO_4^{3-}, SO_4^{2-} and NO_3^- were analysed. The results concluded that groundwater in city is not potable as concentration of Cr^{3+}, TH, TDS and Cl^- was exceeding at all sampling sites, which pose severe health impacts on local people. Thus, the study recommended to consume the water with proper treatment.
18. 67 groundwater samples from urban Bengaluru, India has been collected and analyzed for its quality assessment and were analyzed for Fe^{2+}, NO_3^-, F^-, SO_4^{2-} during pre- and post- monsoon period. WQI and multivariate statistical techniques were also applied. 50% samples were reported to be unfit for drinking and thus need some treatment before consumption. Maximum parameters exceed the permissible limits of BIS-10500. Anthropogenic activities, ion-exchange processes in water and rock-water interaction in aquifer were main causes of groundwater contamination in study area (Gulgundi and Shetty, 2018).
19. 40 water samples from different dug wells/borewells of Kadava River basin of Nashik, India, were collected. This study has been conducted by Wagh et al. (2018) to assess the health risks offered by metals in study region. For assessment, heavy metals (Pb^{2+}, Cr^{3+}, Zn^{2+}, Cd^{2+}, Mn^{2+}, Fe^{2+}, Co^{2+}, Cu^{2+}, Ni^{2+}) were analysed and HPI, HEI, HI were calculated. The study reported that groundwater was not suitable for drinking purposes due to high pollution load from heavy metals. Causes of heavy metal pollution in study area were land use pattern, intensive farming, domestic waste, leachates of fertilizers and pesticides.
20. Heavy metals and radon concentrations in Udhampur area of J&K, India, were assessed by Kumar et al. (2017). Groundwater samples were taken from handpumps, springs &

boreholes and parameters like pH, EC, TDS, Zn^{2+}, Fe^{2+}, Cu^{2+}, Pb^{2+} and Cr^{3+} were analysed. Then the results were compared with BIS & WHO standards. Most of the samples were found within the permissible limits set by WHO while 17.07% of samples had high concentration above safe limits. Overall, study concluded that water was safe for human consumption and household utilizations.

21. Kaur et al. (2017) conducted groundwater quality assessment study for drinking and irrigation purpose in Malwa region of Punjab, India. 24 groundwater samples were chosen and were analyzed for various groundwater quality parameters (Fe^{2+}, As^{3+}, F^-, SO_4^{2-}, NO_3^-), Gibb's Diagram and rock-water interaction. Study found that EC, TH, TA, Ca^{2+}, SO_4^{2-}, F^- and As^{3+} were above permissible limits of WHO and BIS; which indicates unsuitability of water for drinking. Elevated levels of As^{3+} in the study area was reported due to its evaporative environment and agricultural activities. Excessive use of fertilizers, increase in pumping of groundwater and industrial effluents found to be the major reasons of contamination in the study area. So, continuous water quality monitoring and detailed hydrogeochemical investigation were suggested.
22. A cross-sectional study for measuring drinking water quality in Bangladesh has been conducted. A total of 960 household samples were randomly selected and were tested for salinity, pH, WQI, As^{3+}, Mn^{2+} and Fe^{2+}. Study revealed that drinking water was slightly alkaline and salinity was also high. Water quality of majority of households found to be unsuitable for drinking because of high concentration of As^{3+} and Mn^{2+}. Children were found vulnerable to high Mn^{2+} concentration due to their low protective mechanisms. So, awareness among people was suggested to improve water quality and health of people (Akter et al. 2016).
23. A study to analyse the impact of polluted surface water of Budha Nullah on groundwater quality of Ludhiana region has been conducted by Singh et al. (2013). Water samples were taken from handpumps, tube wells and Budha Nullah. Physico-chemical parameters, biological parameters and heavy metals (As^{3+}, B, Fe^{2+}, Zn^{2+}, Pb^{2+}, Ni^{2+}, Cd^{2+}, Cu^{2+}, Cr^{3+}, Mn^{2+}) were analysed. At few places, quality of ground water was found unfit for drinking purpose but can be applied for irrigation purpose. Heavy metals were also found to be within range. Comparative analysis of the result with CPCB values indicated that the water of Budha Nullah is not suitable for outdoor bathing, drinking, irrigation and industrial cooling purpose, propagation of wildlife and fisheries. Dark color of surface water indicates the industrial effluents discharge into water without pre- treatment.

24. Groundwater samples of Jimeta-Yola area of Nigeria were collected from boreholes and dug wells during dry and rainy season. Physico-chemical parameters (Fe^{2+}, Cr (VI), NO_3^-, SO_4^{2-}) and WQI were analysed and values were then compared with WHO standards. The study found that the water quality is good in dry season whereas poor water quality was observed during rainy seasons. Groundwater in dry season found contaminated with NO_3^- and Cr (VI). Overall dry season was found with good water quality as compared to rainy season. Sources of contamination in study area include household solid waste, waste water and sewage effluents. So, water consumption with proper treatment has been suggested (Ishaku J.M, 2011)
25. Prakash and Somashekhar (2006) collected 1026 groundwater samples from Anekal Taluk area of Bangalore, India and were tested for various physico-chemical and biological parameters (Fe^{2+}, NO_3^-, SO_4^{2-}, F^-). It was found that turbidity, calcium and fluoride concentration exceed the permissible limits of BIS. High content of Fe^{2+} was reported due to rock formation. Also, groundwater of this area found to have bacteriological influence. Study concluded that out of 1026 samples, 836 samples found unsuitable for drinking as per BIS standards.

Table 3: Summary of literature review on different heavy metals and indices used to evaluate health risks from contaminated groundwater.

S. No.	References	Study area (source of water)	Heavy metals assessed/Indices used	Results	Research Findings
1.	Dhakshinamoorthy et al. (2025)	Tamil Nadu, India	Iron (Fe^{2+}), Nitrate (NO_3^-), Fluoride (F^-)	Fe^{2+} (0-1.0 mg/l) F^- (0.1-1.1 mg/l), NO_3^- (8-31 mg/l)	• Fe^{2+} was exceeding its limits in 40% samples. • Both geogenic and anthropogenic activities

					were found and continuous monitoring of groundwater was suggested.
2.	Acharya et al. (2023)	Dwarka region of New Delhi, India (groundwater)	Chromium (Cr^{6+}), Copper (Cu^{2+}), Nickel (Ni^{2+}), SO_4^{2-}, NO_3^-, F^- (conc. in mg/L)	Cr^{6+}, Ni^{2+}, Cu^{2+} are Not detectable at ppm level, F^-(0-1.9), NO_3^- (0.02-188.6), SO_4^{2-} (0.0-424.15)	• Maximum samples were reported to be safe under SO_4^{2-}, F^- and unsafe for NO_3^-.
3.	Raja et al. (2021)	Industrial area of Virudhunagar, Tamil Nadu, India (borewells)	Cadmium (Cd^{2+}), Cobalt (Co^{2+}), Zinc (Zn^{2+}), Lead (Pb^{2+}), Manganese (Mn^{2+}), Cu^{2+}, Cr^{6+}, Ni^{2+}, Heavy metal Pollution Index (HPI), Average daily dose (ADD), carcinogenic	Cd^{2+} (0.03-0.05), Ni^{2+} (0.19-0.44), Co^{2+} (0.05-0.26), Cu^{2+} (0.01-0.07), Mn^{2+} (0.003-0.05), Cr^{6+}	• Carcinogenic risks were found from Pb^{2+}, Cd^{2+}, Ni^{2+} and Cr^{6+}. • Non-carcinogenic risks of Pb^{2+} and Cr^{6+} were reported.

			risks (CR), heavy metal evaluation index (HEI), non-carcinogenic risks	(0.02-0.23), Zn^{2+} (0.03-0.66), Pb^{2+} (0.11-0.96), HPI (999-3232), HEI (42-140) (conc. in µg/L)	
4.	Abdelhafez et al. (2021)	Southern-western desert of Egypt (wells)	ADD, Hazard Quotient (HQ), Fe^{2+}, Zn^{2+}, Mn^{2+}, Cu^{2+}, Pb^{2+}, Cd^{2+}, Arsenic (As^{3+}), Selenium (Se^{4+})	_	• Pb^{2+} and Fe^{2+} contamination was reported. • Fe^{2+}, Mn^{2+}, Pb^{2+} and As^{3+} pose chronic threats to children.
5.	Guo et al. (2021)	Bazhou, Central North China Plain (deep groundwater wells)	Human health risk assessment (HHRA), HQ for Iodine (I^-) & Fluoride (F^-) (Children, Men and Women)	For Fluoride, HQ For Fluoride, HQ (0.22-3.1, 0.15-2.2, 0.17-2.4), For	• 65.8% deep groundwater samples were unacceptable.

				Iodine HQ (0.000031 -0.0056, 0.000023-0.0042, 0.000023-0.0042)	• Higher concentration of F^- and I^- for a longer duration can lead to potential impact on the children's health.
6.	Tokatli C, (2021)	Ergene River basin, Turkey (groundwater)	HPI, HEI, HI, HQ, ADD, As^{3+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, Pb^{2+}	_	• As^{3+}, Pb^{2+} and Cd^{2+} pose high health risks. • 50% samples were reported with high health risk factor.
7.	Baloch et al. (2021)	Sarkand, Sindh, Pakistan (Shallow aquifers)	Fe^{2+}, As^{3+}, HHRA, CR, HQ (children & adult)	Fe^{2+} (0-0.43) ppm, As^{3+} (0-10) ppb, For As^{3+}, HQ_c (0-0.000667)	• Out of 95 groundwater samples, only 20 samples were having As^{3+} and

				, HQ_a (0-0.000286), For Fe^{2+} HQ_c (0-0.395), HQ_a (0-0.01229)	Fe^{2+} carcinogenic risks.
8.	Lorestani et al. (2020)	Hamedan-Bahar plain, Western Iran (wells)	As^{3+}, Zn^{2+}, Ni^{2+}, Cr^{3+}, Pb^{2+}, Cu^{2+}, Fe^{2+}, Cd^{2+}, Mn^{2+}, HPI, HEI, ADD (conc. in µg/L)	As^{3+} (36.93-112.66), Cr^{3+} (117.63-894.90), Cu^{2+} (138.16-650.23), Fe^{2+} (2829.63-7157.93), Pb^{2+} (359.03-3580.96), Ni^{2+} (98.76-757.93), Zn^{2+} (173.50-1890.36), HEI (251.7-1202.1), HEI (127.04)	• Pb^{2+} and Ni^{2+} were reported with higher concentration in groundwater of study area. • No relationship between heavy metals concentration and Cancer risks were reported.

9.	Rajkumar et al. (2020)	Nalagarh, Himachal Pradesh, India (groundwater samples)	HPI, HEI, Contamination index (C_d), Cr^{3+}, Fe^{2+}, Cu^{2+}, Mn^{2+}, As^{3+}, Ni^{2+}, Zn^{2+}, Pb^{2+} (conc. in µg/L)	As^{3+} (2-10), Cd^{2+} (0-7), Cr^{3+} (0-94), Cu^{2+} (0-113), Fe^{2+} (8-1366), Mn^{2+} (10-221), Ni^{2+} (11-85), Pb^{2+} (11-62), Zn^{2+} (56-1180), Cd^{2+} (1031-37.87), HEI (10.31-46.87), HPI (10.73-107.50)	• Cr^{3+}, Cu^{2+}, Fe^{2+}, Mn^{2+} and Zn^{2+} originated from lithogenic sources. • As^{3+}, Cd^{2+}, Ni^{2+} and Pb^{2+} originated from anthropogenic sources.
10.	Paneerselvam et al. (2020)	Yercaud area of Tamil Nadu, Southern India (borewells)	Nitrate Pollution Index (NPI), HHRA, HQ	NPI (-0.65 to 3.7), HQ male (1.68E-01 to 2.26E + 01), HQ female (1.99E-01 to 2.67E+00), HQ	• 78% samples were reported to be safe as per NPI. • Higher health risks in case of children

				children (2.28E-01 to 3.06E+00)	were reported.
11.	Lanjwani et al. (2020)	Qambar district of Shahdadkot, Sindh (pumps and wells)	Pb^{2+}, Cd^{2+}, Cu^{2+}, Cr^{3+}, Ni^{2+}, Co^{2+}, Mn^{2+}, As^{3+} (conc. in µg/L)	Cu^{2+} (3.7-81.4), Cd^{2+} (bdl-25.9), Cr^{3+} (100-300), Ni^{2+} (6.9-140), Co^{2+} (0.1-60.7), Mn^{2+} (bdl-95.3), Fe^{2+} (15 .4-279), As^{3+} (bdl-25) where bdl - below detection limits	• High conc. of Ni^{2+}, Cr^{3+}, Pb^{2+} and Cd^{2+} was reported due to drainage wastewater and geological nature of area.
12.	Loh et al. (2020)	Western part of Savannah region of Ghana (boreholes)	Fe^{2+}, Mn^{2+}, As^{3+}, F^-, SO_4^{2-}, PO_4^{3-}, NO_3^- (conc. in mg/L)	Fe^{2+} (0.01-4.13), Mn^{2+} (0.01-0.29), As^{3+} (0.01-0.08), F^- (0.02-2.4), NO_3^- (0.01-5.3), PO_4^{3-}	• Water was reported unsuitable due to elevated levels of F^-, As^{3+} and Fe^{2+} and may resulted from

				(0.01-0.39), SO_4^{2-} (2.5-65.2)	leaching of such ions to the groundwater.
13.	Alidadi et al. (2019)	North east Iran (groundwater samples)	ADD, CR and Non-carcinogenic Risks (adults & children), As^{3+}, Pb^{2+}, Ni^{2+}, Cr^{6+}, Hg^{2+} (conc. in mg/L)	As^{3+} (0.18± 0.058), Pb^{2+} (0.65±0.25), Cr^{6+} (4.58±6.11), Ni^{2+} (1.49± 0.88), CR ($9.62*10^{-7}$ to $8.72*10^{-5}$)	• Daily contaminated water intake via ingestion were found to be 4-10 times higher than those via dermal contact.
14.	Beyene et al. (2019)	Jimma zone of Oromia, Ethiopia (boreholes and wells)	Fe^{2+}, F^-, SO_4^{2-}, NO_3^- (conc. in mg/L)	Fe^{2+} (0.11-0.56), F^- (0.15-11.78), SO_4^{2-} (1.91-42.04), NO_3^- (0.08-13.29)	• High conc. of F- were reported in which ~47% samples exceeded the limits.
15.	Kaur et al. (2019)	Reasi, Jammu and Kashmir, India	Carcinogenic Risks (CR), Pb^{2+}, Cr^{3+}, Cd^{2+}, Cu^{2+} and Zn^{2+}	Zn^{2+} (0.3-1.0), Cu^{2+} (0.3-1.0), Pb^{2+} (0.05-0.8),	• Pb^{2+} and Cr^{3+} were exceeding the WHO

		(groundwater samples)	(conc. in mg/L)	Cr^{3+} (0.05-0.2), CR (Pb^{2+} and Cr^{3+}) for ingestion (1.7E-07 & 1.5E-07), inhalation (9.9E-12 & 1.6E-08), dermal (5.7E-10 & 4.3E-08)	standard limits. • Cd^{2+} was below the detection limits 85i.e., 0.05mg/L.
16.	Khanoranga and Khalid (2019)	Balochistan province of Pakistan (groundwater samples)	As^{3+}, Hg^{2+}, Ni^{2+}, Cd^{2+}, Cr^{3+}, Fe^{2+}, Pb^{2+}, Cu^{2+}, Zn^{2+}, Mn^{2+} (conc. in mg/L)	Cd^{2+} (0.003-0.35), Cr^{3+} (0.01-0.09), Pb^{2+} (0.02-0.1), Cu^{2+} (0.031-0.09), Mn^{2+} (0.02-0.91), Fe^{2+} (0.30-1.10), Zn^{2+} (0.01-0.41)	• Except Cu^{2+}, Zn^{2+} and Mn^{2+}, all heavy metals exceed WHO 2011 permissible limits.

17.	Saraswat et al. (2019)	Surat City, Gujarat, India (borewells, dug wells, open wells and handpumps)	Fe^{2+}, Cr^{6+}, NO_3^-, PO_4^{3-}, SO_4^{2-} (conc. in mg/L)	Fe^{2+} (0.32-6.18), Cr^{6+} (106.58-1205.22), NO_3^- (0.09-0.42), PO_4^{3-} (2.09-9.26)	• Concentration of Cr^{6+} was exceeding at all sampling sites.
18.	Gulgundi and Shetty (2018)	Bengaluru, India (groundwater samples)	Fe^{2+}, NO_3^-, F^-, SO_4^{2-} (for PRM and POM season) (conc. in mg/L)	For PRM, Fe^{2+} (0.05-4.30), F^- (0.11-1.38) For POM, Fe^{2+} (0.05-4.60), F^- (0.11-1.40)	• 50% groundwater samples were reported unsuitable for drinking.
19.	Wagh et al. (2018)	Kadava River basin, Nashik, India (dug wells/bore wells)	Pb^{2+}, Zn^{2+}, Fe^{2+}, Co^{2+}, Cr^{3+}, Ni^{2+}, Cd^{2+}, Mn^{2+}, Cu^{2+}, HEI, HPI, HI (conc. in mg/L)	Pb^{2+} (0.29-1.96), Cd^{2+} (0.005-0.051), Zn^{2+} (0.023-0.209), Fe^{2+} (0.092-3.558), Mn^{2+}	• 82.5% samples represent high pollution risk as per HEI. • 75% samples indicated medium-high pollution

				(0.013-0.142), Co^{2+} (0.001-0.267), Cr^{3+} (0.034-3.516), Cu^{2+} (0.006-0.086), Ni^{2+} (0.114-0.225), HEI (522.84-2010.05), HPI (476.99-1833.65)	risk according to HPI.
20.	Kumar et al. (2017)	Udhampur district, Jammu & Kashmir, India (handpumps, springs, bowli's, boreholes)	Radon (Rn^{2+}), Zn^{2+}, Cd^{2+}, Iron (Fe^{2+}), Cu^{2+}, Ni^{2+}, As^{3+}, Co^{2+}, Pb^{2+}, Cr^{3+}, Mercury (Hg^{2+}) (conc. in mg/L)	Zn^{2+} (0.15-7.52), Fe^{2+} (0.16-1.95), Pb^{2+} (0.01-0.15), Cu^{2+} (0.01-0.08), Cr^{3+} (0.01-0.14)	• Cd^{2+}, Ni^{2+}, As^{3+}, Hg^{2+}, Co^{2+} were present in negligible amount. • 17.07% samples reported with Rn concentration above the

					permissible limits.
21.	Kaur et al. (2017)	Malwa region of SW Punjab, India (groundwater)	Fe^{2+}, As^{3+}, F^-, SO_4^{2-}, NO_3^- (conc. in mg/L)	Fe^{2+} (0.009-7.7), As^{3+} (4.35-23.25), NO_3^- (0.17-9.14), SO_4^{2-} (68.67-692.22), F^- (0.81-2.98)	• High concentration of As^{3+} was reported due to its evaporative environment and agricultural activities.
22.	Akter et al. (2016)	Rural Bangladesh (drinking water source)	Mn^{2+}, Fe^{2+}, As^{3+} (conc. in mg/L)	Mn^{2+} (1-5.5), Fe^{2+} (0.3-2.3), As^{3+} (0.002-8.01)	• Children were reported vulnerable to higher Mn^{2+} concentration due to their low immunity. • Major households used poor quality water for drinking.

23.	Singh et al. (2013)	Budha Nullah and its vicinity in Ludhiana, Punjab, India (handpumps and tubewells)	As^{3+}, Boron (B^{+}), Ca^{2+}, Zn^{2+}, Cd^{2+}, Cr^{3+}, Fe^{2+}, Cu^{2+}, Ni^{2+}, Pb^{2+}, Mn^{2+} (conc. in mg/L)	As^{3+} (0.007-0.014), B^{+} (0.088-0.179), Cd^{2+} (0.004-0.144), Cr^{3+} (0.005-0.021), Cu^{2+} (0.358-11.484), Fe^{2+} (2.447-6.584), Mn^{2+} (2.72-5.24), Ni^{2+} (0.014-8.746), Pb^{2+} (0.354-3.864), Zn^{2+} (0.583-36.02)	• As per CPCB standards, water quality of study area was found unsuitable for drinking, irrigation, outdoor bathing, propagation of wildlife and industrial cooling.
24.	Ishaku J. M (2011)	Jimeta Yola area of Northeast Nigeria (hand dug	Fe^{2+}, Cr^{6+}, NO_3^{-}, SO_4^{2-} (conc. in mg/L)	Fe^{2+} (0.0-5.6), Cr^{6+} (0.0-0.11), NO_3^{-} (3.1-238.8),	• Groundwater in dry season found contaminat

		wells, bore holes, leachates)		SO_4^{2-} (1-122)	ed with NO_3^- and Cr^{6+}. • Overall dry season was found with good water quality as compared to rainy season.
25.	Prakash and Somashekhar (2006)	Anekal Taluk, Bangalore urban district, India (groundwater samples)	Fe^{2+}, NO_3^-, SO_4^{2-}, F^- (conc. in mg/L)	Fe^{2+} (0-10.15), NO_3^- (0.01-6.72), SO_4^{2-} (0-1678.2), F^- (0-16)	• High content of Fe^{2+} was reported due to rock formation.

CHAPTER 3
MATERIALS AND METHODS

3.1 STUDY AREA

Study area lies in the Jammu district of Jammu and Kashmir, India and is selected to evaluate the groundwater quality for irrigation and drinking purposes. In this area, local people are dependent on agriculture for their livelihood and on groundwater for the domestic, irrigation and drinking purpose.

Jammu and Kashmir (J&K) is the northmost part of India. Earlier, it was having its statehood which was ended in 2019 and from then, it has come under the category of Union Territory (UT). Ranbir Singh Pura (R. S. Pura) is a small town situated in Jammu district of J&K, India and is famous all around the world for its Basmati Rice. The alluvial type of soil is found in the study area. Its location lies at 32.63°N 74.73°E and possesses altitude of 270 m (approx.) above sea level. Average daily temperature of the study area in summer is around 44 °C and in winter, it is approx. 6 °C. Average annual rainfall for pre-monsoon and post-monsoon season of year 2022 was 99.5 mm and 114.5 mm respectively. The total area of this town is 245 Km^2, out of which 238.25 Km^2 is rural while 6.75 Km^2 is under urban area. The total population of study area is 1,97,739 (as per 2011 census). This region is selected for study because of its agrarian importance. As this area is well known for production of Basmati rice, so, locals are highly dependent on farming practices. In order to increase the crop yield, farmers are utilizing pesticides and fertilizers in their farms. Hence overuse of fertilizers and pesticides in agricultural fields can contaminate the groundwater. As groundwater is the only major source for irrigation, drinking and other purposes and is deriving either through tube wells, borewells or hand pumps, the locals are prone to contamination due to groundwater pollution from different sources.

Study area (Fig. 2) includes 25 different villages namely main R.S. Pura, Kotli Gala Bana, Agra Chak, Khana Chak, Abdulliyan, Rangpur Sadrey, Mottey, Suchetgarh, Gharana, Purana Pind, Satraiyan, Satowali, Bhadyal Qazian, Khamb, Sunderpur, Musa Chak, Dablehar, Chohala, Kotli Arjan Singh, Biaspur, Seer, Gagian, Nari, Kheper and Jassore. All these sampling sites are shown in Fig. 3. Groundwater samples from these areas were collected for pre-monsoon (May-June) and post- monsoon (Oct.-Nov.) season of year 2022. The samples collected were then tested in the laboratory and were assessed for water suitability for

agricultural and drinking purposes using various indices. The results so obtained were then interpreted and conclusions are drawn on the basis of results obtained.

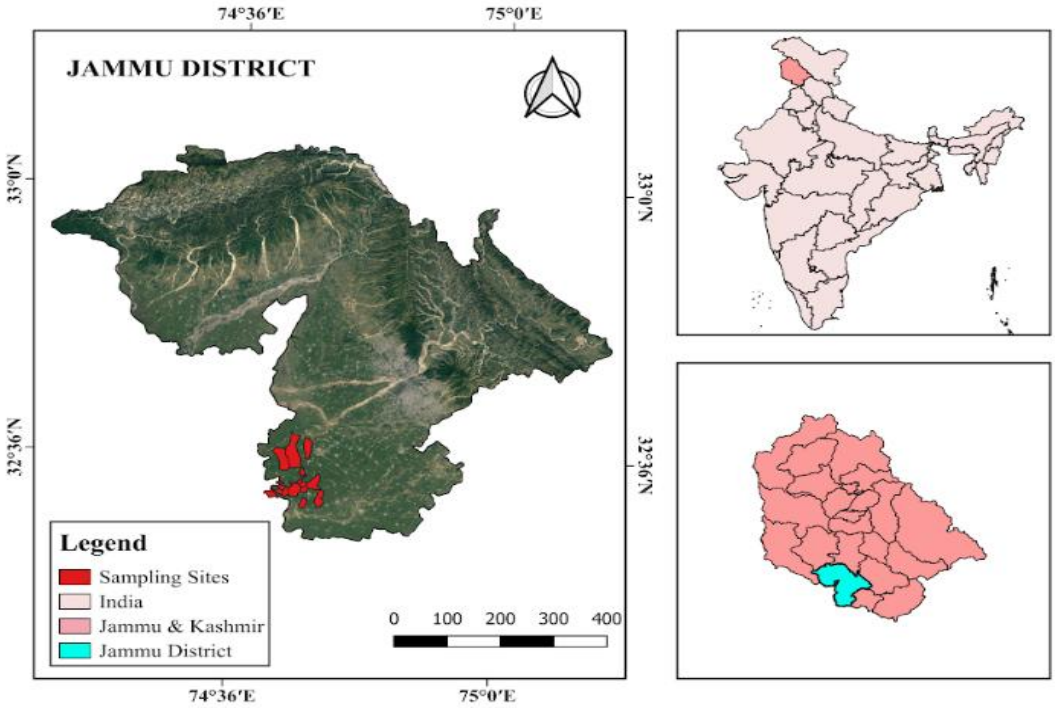

Fig. 2: Map showing the location of study area.

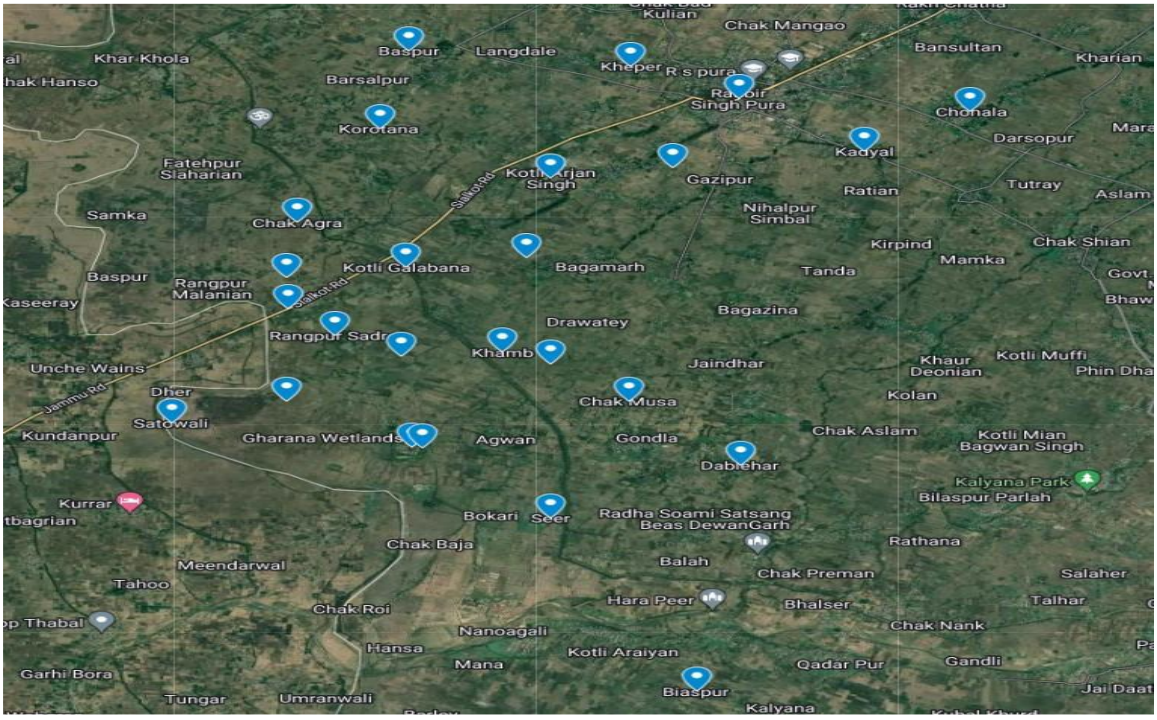

Fig. 3: Sampling locations of the study area.

3.2 SAMPLE COLLECTION

From different locations, twenty-five groundwater samples (in triplets) were collected in pre monsoon and post monsoon season of 2022 from motors, bore wells, hand-pumps and tube wells. The water samples were collected after 10–15 minutes continuous pumping and this step was done to remove the standing water in the water source (Table 4). The water samples were collected in pre cleaned and sterilised 1L capacity of water bottles. Each bottle was carefully labelled and details were recorded properly by following APHA standard procedures. Few parameters such as pH, Total Dissolved Solids (TDS), Temperature, Electrical conductivity were recorded on site. The samples were put in refrigerator and were then carried to laboratory for rest of parameters analysis within 12-24 hrs after sample collection**.** Water samples were acidified in order to preserve them for heavy metals analysis (Kaur et al. 2019, Kaur et al. 2017, Boetang et al. 2016).

Table 4: Latitude and longitude of the sampling Sites and source of water collection.

Sampling Site	Name of Sampling site	Latitude	Longitude	Source of water collection	Depth of water collection source
S1	Khamb	32.59963º	74.740015º	Handpump	90 ft.
S2	Sunderpur	32.59456º	74.75461º	Handpump	70 ft.
S3	Musa Chak	32.58641º	74.73254º	Tubewells	70 ft.
S4	Agra Chak	32.41234º	74.73451º	Tubewells	85 ft.
S5	Dablehar	32.603052º	74.733087º	Handpump	105 ft.
S6	Seer	32.603145º	74.733451º	Handpump	50 ft.
S7	Chohala	32.609114º	74.738634º	Handpump	60 ft.
S8	Gagian	32.609453º	74.738649º	Tubewells	50 ft.
S9	Main R.S. Pura	32.607633º	74.736345º	Handpump	45 ft.
S10	Purana Pind	32.601718º	74.72904º	Handpump	60 ft.
S11	Satraiyan	32.601452º	74.74584º	Handpump	55 ft.
S12	Badyal Qazian	32.41256º	74.78459º	Handpump	65 ft.
S13	Biaspur	32.552505º	74.767842º	Tubewells	70 ft.
S14	Satowali	32.64587º	74.74125º	Handpump	50 ft.
S15	Suchetgarh	32.64578º	74.54891º	Tubewells	55 ft.
S16	Mottey	32.75983º	74.74589º	Handpump	60 ft.

S17	Rangpur Sadrey	32.64578º	74.71234º	Handpump	120 ft.
S18	Abdulliyan	32.65874º	74.79484º	Bore well	250 ft.
S19	Khana Chak	32.62345º	74.64875º	Bore well	300 ft.
S20	Kotli Gala Bana	32.65871º	74.78543º	Handpump	85 ft.
S21	Kotli Arjan Singh	32.620908º	74.756392º	Tubewells	100 ft.
S22	Gharana	32.66478º	74.76658º	Tubewells	105 ft.
S23	Nari	32.627383º	74.766378º	Tubewell	200 ft.
S24	Kheper	32.627606º	74.766788º	Tubewell	200 ft.
S25	Jassore	32.631173º	74.773998º	Tubewells	80 ft.

3.3 PHYSICO-CHEMICAL ANALYSIS

Analysis of Physico-chemical parameters along with heavy metals was done for various water quality parameters such as pH, Electrical conductivity (EC), Total Alkalinity (TA), Chloride (Cl^-), Sulphate (SO_4^{2-}), Total hardness (TH), Fluoride (F^-), Total Hardness (TH), Magnesium (Mg^{2+}), Potassium (K^+), Iron (Fe^{2+}), Nitrate (NO_3^-), Calcium (Ca^{2+}), Sodium (Na^+) as per standard methods (APHA, 1999).

Certified analytical grade reagents of high purity; double distilled de-ionized water and borosil glass wares were used. Parameters such as Turbidity, TA, TH, Cl^-, Mg^{2+}, K^+, Ca^{2+}, Na^+ were tested in the laboratory of division of soil science and agricultural chemistry of SKUAST Jammu while some other parameters such as SO_4^{2-}, Fe^{2+}, F^-, NO_3^-, Zn^{2+}, Pb^{2+}, Cr^{3+}, Cu^{2+}, Ni^{2+}, As^{3+} were analysed in the Nitya laboratories [equipped with ISO 14001: 2015, ISO 9001: 2015 and ISO 45001: 2018 certification, having Accreditation number 51901390123]. Details of analytical method used for each parameter and where the facility was available, is listed in Table 5.

Table 5: Analytical methodology used for various parameters.

S.no.	Parameter	Analytical methods	Organization/ Institute where facility is available
1.	pH	pH meter (Ionix imported pH meter)	Meter owned
2.	Electrical Conductivity (EC)	Electrical Conductivity Meter (Amperus EC meter)	Meter owned
3.	Temperature	Thermometer (Amperus Digital Meter)	Meter owned
3.	Total Dissolved Solids (TDS)	TDS meter (Amperus TDS meter)	Meter owned
4.	Total Hardness (TH)	EDTA Titration Method	SKUAST Jammu
5.	Total Alkalinity (as $CaCO_3$)	Titrimetric Method	SKUAST Jammu
6.	Turbidity	Turbidity meter	SKUAST Jammu
7.	Chloride (Cl^-)	$AgNO_3$ Titration Method	SKUAST Jammu
8.	Calcium (Ca^{2+}) and Magnesium (Mg^{2+})	Titration Method	SKUAST Jammu
9.	Fluoride (F^-)	UV Spectrophotometric Method	Nitya Laboratory Jammu
10.	Sulphate (SO_4^{2-})	UV Visible Spectrophotometer	Nitya Laboratory Jammu
11.	Sodium (Na^+) and Potassium (K^+)	Flame photometric method	SKUAST Jammu
12.	Nitrate (NO_3^-)	UV Visible Spectrophotometer	Nitya Laboratory Jammu
13.	Iron (Fe^{2+})	UV Visible Spectrophotometer	Nitya Laboratory Jammu
14.	Zinc (Zn^{2+})	Atomic Absorption Spectrophotometry (AAS) (Model AA303)	Nitya Laboratory Jammu
15.	Chromium (Cr^{2+})	AAS	Nitya Laboratory Jammu

16.	Lead (Pb^{2+})	AAS	Nitya Laboratory Jammu
17.	Copper (Cu^{2+})	AAS	Nitya Laboratory Jammu
18.	Nickel (Ni^{2+})	AAS	Nitya Laboratory Jammu
19.	Arsenic (As^{2+})	AAS	Nitya Laboratory Jammu

3.4 Assessment of groundwater quality for Drinking Purpose

Various parameters were assessed to check the groundwater suitability for drinking purpose. All the parameters assessed using standard methods described in APHA.

3.4.1 **pH**: pH value of water is basically the assessment of acid-base balance in water and was measured with the help of pH-meter (Ionix imported pH meter). The pH meter was calibrated with the pH buffer powders (available with the kit). Acidic, basic and neutral buffer solutions were prepared by dissolving pH powders having pH 4.01, 9.18 and 6.86 respectively in 250 ml of distilled water. After calibrating the pH meter, pH of the water samples (which were taken in triplicates) were measured. The permissible limit set for pH by BIS and WHO is 6.5-8.5 (Bhunia et al. 2018; Adimalla et al. 2020).

3.4.2 **Electrical Conductivity (EC)**: It represents the salt content/concentration in water and is an important water quality parameter for assessing water suitability for irrigation usage (Bhunia et al. 2018; Shil et al. 2019; Abdelhafez et al. 2021). EC meter was calibrated before sampling by using standard solution of 0.1N Potassium chloride (KCl) solution. EC of the groundwater samples (taken in triplicates) was measured with the help of potable EC meter (Ampereus EC meter) and the values appeared digitally on the EC meter. The permissible limit for EC is 1000 µS/cm as per BIS-2012.

3.4.3 **Total Dissolved Solids (TDS)**: TDS is the determination of salts, minerals, ions, dissolved organic and inorganic substances in the water. TDS of the water samples were determined using TDS meter (Ampereus TDS meter). The water sample was taken in the beaker and the reading was noted down. Then the meter was dipped in

distilled water and cleaned with the help of wipe and similar procedure was carried out for the rest of the water samples.

3.4.4 **Turbidity**: Turbidity is the presence of different types of total suspended particulate matter (Bansal et al. 2018; Baloch et al. 2021). Turbidity of the water samples in Nephelometer Turbidity Units (NTU) was measured with the help of digital Nephelometer. First of all, the meter was calibrated with the blank (distilled water) taken in the cuvette and the meter was set at 0 and 400 NTU in order to minimize the error. Then, the turbidity of all the samples was detected by inserting the samples one by one and the values were displayed digitally on the meter. The limits set by BIS-2012 is 1-5 NTU.

3.4.5 **Temperature**: Temperature is an important factor in water quality determination because it effects the chemical and biological reactions in natural water bodies (Saad et al. 2017; Uqab et al. 2017). Temperature of the groundwater samples was measured by the Ampereus digital meter. Meter was first calibrated and then readings were taken. The water samples were taken in the beaker one by one and noted the readings of the temperature from the meter.

3.4.6 **Total Alkalinity (TA)**: It is the capacity of water to resist acidic changes in pH and is also known for the water ability to neutralize acid. TA is determined using Titrimetric analysis (Volumetric analysis). This titration analysis works on the principle of determining the volume of the solution of known concentration (titrant) by reacting it with the analyte solution (titrand). The titrant is filled in the burette and is added dropwise in the titrand taken in conical flask. The end point of this reaction will be the color change of the analyte solution. For measuring TA, assessment of Phenolphthalein alkalinity and Methyl Orange alkalinity was done.

Reagents used: 0.02N Sulphuric acid (H_2SO_4), Phenolphthalein indicator (1%), Methyl Orange indicator (1%).

Preparation of reagents:

- **0.02N Sulphuric acid (H_2SO_4)**: 500ml distilled water was taken in the conical flask and 0.27ml of H_2SO_4 was added with the help of pipette along the sides of the flask. Makeup was done by adding 500ml distilled water in the volumetric flask.
- **Phenolphthalein indicator (1%):** dissolve 1g of phenolphthalein powder in 50ml of ethyl alcohol in a beaker and added distilled water (50ml) to it.

- **Methyl Orange indicator (1%):** dissolve 1g of methyl orange powder in 20ml of ethyl alcohol in a beaker and added distilled water by makeup to 100ml.

Procedure: First of all, phenolphthalein alkalinity was determined by taking 50 ml of water sample in a flask and then 2-3 drops of phenolphthalein indicator were added. If colour of the water sample does not change, then phenolphthalein alkalinity will be zero. If colour changes to pink on adding the indicator, then the solution was titrated against 0.02N H_2SO_4 solution (which is filled in the burette) till the water becomes colourless (end point) and then record the ml. of 0.02N H_2SO_4. In all the groundwater samples of the study area, Phenolphthalein alkalinity was found to be nil. So, next step is to calculate methyl orange alkalinity, for this, to the same sample added 2-3 drops of methyl orange indicator and continue to titrate it against 0.02N H_2SO_4 solution, filled in burette, till the color of the water sample becomes dark pink (desired end point) and noted down the volume of acid used. TA of the water samples were taken in terms of calcium carbonate ($CaCO_3$) and the concentration were represented in mg/L.

Calculations:

$$\text{Phenolphthalein Alkalinity (PA)} = \frac{Volume\ of\ 0.02N\ H2SO4\ used\ (ml) \times 10\ ppm}{ml.of\ water\ sample\ taken}$$

$$\text{Methyl Orange Alkalinity (MOA)} = \frac{Volume\ of\ 0.02N\ H2SO4\ used\ (ml) \times 10\ ppm}{ml.of\ water\ sample\ taken}$$

$$\text{Total Alkalinity (as } CaCO_3\text{) mg/L} = PA + MOA$$

3.4.7 Total Hardness (TH): Hardness can be due to presence of chlorides, bicarbonates and sulphates of magnesium and calcium in water and can be removed from water either by boiling it or by ion exchange process (Gulgundi and Shetty, 2018; Gabr et al. 2020). Total Hardness in water can be determined using complexometric titration. This titration method involves the titration of the analyte against standard solution of Ethylenediamine tetra acetic acid (EDTA), which is the complexing agent i.e., it forms complex with the Ca^{2+} and Mg^{2+} present in water and this reaction occurs in presence of Eriochrome Black-T (EBT) indicator.

Reagents used: 0.01M standard EDTA (Ethylenediamine tetra acetic acid) solution, Ammonium Buffer solution of pH=10, Eriochrome Black-T (EBT) indicator.

Preparation of reagents:

- **0.01M standard EDTA solution**: dissolve 3.72g of EDTA powder in 1L of distilled water.
- **Ammonium Buffer solution**: dissolve ammonium chloride (1.70g), ammonium hydroxide (12.86g) and EDTA powder (0.13g) in 50ml Distilled water.

Procedure: 50 ml of water sample was taken in a beaker and then added 2-3 drops of ammonium buffer solution and transferred it to the conical flask and added few drops of EBT indicator to the solution. On adding the indicator, color of the water changed to wine red. Titrated this solution against 0.01M EDTA solution, filled in the burette, till the color changed to blue (desired end point) and noted down the volume of acid used (ml). The hardness of the water samples was taken in terms of calcium carbonate ($CaCO_3$) and the concentration of TH were represented in mg/L.

Calculation:

$$\text{Total Hardness as } CaCO_3 \text{ (mg/L)} = \frac{ml\ of\ 0.01M\ EDTA\ used \times B\ \times 1000}{ml\ of\ sample\ used}$$

Where B=1 [∵ 1ml EDTA= 1mg $CaCO_3$= 0.01M EDTA]

3.4.8 Calcium (Ca^{2+}) and Magnesium (Mg^{2+}): Calcium and Magnesium are also an important parameter for assessing groundwater quality as its excess concentration in drinking water can cause health impacts such as kidney stone, Colon Cancer etc. (Sudan S, 2018; Wagh et al. 2020). Concentration of Ca^{2+} and Mg^{2+} ions in the water can be determined using Ethylenediamine tetra acetic acid (EDTA) titration. This titration method occurs in presence of murexide indicator and titration of the analyte was done against standard EDTA solution, which is the complex forming agent i.e., it forms complex with the Ca^{2+}. Mg^{2+} concentration in water was determined by subtracting Ca^{2+} concentration from Ca^{2+} and Mg^{2+} concentration (total hardness).

Reagents used: 0.01M standard EDTA (Ethylenediamine tetra acetic acid) solution, 1% Sodium hydroxide (NaOH) solution, Murexide indicator.

Preparation of reagents:

- **0.01M standard EDTA solution**: dissolve 3.72g of EDTA powder in 1L of distilled water.
- **1% Sodium hydroxide (NaOH) solution:** dissolve 1g of NaOH in 99ml of distilled water.

Procedure: Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) can be determined with the titration method. For analysis, 50ml of water sample was taken in a beaker, to which few drops of 1% NaOH solution were added. Shaking it continuously and then added few drops of murexide indicator, the color of the solution changed to pink. Then this solution was titrated against 0.01M EDTA solution with constant stirring until color changes from pink to purple. Noted down the initial and final readings from the burette.

Calculations:

$$\text{For } Ca^{2+} \text{ (mg/L)} = \frac{V \times N \times Mw\ (Ca) \times 1000}{ml\ of\ sample\ taken}$$

$$\text{For } Mg^{2+} \text{ (mg/L)} = Total\ Hardness\ - Ca^{2+}\ (mg/L)$$

Where, V- Volume of the titrant used (ml)

N- normality of EDTA solution

Mw (Ca)- molecular weight of calcium i.e., 20.04

3.4.9 Sodium (Na^+): Sodium is a silver white metallic element and is ubiquitous in water because of the high solubility of many sodium salts. Sodium concentration in the groundwater was determined using Flame photometer, which works on the principle of measurement of emission of light by vaporized atoms/ ions in the flame.

Reagents used: 1000ppm stock solution of sodium.

Preparation of reagents:

- **1000ppm stock solution of sodium:** dissolve 100mg of sodium chloride (NaCl) in 100ml distilled water.
- **Stock dilutions:** dilutions of 10ppm, 20ppm, 40ppm and 100ppm were prepared by taking 1ml, 2ml, 4ml and 10ml respectively from stock solution and diluting each of them with 100ml of distilled water.

Procedure: For measuring the concentration of sodium ions in the water, flame photometer was calibrated by feeding it with blank (distilled water) first and then with the dilutions of 10ppm, 20ppm, 40ppm, 100ppm. The standard curve was generated by using these dilutions. Once the meter was calibrated, aspirate the sample and noted the reading appear on the digital meter. After the sample aspiration, feed the instrument with the blank so that the previous sample doesn't interfere with the next sample. Repeat this procedure for the rest of the sample analysis.

Calculation:

$$\text{Na (mg/L)} = Conc.of\ Na\ \left(\frac{mg}{L}\right) in\ diluted\ sample * Dilution\ factor$$

3.4.10 Potassium (K^+): Potassium is present in all animal and plant tissues. Generally, low potassium concentration is found in drinking water which do not pose any health concerns but its high dose can lead to nausea and vomiting, diarrhea, hypertension, breath shortness and even heart failure (Sudan S, 2018). Alike sodium, potassium concentration in groundwater is also determined using Flame photometer.

Reagents used: 1000ppm stock solution of potassium chloride (KCl)

Preparation of reagents:

- **1000ppm stock solution of sodium:** dissolve 100mg of potassium chloride (KCl) in 100ml distilled water.
- **Stock dilutions:** dilutions of 1ppm, 10ppm, 20ppm, 40ppm, and 60ppm and 100ppm were prepared by taking 0.1ml, 1ml, 2ml, 4ml and 10ml respectively from stock solution and diluting each of them in 100ml of distilled water.

Procedure: For measuring the concentration of potassium ions in the water, flame photometer was calibrated by feeding it with blank (distilled water) first and then with the dilutions of 1ppm, 10ppm, 20ppm, 40ppm, and 60ppm and100ppm. The standard curve was generated by using these dilutions. Once the meter was calibrated, aspirate the sample and noted the reading appear on the digital meter. After the sample aspiration, feed the instrument with the blank so that the previous sample doesn't interfere with the next sample. Repeat this procedure for the rest of the sample analysis.

Calculation:

$$\text{K (mg/L)} = Conc.of\ K\ \left(\frac{mg}{L}\right) in\ diluted\ sample * Dilution\ factor$$

3.4.11 Chloride (Cl^-): Chloride is present naturally in water but its high concentration in water (used for drinking) can have deleterious impact on metallic pipes, human health, structures, agriculture crops (Kumar et al. 2009; Vardhan et al. 2015). To determine the concentration of chlorides in groundwater samples, precipitation titration specifically Argentometric titration was carried out, which uses silver nitrate ($AgNO_3$) as the titrant. This titration method works on the principle of precipitate formation. When the solution containing chlorides reacted with the $AgNO_3$ solution (in presence

of chromate ions as potassium chromate was used as indicator), the precipitation of $AgCl_2$ occurred and end point is the appearance of reddish-brown color.

Reagents used: 0.1M Potassium Chromate (K_2CrO_4), 0.02M Silver nitrate solution ($AgNO_3$).

Preparation of reagents:

- **0.1M Potassium Chromate (K_2CrO_4)**- dissolve 5g of K_2CrO_4 in 100ml distilled water
- **0.02M Silver nitrate solution ($AgNO_3$)**- dissolve 3.397g of $AgNO_3$ in 500ml distilled water.

Procedure: Chloride was determined using Argentometric titration method. 50ml of water sample was taken in a conical flask and added 2-3 drops of 0.1M K_2CrO_4 in it. On adding potassium chromate solution, color of the solution changed to yellowish green. After that, titrated this solution against 0.02M Silver Nitrate ($AgNO_3$) solution until the appearance of reddish-brown color (desired end point).

Calculation:

$$\text{Cl (mg/L)} = \frac{N \times V \times 35.5 \times 1000}{ml.of\ sample\ used}$$

where N- normality of $AgNO_3$

V- volume of the titrant used (ml)

3.4.12 Fluoride (F^-): Presence of Fluoride in small amounts in drinking water is beneficial for dental health while excess of its concentration can lead to Fluorosis (Khanna P, 2019). The Fluoride present in water can be determined using SPADNS method. This method works on the principle of reaction with zirconium ions to form colorless complex. The concentration of fluoride in water sample is inversely proportional to the color of the solution i.e., if there is high concentration of fluoride in water sample, then the color of the solution becomes lighter. Absorbance of the solution was measured at 570nm.

Reagents used: Stock fluoride solution, zirconyl-acid reagents, SPADNS (sodium 2-(parasulfophenylazo)-1,8-dihydroxy-3,6-naphthalene disulfonate) solution, acid zirconyl- SPADNS reagents.

Preparation of reagents:

- **Stock fluoride solution**: dissolve 221mg of anhydrous fluoride solution in 1L distilled water. From this standard stock solution, prepare dilutions of 0.1ppm, 0.5ppm, 1ppm & 1.5ppm.

- **Zirconyl-acid reagents**: dissolve 133mg of zirconyl chloride octahydrate ($ZrOCl_2.8H_2O$) in 25ml of distilled water. To this, add 350ml of conc. HCl and dilute it to 500ml with distilled water.
- **SPADNS Solution**: dissolve 958mg of SPADNS in 500ml of distilled water.
- **Acid zirconyl- SPADNS reagents**- mix equal volume of SPADNS solution and zirconyl- acid reagents.

Procedure: It was determined using SPADNS colorimetric method. For estimating the fluoride concentration, firstly, standard curve was plotted using dilutions (0.1ppm, 0.5ppm, 1.0ppm and 1.5ppm). 50ml of water sample was taken in a beaker and added 10ml of acid-zirconyl- SPADNS reagents in it. Then, the solution was mixed properly and finally, absorbance of the solution was measured under UV visible spectrophotometer at 570nm wavelength.

Calculation:

$$\text{Fluoride (mg/l)} = \frac{W \times V1}{ml.of\ sample\ used\ \times V2}$$

Where W- µg of F observed from plotted curve

V1- final volume of sample (ml)

V2- vol. of sample used for colour development (ml)

3.4.13 Nitrate (NO_3^-): Nitrates are highly soluble in water and can easily penetrate into the groundwater through soil (Kumar et al. 2009). Nitrate-Nitrogen (NO_3-N) in groundwater can be determined using UV-Visible spectrophotometer. Nitrate calibration curve follows Beer's law up to 11mg/L. For nitrates assessment in water, first nitrate absorbance was measured at 220nm and another at 275nm. Since concentration of organic matter also absorbs at 220nm but cannot absorb at 275nm, therefore, absorbance measurement at 275nm was done in order to avoid organic matter interference in the water.

Reagents used: 1N HCl, standard nitrate stock solution, potassium nitrate (KNO_3).

Preparation of reagents:

- **Standard nitrate stock solution:** dissolve 0.7218g of KNO_3 in distilled water and dilute it to 1000ml.
- **Dilutions:** prepare 1ppm, 2ppm, 4ppm, 6ppm and 8ppm dilutions from the standard nitrate stock solution.

Procedure: Nitrate can be determined using UV Visible Spectrophotometer. For nitrates assessment in groundwater, standard curve of NO_3-N was plotted using

dilutions (1ppm, 2ppm, 4ppm, 6ppm and 8ppm). Then calibrate the spectrophotometer by inserting blank (distilled water) and dilutions. After calibration, 50ml of water sample was taken in a beaker and added 1ml HCl solution to it. Then, samples were inserted one by one and noted down the readings first at wavelength 220nm and then at 275nm to determine the interference of organic matter. The final absorbance was calculated and the values were noted down. These values were then used to determine the nitrate concentration from the calibration curve.

Calculation:

Final absorbance of the solution can be calculated as follows:

Final absorbance = $Absorbance\ at\ 220nm - 2 * (absorbance\ at\ 275nm)$

3.4.14 Sulphate (SO_4^{2-}): Sources of sulphate (SO_4^{2-}) in groundwater include industrial wastes, gypsum, dissolution of salts of sulphuric acid etc. It is considered as the less toxic anions and is soluble in water. When present in excess, it has the ability to cause catharsis, laxative effect, material/building damage, gastrointestinal irritation etc. in humans (Wagh et al. 2020; Jude et al. 2023). Concentration of Sulphate in water samples were determined using UV-Visible spectrophotometer.

Reagents used: 1ml conditioning reagent, Barium Sulphate ($BaSO_4$), 1ml concentrated hydrochloric acid (HCl), standard sulphate solution.

Preparation of reagents:

- **1ml conditioning reagent**: dissolve 75g of NaCl in 300ml of distilled water. Add 30ml concentrated HCl, 100ml of 95% ethyl alcohol and 50ml glycerol into it and give it a mix.
- **Standard sulphate solution**: dissolve 0.1479g of anhydrous Na_2SO_4 in distilled water and final volume make up to 1000ml.

Procedure: Sulphate content in the water was determined using UV Spectrophotometer. Firstly, standard sulphate solution was prepared by taking 10ml, 20ml, 30ml, 40ml and 50ml in five different flasks (containing 100ml distilled water each). Then the standard calibration curve was plotted. After calibrating the instrument, 25ml of sample was taken in a beaker,1ml concentrated hydrochloric acid (HCl) and 1 ml conditioning reagent were added to it. After that, added a pinch of Barium Sulphate ($BaSO_4$) in the beaker. On adding $BaSO_4$, if the solution does not turn milky, then it indicates the absence of sulphate ions in the sample and if the

solution turns milky, then wait for 5 minutes and noted down the absorbance reading under UV Spectrophotometer (wavelength = 420nm).

Calculation:

$$\text{Sulphate } (SO_4^{2-}) \text{ (mg/l)} = \frac{standard\ conc\ \times \text{sample absorbance} \times \text{dilution factor}}{standard\ absorbance}$$

3.4.15 Iron (Fe^{2+}): Elevated levels of iron in drinking water can lead to liver diseases (Khanna P, 2019). The acceptable limit set for iron in drinking water by BIS 2012 is 0.3 mg/L.

Reagents used: Concentrated hydrochloric acid (HCl), phenanthroline solution, hydroxylamine solution, sodium acetate solution, ammonium acetate buffer solution, standard iron solution, stock iron solution.

Preparation of reagents:

- **Phenanthroline solution**: dissolve 50mg of 1,10- phenanthroline monohydrate in distilled water (50ml). To this solution, add 1ml conc. HCl.
- **Hydroxylamine solution**: dissolve 5g of hydroxylamine (NH_2OH) in 50ml of distilled water.
- **Sodium acetate solution**: dissolve 100g of sodium acetate in 400ml of distilled water.
- **Ammonium acetate buffer solution**: dissolve 125g of ammonium acetate in 25ml of distilled water.
- **Stock iron solution**: add 10ml conc. H_2SO_4 to 25ml distilled water. To this solution, add ammonium iron (II) sulphate and 0.1N potassium permanganate until light pink colour persists. Now make up this solution with distilled water up to 1000ml.
- **Standard iron solution**: take 50ml of standard stock iron solution and dilute it with distilled water up to 1000ml.

Procedure: In order to determine the iron concentration in the water samples, firstly calibration curve with dilutions was prepared (0.1ppm, 0.2ppm, 0.3ppm, 0.4ppm and 0.5ppm). 50ml of water sample was taken in a beaker, added 2ml concentrated hydrochloric acid (HCl), 1ml hydroxylamine solution and 50ml distilled water. Now, this solution was heated in oven until its volume reduces to 15-20ml. After heating, 4-5 glass beads were added in order to uniform the temperature of the solution. Then, this solution was transferred to volumetric flask of 100ml capacity. To this solution, added 4ml phenanthroline solution and 10ml ammonium acetyl buffer. Makeup of this

solution to 100ml was done with distilled water. Now, take UV spectrophotometer reading at 510nm with blank first and then with samples.

3.4.16 Heavy Metal analysis: For heavy metals analysis, the water samples were preserved by adding 1ml of concentrated nitric acid (HNO_3) per liter of water sample. Heavy metals analyzed were Copper (Cu^{2+}), Zinc (Zn^{2+}), Chromium (Cr^{3+}), Lead (Pb^{2+}), Arsenic (As^{3+}) and Nickel (Ni^{2+}). Atomic Absorption Spectrophotometer (Model AA 303) was used for the analysis of all these heavy metals in the groundwater samples. AAS works on the principle of Beer-Lambert's law which states that the concentration of metal present is directly proportional to the absorbance of metal.

Heavy metals analyzed (Cu^{2+}, Zn^{2+}, Cr^{3+}, Pb^{2+}, As^{3+} and Ni^{2+}) using AAS equipped with lamps, specific for each heavy metal analysis. For each heavy metal, specific CRM (certified reference material) of 1000ppm and cathode ray tube were used to determine the concentration of metals present. Instrument was calibrated first with blank (distilled water) and then with stock dilutions. Standards and dilutions for each heavy metal were prepared such as for Zn^{2+} (0.2 ppm, 0.4 ppm, 0.6 ppm, 0.8 ppm, 1.0 ppm), Cr^{3+} (1 ppm, 2 ppm, 3 ppm, 4 ppm, 5 ppm), Ni^{2+} (1 ppm, 2 ppm, 3 ppm, 4 ppm, 5 ppm), Pb^{2+} (2 ppm, 4 ppm, 6 ppm, 8 ppm, 10 ppm), Cu^{2+} (0.2 ppm, 0.4 ppm, 0.6 ppm, 0.8 ppm, 1.0 ppm), As^{3+} (0.0 ppm, 0.005 ppm, 0.01 ppm, 0.015 ppm, 0.02 ppm). The absorbance of the blank solution was taken before analysis. Absorbance was then plotted against concentration values. The linear calibration curve was found between absorbance and concentration ensuring accuracy of procedure. Hollow cathode ray tubes/lamps for each heavy metal (Cu^{2+}, Zn^{2+}, Cr^{3+}, Pb^{2+}, As^{3+} and Ni^{2+}) were taken with different wavelength settings i.e., for Cu^{2+} = 324.8 nm, Cr^{3+} = 357.9 nm, Zn^{2+} = 213.9 nm, As^{3+} = 193.7 nm, Pb^{2+} = 217 nm and Ni^{2+} = 232.0 nm. the concentration of all the metals was digitally displayed on the computer screen and were expressed in ppm.

3.4.17 WATER QUALITY INDEX (WQI): WQI is an effective method for evaluating the overall water quality. It rates the quality of water and determines the suitability of water for drinking (Ishaku, J.M, 2011; Khadse et al. 2016; Ahada and Suthar, 2018; Shil et al. 2019; Kumari and Rai, 2020). WQI calculation involves 3 steps and are given as: (i) selection of water quality parameters (ii) evaluation of quality function for individual parameter and (iii) application of formulas. After applying the above-mentioned steps, a single value was obtained which can be find out from the table 2

and therefore useful in determining water suitability for drinking. WQI was determined using steps mentioned below:

Step 1: In first step, weight was assigned to individual parameter based on its utmost importance in water quality assessment. Maximum weight of 5 can be assigned. For e.g., Nitrate-5, sulphate-4, magnesium-1.

Step 2: In this step, relative weight (W_i) for individual parameter was calculated using formula given below:

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

Where w_i- weight of individual parameter,

n- number of parameters

The relative weights of every parameter have been calculated and are listed in table 6.

Step 3: This step assign Quality rating scale (q_i)

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

where C_i- concentration of individual parameter

S_i- standard values of parameters set by BIS

Step 4: To calculate WQI, SI_i was determined for individual parameter using:

$$SI_i = W_i * q_i$$

$$WQI = \sum SI_i$$

where SI_i- subindex of i^{th} parameter

The values were calculated and classification was done by using the WQI values listed in Table 7 (Ramakrishaniah et al. 2009; Gulgundi and Shetty, 2018; Khanoranga and Khalid, 2019; Loh et al. 2020).

Table 6: Relative weights of hydrochemical parameters.

S. No.	Physico-chemical Parameters	Assigned Weight (wi)	Relative Weight (Wi= wi/∑wi)	BIS standard (Si)
1.	pH	4	0.07	7.5
2.	TDS (mg/L)	5	0.09	500
3.	EC (µS/cm)	4	0.07	500
4.	HCO_3^- (mg/L)	3	0.05	120
5.	Cl^- (mg/L)	4	0.07	250
6.	NO_3^- (mg/L)	5	0.09	45
7.	F^- (mg/L)	5	0.09	1
8.	SO_4^{2-} (mg/L)	4	0.07	200
9.	Ca^{2+} (mg/L)	3	0.05	75
10.	Mg^{2+} (mg/L)	3	0.05	30
11.	Na^+ (mg/L)	2	0.04	200
12.	K^+(mg/L)	2	0.04	12
13.	Fe^{2+} (mg/L)	4	0.07	0.3
14.	Pb^{2+} (mg/L)	4	0.07	0.01
15.	Cu^{2+} (mg/L)	4	0.07	0.05
		∑wi= 56	∑Wi=1	

Table 7: Classification of water based on Water Quality Index.

Water Quality Index values	Water classification
Less than 50	Excellent
50 to 100	Good
100 to 200	Poor
200 to 300	Very poor
Greater than 300	Unsuitable

3.5 Assessment of Groundwater for Irrigation Purpose

Assessment of irrigation water quality is generally carried out because it can hamper crop production, soil fertility and soil health (Houatmia et al. 2016; Zaman et al. 2018; Chen et al. 2019). The nature of groundwater changes with the depth of water table, varies from land to land and also changes with the change in the concentration of dissolved solids in it (Shil et al. 2019; Osta et al. 2022). Important indices which valuate the suitability of groundwater for irrigation purposes are Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), Kelly's Index (KI), Sodium Percent (Na%) etc. (Acharaya et al. 2018; Chaudhary and Satheeshkumar, 2018; Abassnia et al. 2018).

3.5.1 Irrigation Water Quality Index (IWQI)

This index helps in assessing the water suitability for the agricultural purpose. The IWQI was determined using parameters- SAR, EC, Cl^-, Na^+ and HCO_3^- and was calculated using equation:

$$IWQI = \sum_{i=1}^{n} Q_i W_i$$

Based on individual value of water quality parameter, the cumulative/aggregative weights (Wi) and water quality parameter (Qi) values were calculated using equation mentioned below:

$$Qi = Qmax - \{\frac{[(Xij - Xinf) * Qimap]}{Xamp}\}$$

Where Qmax- highest Qi value for individual class, Xij- obtained value of individual parameter, Xinf- lower limit value of individual class, Qimap- amplitude of class, Xamp- amplitude of class to which parameter belongs.

Wi values were finally normalized by using following formula given below:

$$Wi = \frac{\sum_{J=1}^{k} F_j A_{i_j}}{\sum_{j=1}^{k} \sum_{i=1}^{n} F_j A_{ij}}$$

Where Wi and F- comparative weights of the IWQI physicochemical characteristics

i - constant value, Aij- parameter i can be described by factor j

The number of parameters used in the IWQI ranged from1 to n, while the number of factors taken in the IWQI ranged from 1 to k. After calculating all these steps, a single value of IWQI was obtained, which is helpful in classifying water as per the values

given in Table 8 [Tegegne et al. 2023; Osta et al. 2022; Abassnia et al. 2018; Abassnia et al. 2018 (a):].

Table 8: Classification of irrigation water usage as per IWQI.

IWQI Range	Restriction Water Category
Between 0 and 40	Severe
Between 40 and 55	High
Between 55 and 70	Moderate
Between 70 and 85	Low
Between 85 and 100	No

3.5.2 Sodium Adsorption Ratio (SAR): is a water quality parameter which is helpful in assessing the irrigation water suitability. It focuses on assessing the alkali or sodium hazards while using the water for irrigation purposes (Lanjwani et al. 2020; Chen et al. 2019). If sodium content is high, then alkali hazard is also high; conversely if the value of calcium and magnesium is high then the alkali hazard is less. Exchange of Na^{+} with Ca^{2+} or Mg^{2+} can affect the permeability and physical properties of the soil (Saraswat et al. 2019; Shil et al. 2019; Abdelhafez et al. 2021). If the concentration of sodium ions becomes excessive, then the soil will become sodic soil (National Institute of Hydrology, Roorkie, 1996-97; Houatmia et al. 2016; Sadashivaiah et al. 2008; Chen et al. 2019; Lanjwani et al. 2020). SAR is calculated using formula and all ionic concentrations are represented in milliequivalent per liter (meq/L):

$$\text{SAR} = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

SAR classification has been given by US Salinity Laboratory, Department of agriculture (USSL), USA and categorize the water for agricultural purposes into different classes (Table 9) (Sadashivaiah et al. 2008; Chen et al. 2019; Lanjwani et al. 2020; Abdelhafez et al. 2021; Sharma et al. 2021).

Table 9: Classification of irrigation waters as per SAR classification of USSL, USA.

SAR Value	Water Class
>26	Poor
18-26	Fair
10-18	Good
<10	Excellent

3.5.3 Sodium Percentage (Na%): Sodium percent also helps in determining the suitability of irrigation water and evaluates the hazards of sodium in irrigation water (Rao N S, 2006; Acharya et al. 2018; Baterseh et al. 2021). Sometimes, it is also termed as Soluble Sodium Percentage (SSP) (Acharya et al. 2018; Chaudhary and Satheeshkumar, 2018). When the sodium ions concentration is high in irrigation waters, then sodium ions have the ability to replace ions of magnesium and calcium in the soil, thus tend to reduce the soil permeability (Chen et al. 2019; Madhav et al. 2018; Lanjwani et al. 2020; Shil et al. 2019). It was determined by applying formula:

$$\text{Na\%} = \frac{Na^{+}}{(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})} * 100$$

where all ionic concentrations are expressed are in meq/l. Wilcox (1955) classified irrigation waters into various classes and is given in the below mentioned Table 10 (Houatmia et al. 2016; Chaudhary and Satheeshkumar, 2018; Baterseh et al. 2021; Raheja et al. 2024).

Table 10: Classification of water based on the Wilcox (1955) classification.

Sodium Percent (Na%)	Water Classification
Greater than 80	Unsuitable
60 to 80	Doubtful
40 to 60	Permissible
20 to 40	Good
Less than 20	Excellent

3.5.4 Residual Sodium carbonate (RSC): This index determines the effect of carbonate and bicarbonate ions on the quality of groundwater used for agricultural purposes. If irrigation waters have high concentration of carbonates and bicarbonates, then calcium and magnesium start precipitating due to concentrated water in the soil. As a result, sodium concentration increases in the soil by forming sodium carbonate which effects the soil structure and crop production (Ibrahim et al. 2023; Sadashivaiah et al. 2008). RSC can be calculated using equation given below:

$$RSC= (HCO_3^{-}+ CO_3^{2-}) - (Mg^{2+}+ Ca^{2+})$$

where all ionic concentrations are expressed are in meq/l. Based on the values of RSC, irrigation water can be classified into different classes and are listed in table 11 (Raheja et al. 2024; Ayyandurai et al. 2022; Singh et al. 2020; Soleimani et al. 2018).

Table 11: Irrigation water classification based on RSC values.

RSC Values	Water classification
< 2.5	Safe
= 2.5	Is of marginal quality
> 2.5	Is not appropriate

3.5.5 Permeability Index (PI): This index is also known as Doneen's Permeability Index and check the appropriateness of water for irrigation usage. Generally, the soil permeability is proportional to increased values of Ca^{2+}, Na^{+}, Mg^{2+} and HCO_3^{-} ions due to continuous exposure by irrigation water (Baloch et al. 2021; Jude et al. 2023; Chidambaram et al. 2022; Saraswat et al. 2019)**.** Doneen (1964) gave an equation to determine the permeability index which categorize the water used for irrigation and is listed in Table 12 (Raheja et al. 2024; Rawy et al. 2019; Rawat et al. 2018: Shil et al. 2019; Singha D, 2017; Houatmia et al. 2016). PI was determined using equation given below:

$$PI=\frac{Na^{+}+\sqrt{HCO_3^{-}}}{(Na^{+}+Mg^{2+}+Ca^{2+})} * 100$$

Where, ionic concentrations are in meq/L.

Table 12: Doneen's Classification of water quality based on Permeability Index value.

PI Values	Water Category
<25	Unsuitable for irrigation use
25-75	Moderately suitable
>75	Suitable

3.5.6 Kelly's Index (KI): Irrigation waters can be classified based on Kelly's Index for irrigation usage (Rawat et al. 2018; Madhav et al. 2018; Baloch et al. 2021). It is termed as Kelly's Ratio (KR), given by Kelly in 1940 and modified by Paliwal in 1972, and is described as measurement of sodium (Na^{+}) ions against magnesium (Mg^{2+}) and calcium (Ca^{2+}) ions (Rawat et al. 2018; Rawy et al. 2019; Ayyandurai et al. 2022; Shil et al. 2019). It was calculated by using formula mentioned below:

$$KI = \frac{Na^{+}}{(Ca^{2+}+Mg^{2+})}$$

Ionic concentration representations in meq/L. The water classification on the basis of KI is given in Table 13.

Table 13: Water classification based on Kelly's Index.

Values of KI	Classification of Water (for irrigation)
Lesser than 1	Suitable
Greater than 1	Surplus sodium
Lesser than 2	Deficiency of sodium

3.5.7 Piper Trilinear Diagrams: These diagrams/plots are used to analyze the predominant ion present in the groundwater of a particular area. These diagrams also help in plotting multiple samples on the same plot and grouped the samples based on hydrochemical facies of groundwater. These diagrams generally include three components i.e., two triangles, one for plotting anions i.e., chlorides, sulphates, bicarbonates (present on the lower right area of the plot) and other for plotting cations, i.e., calcium, magnesium, sodium (present on the lower left area of the plot) and one diamond shaped field which is used to assess the hydro-geochemical facies concept (Sadashivaiah et al. 2008; Kumar et al. 2013). These are also helpful in evaluating the relationship among various groundwater samples and the groundwater types (Guo et al. 2021; Osta et al. 2022). 'Grapher software' was used to plot the Piper-Trilinear diagrams for pre-monsoon and post-monsoon season.

3.5.8 Wilcox Diagram: The Wilcox's Diagram (Wilcox 1948) represents suitability of groundwater quality for irrigation purposes by plotting graph between Salinity Hazard [represented as Electrical Conductivity (EC)] and Sodium content in water [represented as Sodium Percentage (Na%)] (Baterseh et al. 2021; Subramaniyan et al. 2022; Wilcox 1955). This diagram is basically a plot in which irrigation water is classified into five categories: 'Excellent to good category', 'good to permissible' category, 'permissible to doubtful' category, 'doubtful to unsuitable' category and 'unsuitable' category (Rawat et al. 2018; Tegegne et al. 2023; Ayyandurai et al. 2022; Sarkar et al. 2022). Wilcox diagrams for both the seasons were prepared by Diagrammes Software version 8.44.

3.6 Assessment of groundwater for Health risks

3.6.1 Human Health Risk Assessment (HHRA): This assessment method evaluates the effect of consuming tainted groundwater on the health of humans. HHRA impacts can be classified as carcinogenic (cancer-causing) and non-carcinogenic (Baloch et al. 2021; Kaur et al. 2019; Paneerselvam et al. 2020). The purpose of calculating this index is to assess the impacts of drinking polluted water on the health of people residing in the study area and thus, can be determined by using equation:

$$\text{ADD} = \frac{\text{Cw} * \text{EF} * \text{IR} * \text{ED}}{\text{AT} * \text{Bw}}$$

Where, ADD - Average daily dose (mg/kg/day), Cw- concentration of contaminant in water (mg /L), EF- frequency of exposure (Days/year), IR- rate of ingestion (L/day), ED- duration of exposure (Years), AT- average time of exposure (Days), Bw- Body weight (Kg) (Kaur et al. 2019; Paneerselvam et al. 2020; Baloch et al. 2021). The benchmark values for these parameters are given in Table 14.

Table 14: Standard values of parameters for various age groups.

Parameters	Children	Women	Men
Cw	-	-	-
EF	365	365	365
IR	0.78	2.5	2.5
ED	12	67	64
AT	4380	24455	23360
Bw	15	55	65

3.6.2 Carcinogenic risks (CR): It is reported that the heavy metal ingestion through contaminated drinking water can enhance the risks of carcinogenic as well as non-carcinogenic factors on human health (United State Environment Protection Agency (USEPA); Alidadi et al. 2019). USEPA has defined Carcinogenic risks or Cancer Risks as the cumulative ability of a person to forge cancer over his/her life span due to contact with a possible cancer-causing agent (Kaur et al. 2020). It is determined using equation given as follows:

$$\text{CR} = CDI * CSF$$

Where, CDI- chronic daily intake of individual metal and CSF- cancer slope factor which differs from one metal to another.

CR value should be within limits prescribed by USEPA (10^{-6} to 10^{-4}) (Abdelhafez et al. 2021; Paneerselvam et al. 2020; Alidadi et al. 2019). If CR value is greater than 10^{-4}, then the risks will not be acceptable, which means that the drinking water can have severe health hazards when it exceeds this prescribed limit and then that water should be given some treatment or remediation before consumption (Baloch et al. 2021).

3.6.3 Non-carcinogenic risks: Non-carcinogenic risks can be determined using Target Hazard Quotient (THQ) and Hazard Index (HI) in different age groups of humans (Paneerselvam et al. 2020). THQ can be defined as the ratio of reference dose (RfD) to the ADD value of individual heavy metal (Khanoranga and Khalid, 2019; Paneerselvam et al. 2020; Baloch et al. 2021; Guo et al. 2021; Abdelhafez et al. 2021). THQ are determined using equation:

$$\text{THQ} = {}^{ADD}/_{RfD}$$

$$\text{Total THQ or HI} = \sum \text{THQ}$$

where RfD refers to reference dose (µg/Kg/day) and is defined as the continuous daily exposure throughout a person's life without significant risk of adverse effects (Abdelhafez et al. 2021; Alidadi et al. 2019). THQ value lesser than 1 implies that exposed population is safe and THQ value greater than 1 represents chronic risks and thus that water needs some remediation before use (Khanoranga and Khalid, 2019; Abdelhafez et al. 2021; Guo et al. 2021).

3.6.4 Heavy metal pollution index (HPI): This index is used to determine the heavy metal contamination in groundwater and can be calculated using following steps:
Step1: First step was to calculate unit weight of i^{th} parameter (W_i) with the help of equations given below:

$$\text{Wi} = \frac{K}{S_i}$$

Where, K-constant and can be determined as $K = \frac{1}{\sum_{i=1}^{n} \frac{1}{S_i}}$

S_i= standard value of i^{th} parameter for heavy metal.

Step 2: Subindex (Q_i) of individual heavy metal was calculated by following equation:

$$Qi = \sum_{i=1}^{n} \frac{|M_i - I_i|}{S_i - I_i} \times 100$$

Where, n- number of parameters chosen

M_i- measured concentration of i^{th} parameter for heavy metal

I_i- ideal concentration of i^{th} parameter for heavy metal.

Step 3: Finally, HPI was calculated from following equation:

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i}$$

Based on the HPI value obtained for individual heavy metal, classification of groundwater was done. HPI value of individual heavy metal greater than 100 indicates the groundwater contamination with that particular heavy metal (Wagh et al. 2018; Lorestani et al. 2020; Raja et al. 2021; `Tokatli, C, 2021).

3.6.5 Heavy metal evaluation index (HEI): HEI was calculated to indicate the groundwater quality for drinking usage with reference to the heavy metals present. This index classified the groundwater samples based on HEI which is calculated using equation as follows:

$$HEI = \sum_{i=1}^{n} Hc/Hmax$$

Where Hc is the i^{th} metal concentration and H_{max} is the maximum advisable limit of i^{th} metal. The classification of HEI is given as 'low' if its value is less than 10, is 'medium' if its value ranged between 10-20 and is 'high' if its value is greater than 20 (Lorestani et al. 2020; Tokatli, C, 2021; Raja et al. 2021). HEI Classification is given in Table 15:

Table 15: Water classification based on HEI values.

S. No.	HEI Value	Water contamination
1.	< 10	Low
2.	10- 20	Medium
3.	> 20	High

3.6.6 Nitrate Pollution Index (NPI): It is applied to measure the nitrate content in the groundwater, thus making that water unfit for different usages. Based on NPI values, water

classification can be done (Paneerselvam et al. 2020). NPI is determined using equation given below and classification is listed in Table 16:

$$NPI = \frac{Cs - HAV}{HAV}$$

Where Cs- quantified concentration of nitrate in sample and HAV- human acceptable value for nitrate (20 mg/L).

Table 16: Water classification on the basis of NPI.

NPI Concentration	Water Classification
greater than 3	very significant
2.1-3	Significant
1.1-2	Moderate
0-1	Light
less than 0	Clean

3.7 Statistical Analysis

3.7.1 Descriptive statistics: Descriptive statistical analysis was performed using Microsoft Excel software. In this, calculation of mean, minimum, maximum and standard deviation was done.

3.7.2 Pearson Correlation: It is an important tool for analysing the interrelation between different parameters. It helps to determine whether one variable increases with the increase in other variable or if one variable increases with the decrease in other variable or represents no relationship between the two variables (Ravikumar et al. 2015; Shil et al. 2019). The correlation value is represented by 'r' and its value lies in the range from -1 to +1 depicting negative and positive interaction respectively. The correlation values are classified as 0.01- 0.29 (weak), 0.3- 0.69 (moderate), 0.7- 1.0 (strong) interaction (Saraswat et al. 2019; Wagh et al. 2018). In the present study, Pearson correlation analysis has been done by using Microsoft Excel with the aim to identify the relationship between different water quality parameters.

3.7.3 Principal Component Analysis (PCA): PCA is an important tool used to determine the leading variable which has the greatest contribution in the water contamination. It is considered a good tool for understanding important

parameters that are needed for the interpretation of results and avoid some insignificant data so that the entire dataset can be reduced (Saraswat et al. 2019; Wagh et al. 2018). It transforms the original variables into new variables without losing important information from the dataset. Its results can be categorized as > 0.70 (strong), 0.50- 0.70 (moderate) and < 0.50 (weak) relation. The number of Principal Components (PCs) are used that have an eigen value greater than 1 (Shil et al. 2019; Saraswat et al. 2019; Tajwar et al. 2023). In the present study, PCA was performed by using XLSTAT-2024 software.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Assessment of physico-chemical parameters for drinking purpose

In arid and semi-arid regions, groundwater serves essential functions for drinking, irrigation and industrial activities (Mjemah and Mariki, 2021; Tegegne et al. 2023). The access to clean drinking water is crucial for maintaining human health and overall well-being. However, the safety of groundwater is of main concern for various purposes (Tokatli C, 2021). The World Health Organization stated that: "sufficient, safe, and accessible water must be available to all for sustainability." Hence, estimation of physical and chemical properties for groundwater suitability becomes mandatory for its sustainability (Tegegne et al. 2023). Results of Physico-chemical parameters of groundwater samples of study area in Pre-monsoon (PRM) and Post-monsoon (POM) season with BIS-2012 and WHO-2011 drinking water standards and have been given in Table 18.

4.1.1 pH: pH of water indicates acid-base balance in water. pH does not impact directly on human health but its impact can be seen as some change in the taste of water if it is too high or too low. Drinking water having low or high pH can have adverse effect on the skin, eyes and mucous membrane of humans (Akter et al. 2016; Bhunia et al. 2018; Abdelhafez et al. 2021). The permissible limit set for pH by BIS-2012 and WHO-2011 is 6.5-8.5 (Bhunia et al. 2018; Adimalla et al. 2020). In the study region, all the water samples were found to be within the safe limits set by WHO and BIS. pH of different sampling sites ranged from 6.00-6.87 with mean value of 6.43 in the PRM, indicating slightly acidic nature of groundwater. During POM it ranged from 6.12- 7.13 with an average of 6.57, indicating groundwater is slightly acidic to neutral in nature. Similar findings have been published by various research studies conducted in various parts of India and in the world (Abbulu and Rao, 2013; Aslam and Raina, 2016; Beyene et al. 2019; Ajmal et al. 2022). Comparison of pH of both seasons is graphically presented in Fig.4.

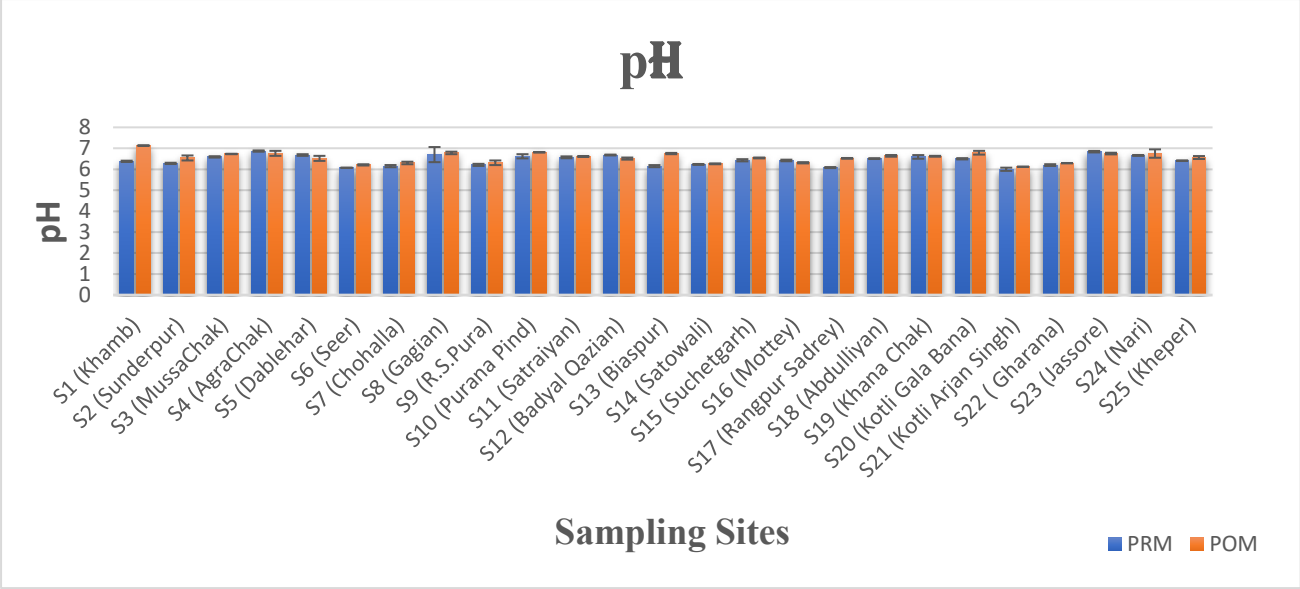

Fig.4: Comparison of pH for Pre- (PRM) and Post monsoon (POM) season.

4.1.2 Electrical Conductivity (EC): EC/ Electrical Conductivity signifies the concentration of salt content in water and is one of the important parameters for assessing the groundwater quality (Bhunia et al. 2018; Shil et al. 2019; Abdelhafez et al. 2021). EC of the study area ranges from 356 µS/cm to 1172 µS/cm with an average of 676.84 µS/cm in PRM while it ranged from 394-1037 µS/cm with a mean of 622.37 µS/cm during POM in the study area. The permissible limit for EC is 1000 µS/cm as per BIS-2012. All the sampling sites except S14 (Satowali) found within the permissible limits in both the seasons. High EC in the groundwater can occur due to presence of several salts and minerals which lead to high salinity in the groundwater. Other reasons for high EC in groundwater include water drained from agricultural fields, municipal wastewater, rainfall, presence of salts and dissolved minerals in the rock or soil naturally (Gautam et al. 2023; Kauser et al. 2022; Shil et al. 2019). Sudan S, 2018 reported EC of Satowali, Suchetgarh and R.S. Pura to be 640 µS/cm, 610 µS/cm and 510 µS/cm respectively but in present investigation it has been increased to 1172 µS/cm, 942 µS/cm and 731 µS/cm respectively. Results of present study are also supported by study conducted in Patna, Bihar, India by Zafar et al. 2020, where EC ranged from 300-1700 µS/cm. High concentration of EC in the study area is due to agricultural runoff, increase in the temperature of water and human activities. Comparison of EC of both seasons is graphically presented in Fig.5.

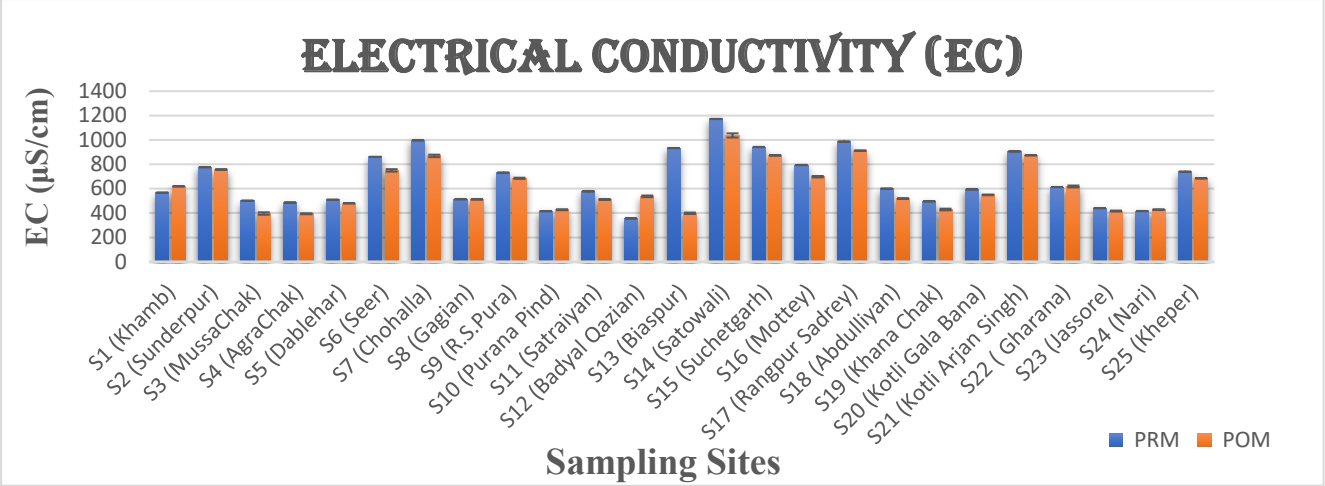

Fig.5: Electrical Conductivity (µS/cm) for Pre- (PRM) and Post monsoon (POM) season.

4.1.3 Temperature: Higher temperature in water bodies can lead to higher microbial growth and can cause odour, colour, taste and corrosion problems (Bernard and Ayeni, 2012; Asadi et al. 2019). Temperature of the study area fluctuated from 25.6 to 33.2 ºC with an average of 29.19 ºC during PRM season while 24.5 to 34.4 ºC with an average of 29.35 ºC during POM season. This variation of the temperature in both the seasons can be due to the different water table depths of the groundwater sources of the study area. It is reported by Tajwar et al. 2023 that the temperature of groundwater is approximately constant through the year but can experience a slight rise with increasing depth of the groundwater sources. Fig. 6 represents the comparison of the PRM and POM season of the study area.

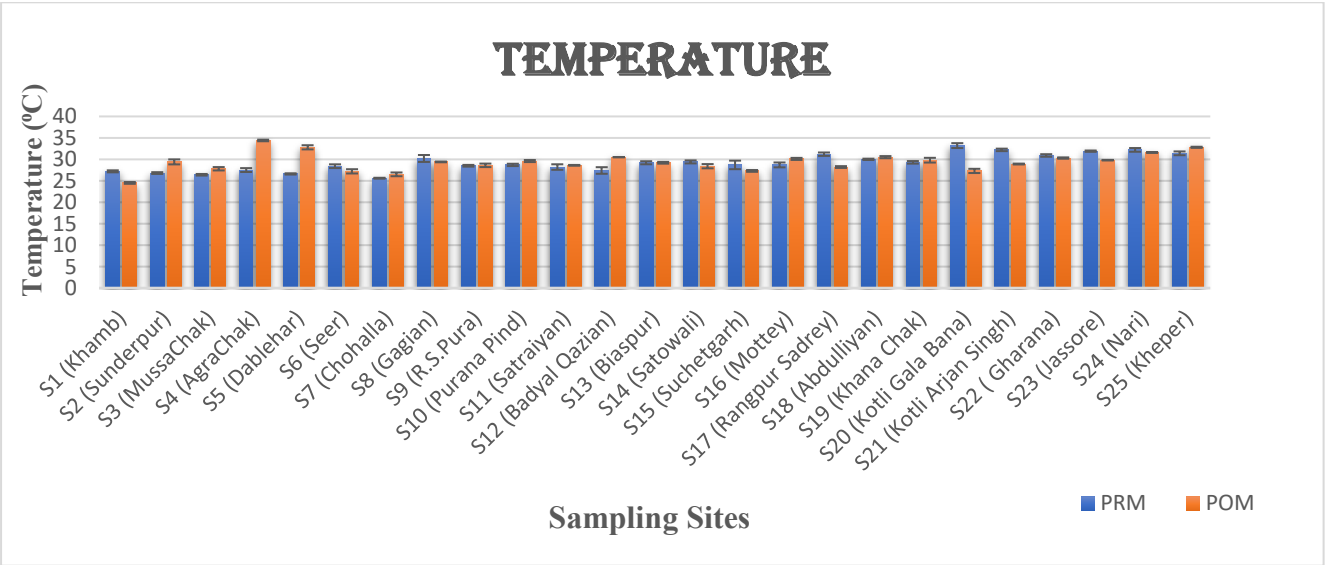

Fig.6: Temperature values for Pre- (PRM) and Post monsoon (POM) season.

4.1.4 Turbidity: Turbidity represents the total suspended solid concentration in water (Kumar et al. 2009; Baloch et al. 2021; Kumar et al. 2022). Higher values of turbidity indicate higher levels of pathogens such as bacteria, viruses and parasites. Drinking water having high turbidity can cause nausea, cramps and diarrhoea (Prakash and Somashekhar, 2006; Bernard and Ayeni, 2012; Kaur et al. 2017). During PRM season, its value ranged from 0.0-0.3 Ntu with an average of 0.05 Ntu and 0.0-0.2 Ntu with an average of 0.03 Ntu in the POM season, indicating no contamination in the groundwater of the study area. Turbidity values for both the seasons are found within the permissible limits set by BIS-2012 and WHO-2011. Fig. 7 depicts the turbidity of the groundwater of the study region.

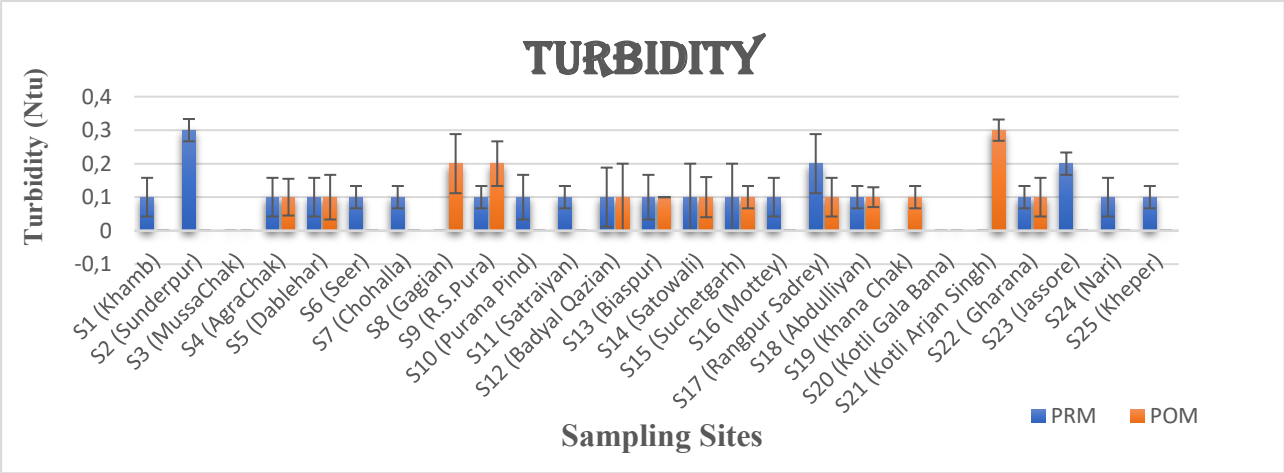

Fig.7: Turbidity (Ntu) for Pre- (PRM) and Post monsoon (POM) season.

4.1.5 Total Dissolved Solids (TDS): TDS refers to the measurement of minerals, salts, ions, dissolved organic and inorganic substances in the water. Consumption of water with high TDS values can pose various unfavourable physiological reactions, gastrointestinal irritation and distort the taste of water (Saraswat et al. 2019; Kumar et al. 2017). TDS of water samples of study area ranged from 208 mg/L- 596 mg/L having mean of 330.72 mg/L for PRM season while 197 mg/L – 814 mg/L having mean of 346.85 mg/L for POM season. Values of TDS for sampling sites namely, Seer (S6), Satowali (S14) and Rangpur Sadrey (S17) were exceeding the acceptable limits of BIS-2012 and WHO-2011 drinking water standards for PRM while Chohalla (S7), Satowali (S14) and Rangpur Sadrey (S17) for POM season. Other samples in both the

seasons are under the permissible limits of BIS-2012 and WHO-2011 drinking water limits. Results of present study are in accordance with the study conducted in Una district of Himachal Pradesh, India where average TDS of 331 mg/L was reported (Gautam et al. 2023). TDS classification of water samples for PRM and POM season is given in Table 17 (Saraswat et al. 2019; Wagh et al. 2020). As per classification, 48% and 52% of samples are falling under excellent and good category of TDS classification respectively for PRM season and for POM 52%, 44% and 4% of samples fall under excellent, good and fair category of TDS classification respectively. TDS concentration of both season is graphically presented in Fig.8.

Table 17: **Classification of water for drinking purpose according to TDS values.**

TDS Value range (mg/L)	Water Class	% of water samples	
		PRM	POM
<300	Excellent	48%	52%
300-600	Good	52%	44%
600-900	Fair	Nil	4%
900-1200	Poor	Nil	Nil
>1200	Unacceptable	Nil	Nil

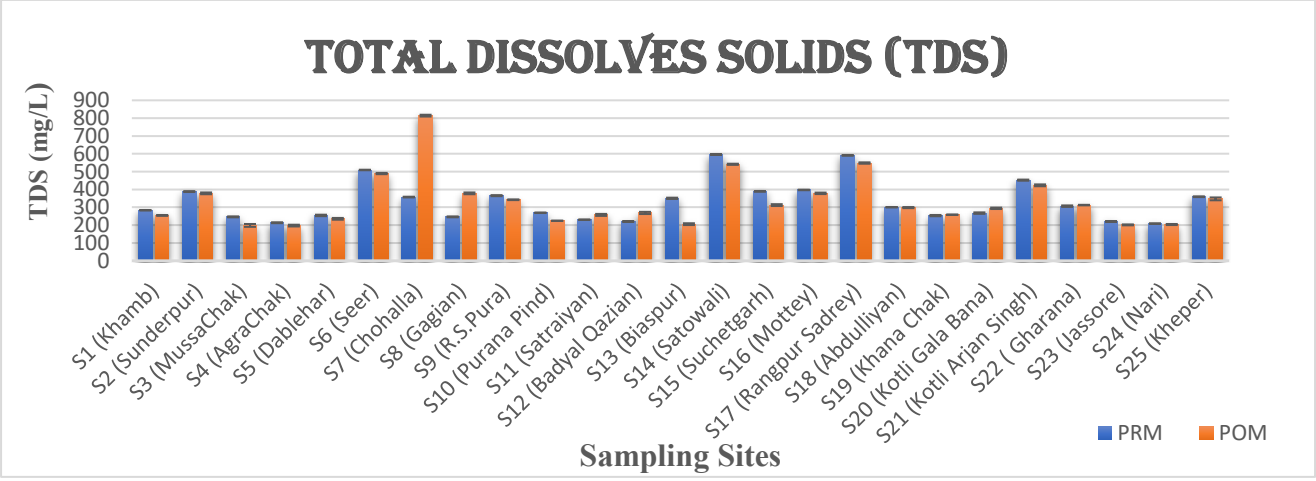

Fig.8: Total Dissolved Solids (mg/L) for Pre- (PRM) and Post monsoon (POM) season.

4.1.6 Total Alkalinity (TA): Total Alkalinity can be defined as the capacity of water to neutralize acid. Elevated level of alkalinity implies higher levels of calcium

carbonate ($CaCO_3$) which can decrease the water's acidity (Gugulothu et al. 2022). Higher concentration of bicarbonate can occur due to leaching of mineral substances in the soil (Gulgundi and Shetty, 2018). TA of the water samples in the study area ranged from 65-185 mg/L with an average of 104.11 mg/L for POM season while 100-250 mg/L with an average of 162.88 mg/L for the PRM season. The permissible limit of TA set by BIS-2012 is 600 mg/L and all the water samples were found to be within permissible limits. For PRM season, 24% samples [S1 (Khamb), S13 (Biaspur), S14 (Satowali), S15 (Suchetgarh), S17 (Rangpur Sadrey) and S21 (Kotli Arjan Singh)] were exceeding the permissible limits set by BIS-2012 and WHO-2011 while all samples reported to be within permissible limits for POM season. In the groundwater of the study area, only bicarbonates (HCO_3^-) ions were found to be present while carbonate (CO_3^{2-}) and hydroxyl ions (OH^-) were found to be absent. Similar results have been reported by the studies conducted in Samba district of Jammu and Kashmir, India (Khanna P, 2019) and in Jammu district of Jammu & Kashmir, India (Sudan S, 2018) where only bicarbonate ions were reported in the groundwater of their respective study areas. The results of TA for present study are also supported by pH values of present study as the Phenolphthalein alkalinity was reported to be zero since pH values of all the water samples were less than 8 which indicates presence of bicarbonates ions. TA of groundwater samples of study area in different season is represented in Fig. 9.

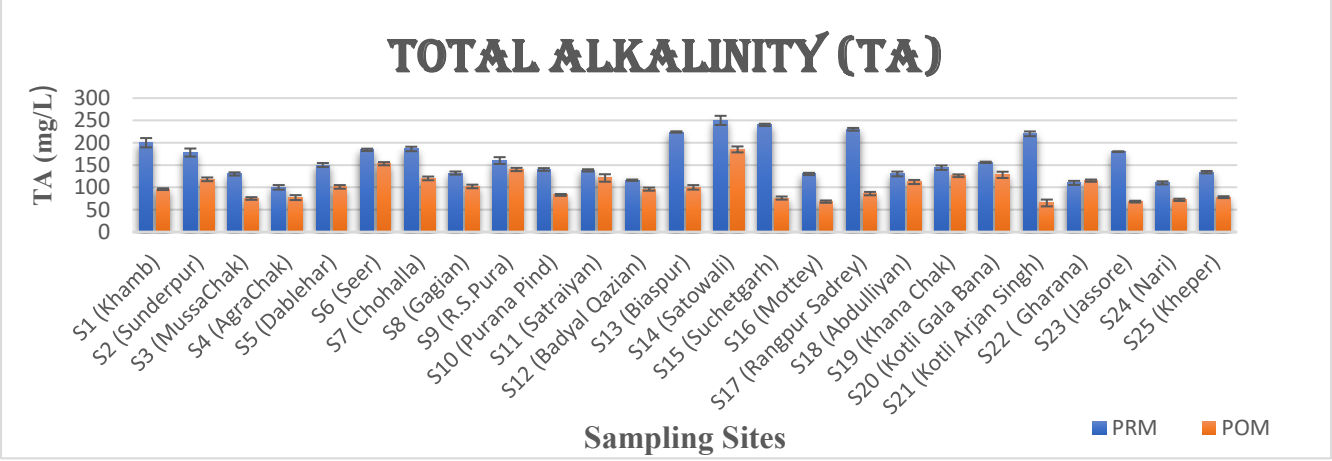

Fig.9: Total Alkalinity (mg/L) values for Pre- (PRM) and Post monsoon (POM) season.

4.1.7 Total Hardness (TH): Presence of hardness in water is due to the occurrence of chlorides and sulphates of magnesium and calcium (Vasanthavigar et al.

2010; Gulgundi and Shetty, 2018; Gabr et al. 2020). It can cause scaling, closure/blockage of industrial pipes and even health issues (Vasanthavigar et al. 2010). The permissible limit of Hardness is 600 mg/L (BIS-2012). TH of water samples from the study region lies between 200-560 mg/L (av. 305.88 mg/L) for PRM and for POM season, the range for TH varied from 183-520 mg/L (av. 299.32 mg/L). 40% samples in both the seasons were found above the acceptable limits set by BIS-2012 and WHO-2011 drinking water standards. Highest TH was observed at S17 (Rangpur Sadrey) during both the seasons. According to Sudan S, 2018, Khanna, P, 2019 and Jasrotia et al. 2019, 305.8 mg/L and 300 mg/L are the respective averages of TH for pre-monsoon and post-monsoon season in various districts of Jammu, Jammu and Kashmir, India. Overall, the samples of the study area found to be safe as per TH and comparison of both seasons are graphically presented in Fig. 10.

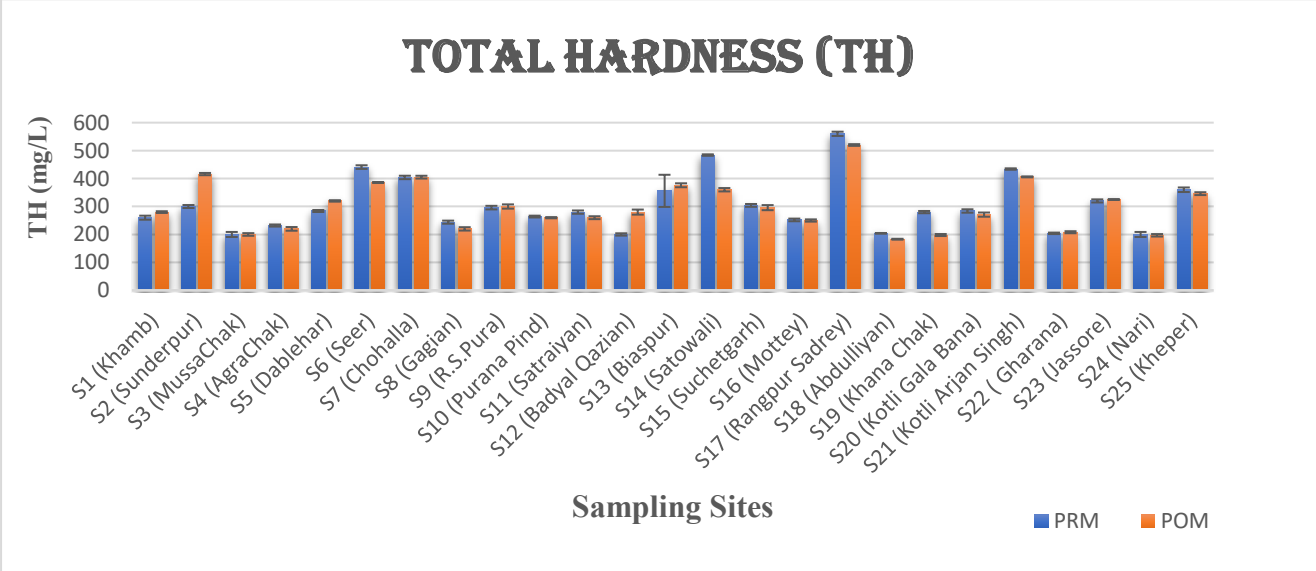

Fig.10: Total Hardness values of groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.1.8 **Calcium (Ca^{2+}):** Calcium plays a crucial role in the functioning of human cells and the structure of bones. It is available in groundwater because of its presence in rocks and its solubility in water (Sudan S, 2018). Taking lesser amount of Ca^{2+} may lead to various health problems like osteoporosis while high concentration of calcium in drinking water can lead to bladder or kidney stone, Colon Cancer etc. (Saleem et al. 2016; Wagh et al. 2020). The acceptable limit set for Ca^{2+} by BIS-2012 and WHO-2011 is 75 mg/L. Ca^{2+} concentration in the

study region varied from 47.09-117.75 mg/L with an average of 88 mg/L and 42.13-117.74 with an average of 81.4 mg/L for PRM and POM season respectively. 18 out of 25 sampling sites i.e. 72% samples were reported with Ca^{2+} concentration above the permissible limits of BIS and WHO in both the seasons. Credible causes for the high content of Ca^{2+} in study area include the dissolution of dissolved salts and minerals naturally in groundwater. High calcium content in the groundwater of the study area could lead to the problem of scaling in the pipes, taps, health issues such as kidney stones, hair and skin dryness. So, drinking water must be boiled before usage is highly recommended. Higher calcium concentrations in groundwater and similar health effects have also been observed by Kumari and Rai, 2020 in Haryana region of India. Ca^{2+} concentration in groundwater of study area of both seasons has been presented in Fig. 11.

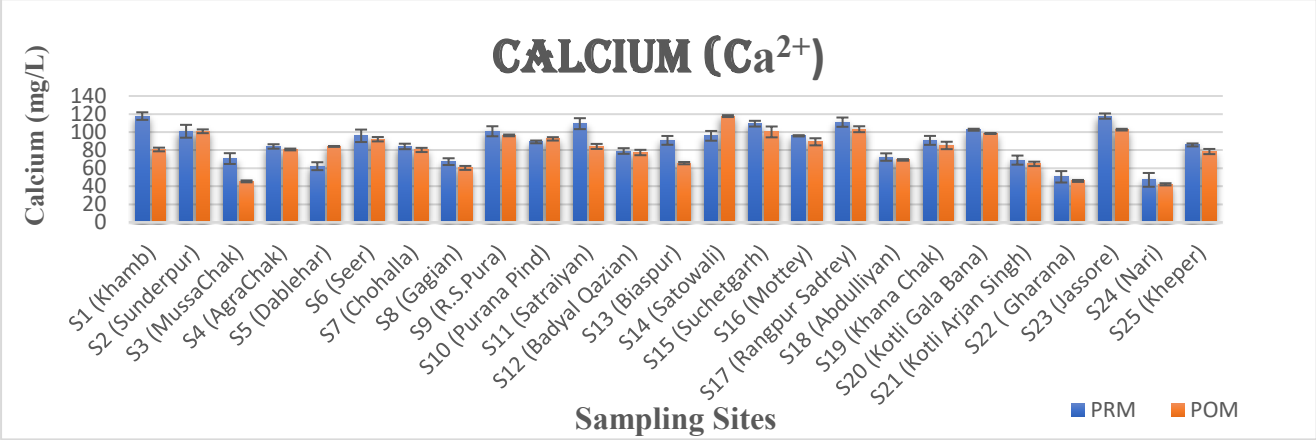

Fig.11: Calcium (Ca^{2+}) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.1.9 **Magnesium (Mg^{2+}):** Magnesium is present naturally in groundwater. Magnesium deficiency can lead to various human risks such as hypertension, cardiac and vascular disorders, eclampsia in pregnant women, osteoporosis, acute myocardial infection etc. (Saleem et al. 2016; Sudan S, 2018). The consumption of Mg^{2+}-rich water can lead to colon cancer (Wagh et al. 2020). The permissible limits for Mg^{2+} as prescribed by BIS-2012 is 100 mg/L. Mg^{2+} content of water samples in the study region varied from 120.94 - 448.98 mg/L with a mean of 217.81 mg/L in PRM while 112.8 – 416.8 mg/L with mean of 221.3 mg/L in POM season. All the groundwater samples (100%) of the study

region exceeded the standard limits set by BIS-2012 and WHO-2011 in both the seasons. Probable causes of magnesium in the groundwater includes mineral and salt dissolution, limestone hardness. A study conducted by Veeraswamy et al. 2019 in Chittor district of Andhra Pradesh, India, reported average concentration of Mg^{2+} to be 217.78 mg/L, which are in accordance with result of present study. Mg^{2+} concentration for both seasons has been presented in Fig. 12.

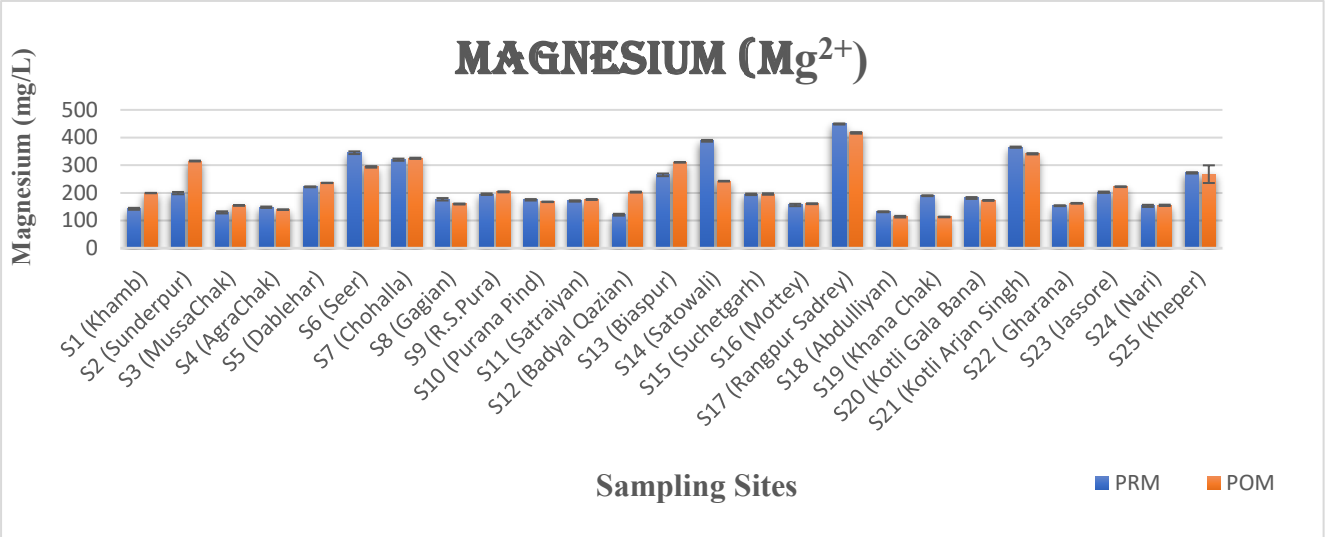

Fig.12: Magnesium (Mg^{2+}) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.1.10 **Sodium (Na^+):** Sodium is a metallic element, silver white in colour, which is present in water in very minute amount. Sodium ions have high solubility. Various sources of Sodium include natural sources, agricultural activities, water treatment chemicals, domestic water softeners and sewage effluents (Abbasnia et al 2018(a)). If Sodium concentration in drinking water exceeds the permissible limits i.e., 200 mg/L, then it can lead to many diseases namely, hypertension, kidney damages, headache etc. (Sudan, 2018; Wagh et al. 2020). The Permissible limit of Na^+ in drinking water as set by BIS- 2012 and WHO-2011 is 200 mg/L. Na^+ content in the groundwater of study area varied between 23.02- 46.71 (average- 35.56 mg/L) for PRM and 11.63 – 45.21 mg/L (average- 29.82 mg/L) for POM season. All the groundwater samples i.e. 100% of samples were found safe for drinking purposes as all samples were within the permissible limits (200 mg/L) of BIS- 2012 and WHO-2011. Satowali (S14) was found to have maximum sodium concentration for both the seasons (Fig.

13). Studies conducted in South-west region of Delhi, India by Acharya et al. 2018 reported sodium concentration in the range of 1.00- 33.91 mg/L and 0.44 – 48.25 mg/L in Azerbaijan region of North-west in Iran (Asadi et al. 2019) with the conclusion that the sodium content in the groundwater of their respective study areas were reported to be safe as per limits set by BIS and WHO drinking water standards respectively.

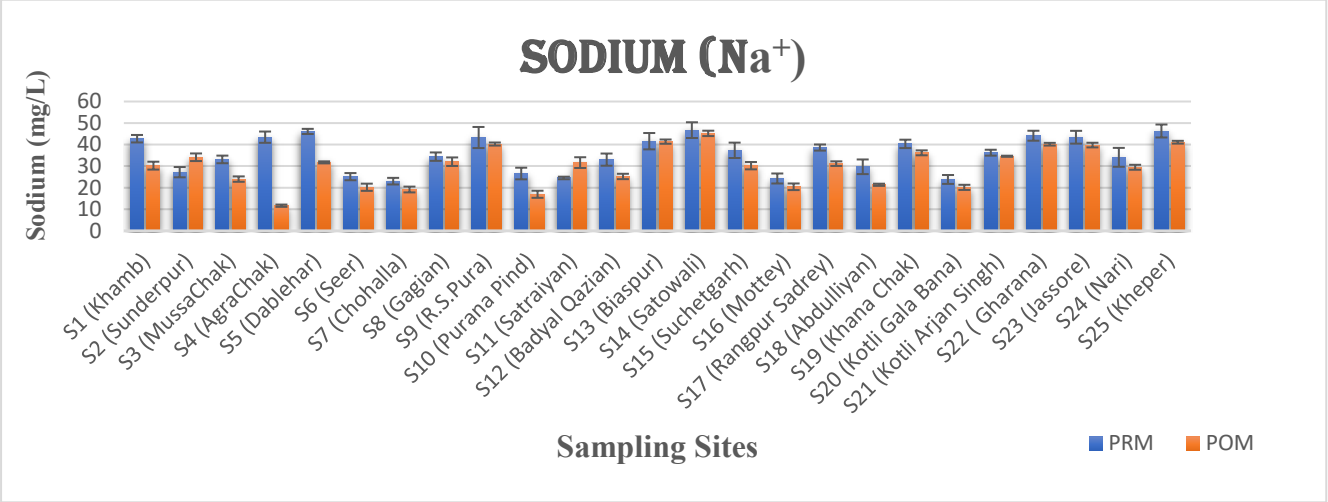

Fig.13: Sodium (Na^+) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.1.11 **Potassium (K^+):** Potassium plays an important role in all plant and animal tissues and also maintains metabolism of living organisms. At very low concentration in drinking water, it does not pose any health concerns but its high doses can lead to nausea and vomiting, hypertension, kidney, lung and cardiovascular diseases, chest tightness, diarrhoea, shortness of breath and heart failure (Sudan S, 2018; Lanjwani et al. 2020). Sources of Potassium include weathering of rocks, use of Potassium Permanganate in water treatment, excessive use of K^+-rich fertilizers, use of potassium chloride for water softening etc. (Khanoranga and Khalid, 2019; Wagh et al. 2020; Gugulothu et al. 2022). The acceptable limit of K^+ set by BIS-2012 is 12 mg/L. The concentration of Potassium in the groundwater of study area in PRM season lies between 12.21- 15.01 mg/L with an average of 13.74 mg/L while for POM 0.19-4.29 mg/L with average 1.37 mg/L. All the water samples (100%) in the PRM season were found above the acceptable limits of BIS-2012 drinking water standards (Fig. 14). Research findings from different studies carried out by Rao

N S, 2006, Saraswat et al. 2019, Tajwar et al. 2023 reported average concentration of potassium during PRM season to be 27.21 mg/L, 14.21 mg/L and 12 mg/L respectively. Studies conducted in different regions of India and across world such as in Andhra Pradesh, India (Rao N S, 2006); Gujarat, India (Saraswat et al. 2019); Hatiya, Bangladesh (Tajwar et al. 2023) also reported higher concentration of potassium during pre-monsoon season as compared to post-monsoon season. High concentration of potassium indicates the excessive application of potassium rich fertilizers, along with some natural weathering of rocks in the groundwater of the study area.

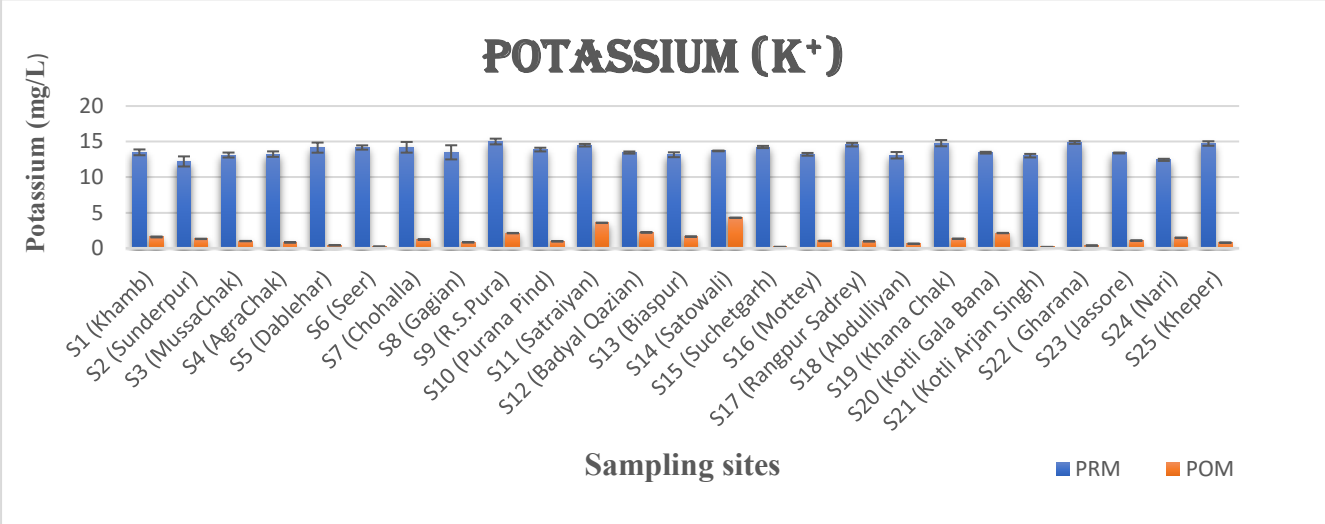

Fig.14: Potassium (K^+) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.1.12 **Chloride (Cl^-)**: It is found naturally in various water sources and primarily originates from the dissolution of salts particularly as table salt (NaCl), activities carried out in agricultural area, weathering of halite material, industrial waste, sewage, domestic waste, fertilizers, chlorine as a disinfectant, leachate etc. (Kanga et al. 2020; Wagh et al. 2020). High chloride content in water can have deleterious effect on metallic pipes, structures, agriculture crops (Kumar et al. 2009; Vardhan et al. 2015). In PRM, Chloride content ranged from 8.52-113.6 mg/L with an average of 32.52 mg/L. For POM period, Cl^- ranged from 11.4-99.4 mg/L with mean of 37.24 mg/L. Acceptable limit for Chloride in drinking water is 250 mg/L (BIS-2012 and WHO-2011). All the water samples were found safe for drinking as per BIS-2012 and WHO-2011 and are presented in Fig. 15. Studies conducted by Ahada and Suthar, 2018 in Malwa area of Punjab,

India and by Bhunia et al. 2018 in Neyshabur region of Iran reported that the chloride concentration in their respective regions was below 250 mg/l, indicating no chloride contamination in their study areas.

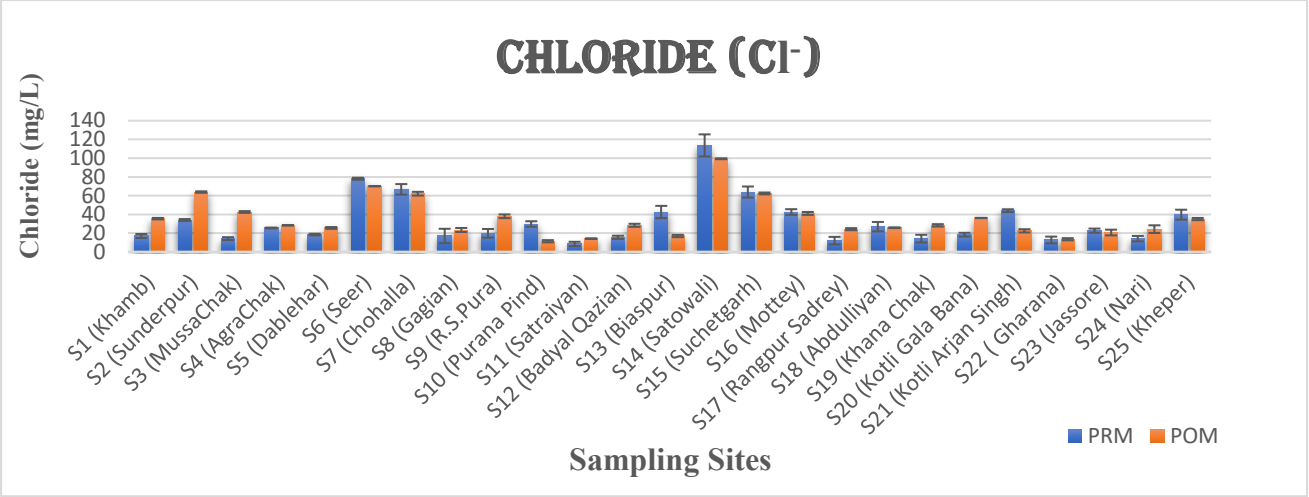

Fig.15: Chloride (Cl^-) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.1.13 **Fluoride (F^-)**: Fluoride is a key trace element commonly found naturally in groundwater. It is responsible for keeping healthy teeth and bone development. Small concentration of Fluoride in drinking water is important for dental health while its excessive concentration can lead to skeletal fluorosis (Yadav and Kumar, 2020; Subramaniyan et al. 2022). Major sources of Fluoride in groundwater includes dissolution of this mineral present in geological formations, leaching from fluoride rich rocks (Kumar et al. 2013; Khanna P, 2019; Yadav and Kumar, 2020). Permissible concentration of Fluoride in drinking water is 1.5 mg/L as set by BIS 2012 and WHO- 2011. In the present study, content of fluoride in groundwater was recorded between 0.12-0.9 mg/L with an average of 0.56 mg/L for PRM and 0.1-0.76 mg/L (av. 0.44 mg/L) for POM season. All the samples of the study area in both the seasons fall under the safe limits of BIS -2012 and WHO- 2011 (Fig. 16). Various research studies such as Baloch et al. 2021 (average fluoride concentration - 0.25 mg/L); Acharya et al. 2018 (fluoride concentration range 0.0-0.10 mg/L); National Institute of Hydrology, Roorkie, 1997 (average fluoride concentration - 0.40 mg/L) reported fluoride concentration within the safer limits of set drinking water standards.

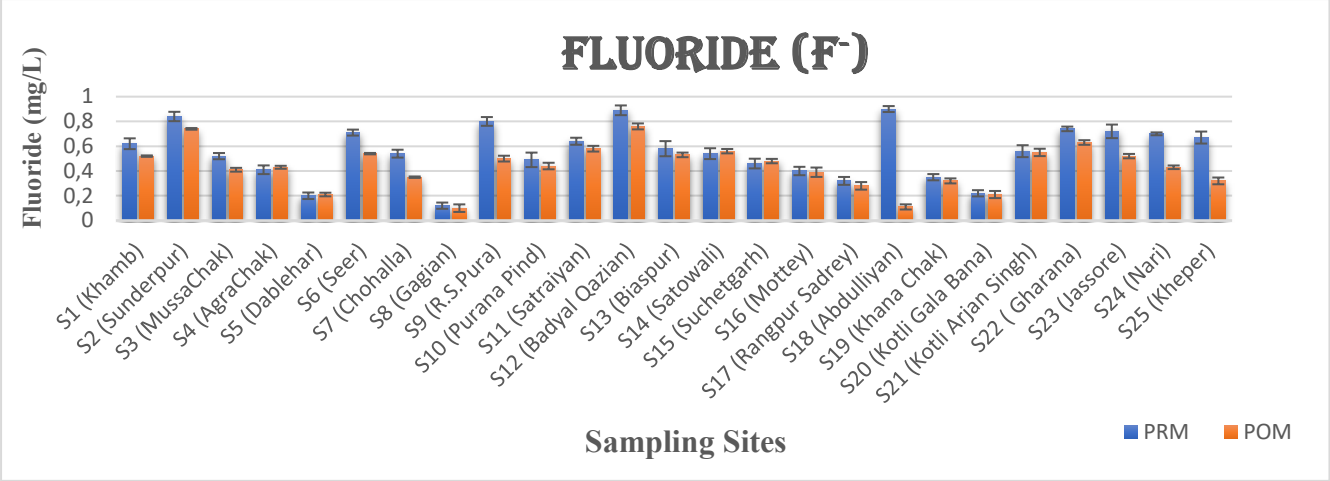

Fig.16: Fluoride (F^-) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.1.14 **Nitrate (NO_3^-):** Nitrate is present in ground water and is one of the main components of chemicals and fertilizers. Sources of nitrate contamination includes Nitrogen rich fertilizers, contamination from septic tanks and sewage effluents, nitrogen cycle, legume plants, domestic and industrial discharge (Gulgundi and Shetty, 2018; Kanga et al. 2020). It was reported by various studies that high content of the nitrate can lead to thyroid disease, by interference with uptake of iodide, diabetes, hypertension, blue baby syndrome/ Methemoglobinemia in children (a condition in which baby's skin becomes blue due to a reduced amount of haemoglobin in the blood) and can also lead to growth of algae and other organisms that cause undesirable taste and odour in water (Abbasnia et al. 2018(a); Wagh et al. 2020). These are highly soluble in water and hence has the ability to easily penetrate through soil into the groundwater (Kumar et al. 2009). The standard limit of NO_3^- in the drinking water is 45mg/L as set by BIS guidelines. NO_3^- concentration in the groundwater of study area for PRM was found to be 0.94- 4.56 mg/L (av. 2.46 mg/L) for PRM season and 0.78 – 4.5 mg/L (av. 2.28 mg/L) for POM season. Groundwater of the study area were under the acceptable limits of nitrates set by BIS-2012 and WHO-2011 in both the seasons. Studies conducted by Prakash and Somashekhar, 2006; Mjemah and Mariki, 2021 and Naidu et al. 2021 in different regions of India and across World namely, Anekal Taluk region of Bangalore, India; Makutupora area of Tanzania and Sindhudurg region of Maharashtra, India were reported with average nitrate concentration 2.00 mg/L,

2.91 mg/L and 2.39 mg/L respectively in the groundwater of their respective study areas. The result findings of the above-said studies are in accordance with the results of present study. The results of present study for nitrates are also supported by Nitrate Pollution Index (NPI), calculated for assessing groundwater contamination with nitrate in the study area, where also no nitrate pollution was reported. Comparison of Nitrate contamination in both seasons in groundwater of study area is represented in Fig. 17.

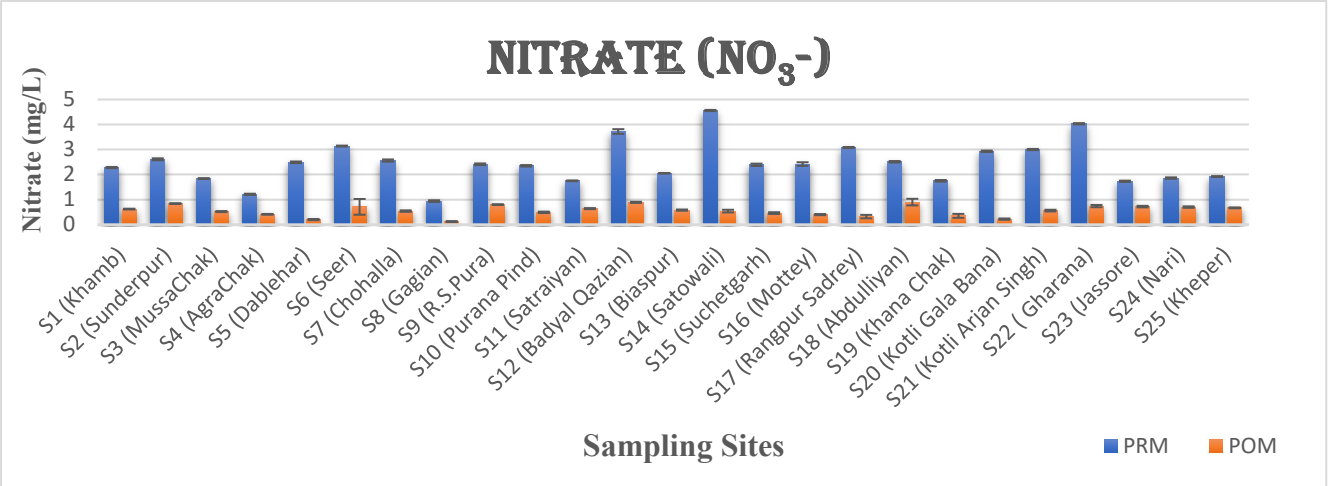

Fig.17: Nitrate (NO_3^-) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.1.15 **Sulphate (SO_4^{2-})**: Sulphate (SO_4^{2-}) in groundwater is mainly derived from the dissolution of salts of sulphuric acid, from gypsum on oxidation of pyrites and is also present in industrial wastes. It is one of the least toxic anions and is soluble in water. It produces catharsis, dehydration, laxative effect and gastrointestinal irritation effect upon human beings when it is present in excess and can also cause material damage (Wagh et al. 2020; Jude et al. 2023). The permissible limit set for sulphate in drinking water by BIS-2012 is 400 mg/L. Sulphate content in study area varied from 15.09-49.12 mg/L with an average of 30.03 mg/L for PRM while 11.65- 46.15 mg/L with a mean of 26.66 mg/L for POM season. All samples were within the permissible limit and are shown in Fig. 18. Researches with similar findings include Abbulu and Rao, 2013 (Vishakhapatnam, Andhra Pradesh, India) and Boateng et al. 2016 (Ejisu-Juaben Municipality, Ghana), where the average sulphate content in the

groundwater were found to be 25.4 mg/L and 45 mg/L and thus reported to be within the permissible limits.

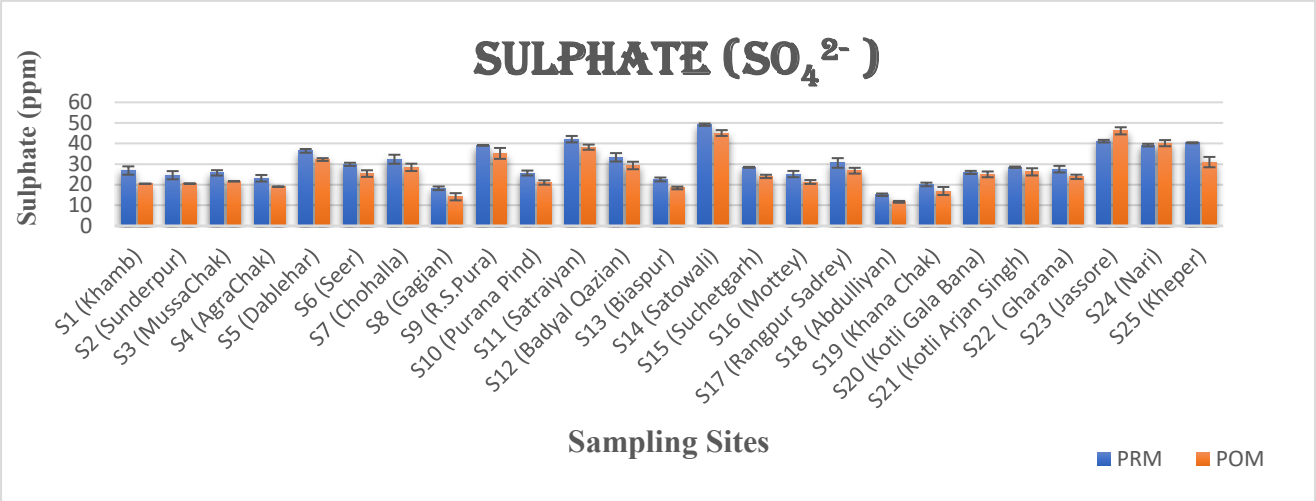

Fig.18: Sulphate (SO_4^{2-}) concentration in study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.2 Heavy metals assessment in groundwater of study area

4.2.1 Iron (Fe^{2+}): Presence of higher amounts of iron in the groundwater can occur due to some localized effects or rusting of pipes (Singh et al. 2012). High concentration of iron in drinking water can lead to various human health risks such as stomach problems, skin disease, liver fibrosis, gastrointestinal problems, zinc absorption, haemochromatosis (hereditary issue) (Akter et al. 2016; Kumar et al. 2017; Khanna P, 2019; Palmajumdar et al. 2021). Excess concentration in water can lead to an inky flavour, offensive taste and colour of water. When exposed to air, iron results in rusty colour and turbidity (Singh et al. 2012; Abdelhafez et al. 2021). The acceptable limit for iron is 0.3 mg/L in drinking water by BIS-2012. Fig. 19 represents the variation of Iron content and showed wide range from 0.3 ppm at Khamb (S1) to 0.94 ppm at Gharana (S22), average of 0.57 ppm, in PRM season whereas for POM season, its concentration varied from 0.01 ppm at Khamb (S1) to 0.53 ppm at Seer (S6) with an average of 0.25 ppm. All the water samples in the PRM season were exceeding the acceptable limits of 0.3 mg/L while 48% samples in POM were exceeding the allowable limits of set standards. It can be concluded that the concentration of iron in groundwater was higher in pre-monsoon as compared to post-monsoon season and can be due to leaching process. Findings of present study are in

accordance with studies conducted in different regions of the world namely, Abdelhafez et al. 2021 (New Valley Governorate, Egypt); Akter et al. 2016 (Rural Bangladesh); Palmajumdar et al. 2021 (Bankur district, West Bengal, India) where it was reported that the increase in concentration of Fe^{2+} during pre-monsoon is because of leaching from the thick layers of soil after post-monsoon season. Increased amount of iron in study area's groundwater may include groundwater movement through iron-bearing rocks, movement of water from handpumps and agricultural runoff. Present study revealed that the groundwater of the study area was found contaminated with the iron content and thus can cause severe stomach related problems, liver related issues, less zinc absorption in the human body. Thus, locals are advised to use water for drinking purpose only after boiling the water or can use the water filters in their homes.

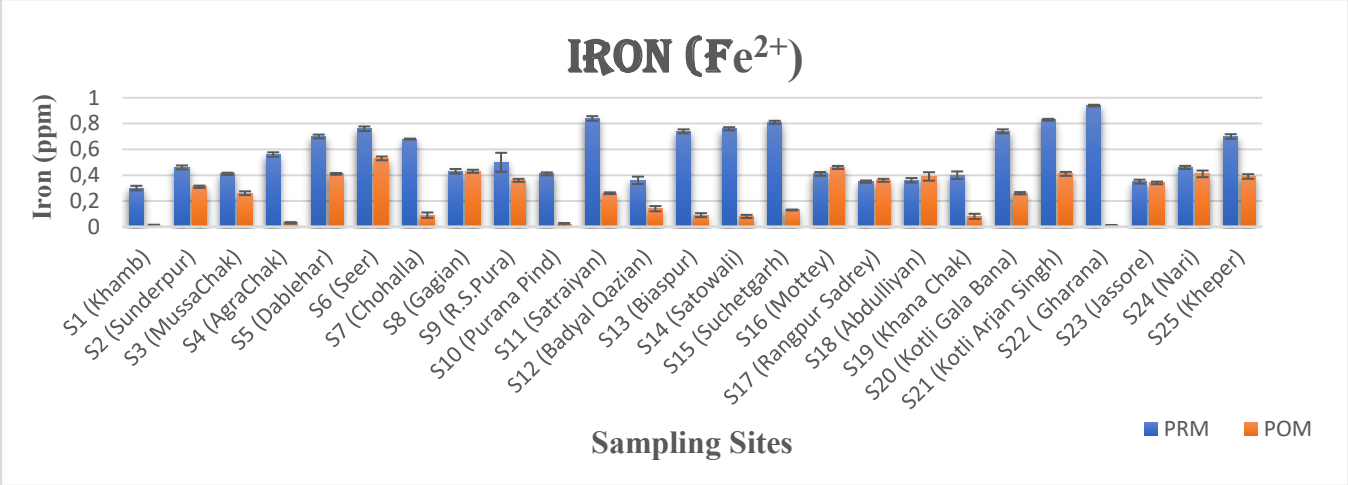

Fig. 19: Iron (Fe^{2+}) concentration in study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.2.2 **Zinc (Zn^{2+}):** Ingestion of zinc in higher amount can cause anaemia, kidney related issues, diarrhoea, stomach and pancreatic disorders etc. (Kumar et al. 2017). Major sources of Zn^{2+} include traffic sources, vehicle tyres, paints, dyes, galvanized pipes, production of corrosion-resistant alloys etc. (Kaur et al. 2019; BIS-10500, 2012). During PRM season, Zn^{2+} concentration in study region varied from 0.11-0.25 ppm with an average of 0.17 ppm whereas in POM season, its concentration varied from 0.05-0.16 ppm with a mean of 0.09 ppm. Since no contamination of zinc was reported as all the samples were under the

acceptable limits (5ppm) of BIS-2012 standards for both the seasons and hence found to be safe for drinking usage. The findings of the present research align with the findings reported by other researchers (Kumar et al. 2017; Kaur et al. 2019; Khanoranga and Khalid, 2019). These studies reported that both manmade factors such as pollution, industrial activities etc. and natural factors like weathering of rocks are equally responsible for degradation of the groundwater (Khanoranga and Khalid, 2019). Zn^{2+} concentration in both seasons of study area is given in Fig. 20.

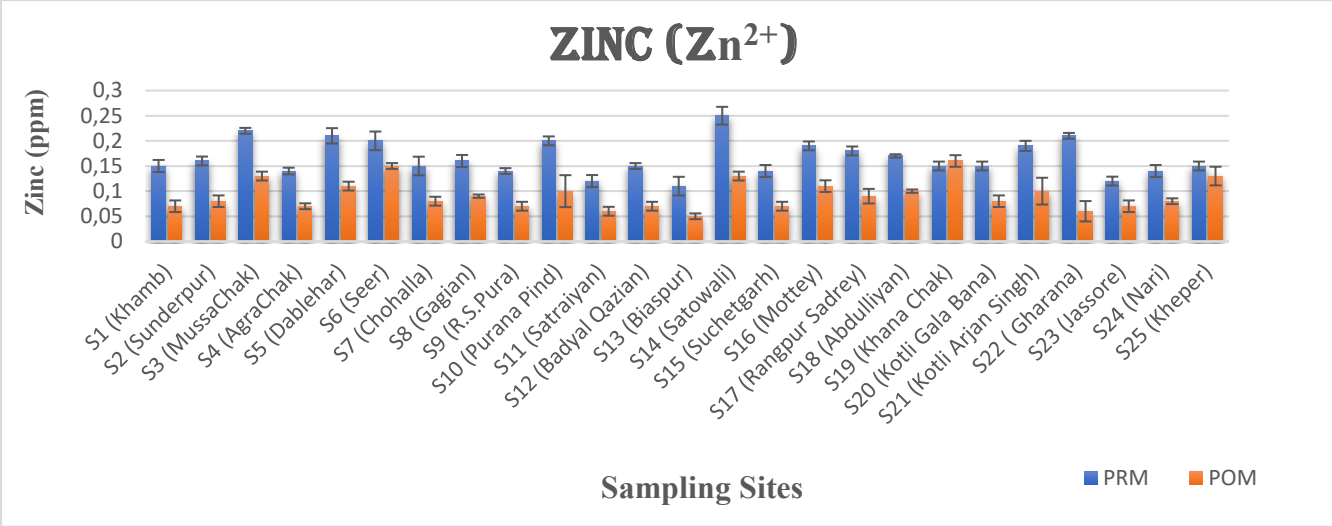

Fig.20: Zinc (Zn^{2+}) concentration in study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.2.3 **Copper (Cu^{2+}):** Cu^{2+} is mainly released from vehicular emissions, agricultural activities, industrial and mining activities, combustion of coal in brick kilns and use of other low- quality fuel for combustion (Kaur et al. 2019; Khanoranga and Khalid, 2019; BIS-10500, 2012). If concentration of copper in drinking water is too low or too high, it can lead to various health impacts such as anaemia, kidney and liver damage, digestive disturbances, gastrointestinal irritations, bitter or metallic taste, effect on central nervous system, depression etc. (BIS-10500, 2012; Sudan S, 2018; Alidadi et al. 2019). Cu^{2+} content in the present study varied from 0.04-0.25 ppm with a mean of 0.10 ppm during PRM season where 76% samples exceed the permissible limits (1.5mg/L) while for POM, values of Cu^{2+} ranged from 0.01-0.19 ppm with a mean of 0.08 ppm was found in the groundwater of study area, 68% samples exceed the permissible limits of BIS-2012 and WHO-2011 standards. Highest concentration of Cu (i.e.,

0.25mg/L) was found at S-15 (Suchetgarh) during PRM season. Similar findings have been reported by a research study done in Jammu region of J&K, India, where village Suchetgarh was reported to be highly contaminated with concentration of Mg^{2+}, Cu^{2+} and EC (Sudan S, 2018). Raja et al. 2021 conducted a study on the groundwater of the Virudhanagar region of Tamil Nadu, India and reported average copper concentration to be 0.03 mg/L. In other study, it was reported that around 43% of drinking water of Sonora area of Mexico have very high levels of Cu^{2+}, As^{3+} and Pb^{2+} (Alidadi et al. 2019). In the study area, copper contamination was reported and probable causes of copper may include agricultural activities (usage of copper-based fungicides), naturally present in soil, leaching from household plumbing, which can further have various health impacts on the people residing in the study area. So, use of water filters or RO is recommended. Concentration of Cu^{2+} in both seasons is presented in Fig. 21.

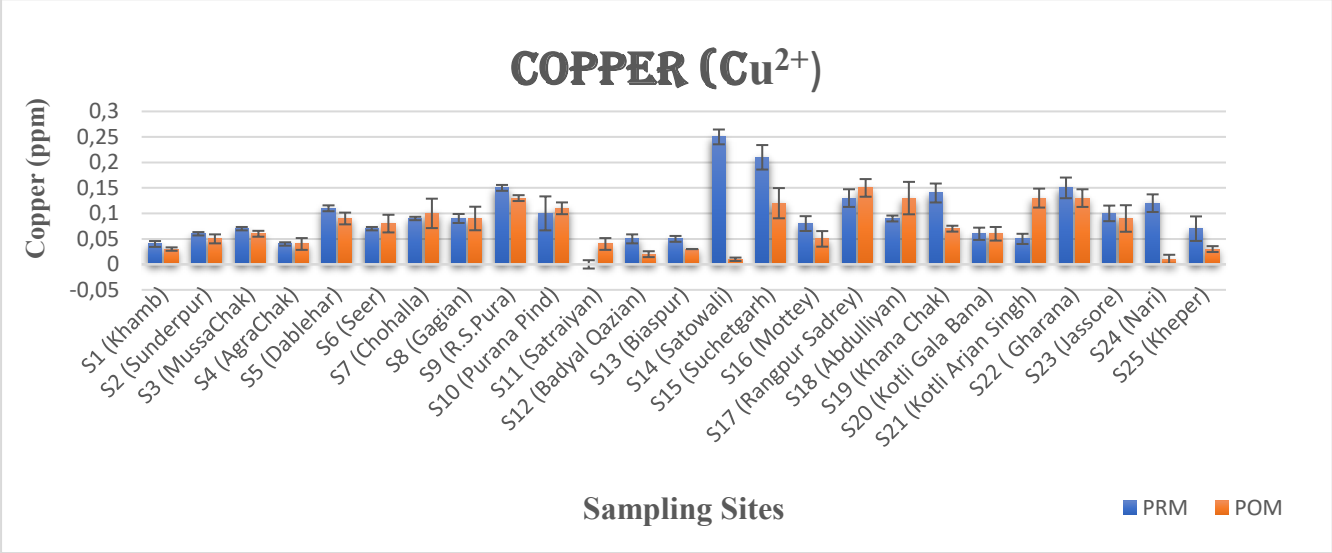

Fig.21: Copper (Cu^{2+}) concentration in study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.2.4 **Lead (Pb^{2+}):** Lead is highly toxic metal and its sources include vehicular emissions, during combustion process (use of coal as well as other low- quality fuel), gases released from chimneys, industrial activities, agricultural discharge, huge quantities of Pb^{2+} is released during use of petrol and diesel in automobiles (Kumar et al. 2017; Kaur et al. 2019; Raja et al. 2021). High concentration and long exposure duration of Pb^{2+} to human body can lead to anaemia, burning in mouth along with inflammation of the gastro-intestinal tract, abdominal pain,

central nervous system damage, paralysis, harmful for cerebrum, effect on kidney and even can lead to death (Sudan S, 2018; Alidadi et al. 2019; Kaur et al. 2019; Khanoranga and Khalid, 201 9). Contamination of Pb^{2+} was reported during both the seasons in the study region. In PRM and POM seasons, at many sites Pb^{2+} concentration was not detectable at ppm level in groundwater of study area but wherever detected its concentration was reported beyond the permissible limits (0.01 mg/L) of BIS-2012 and WHO-2011 set standards. Satowali (S-14) village followed by Suchetgarh (S-15) were found to have the highest concentration of Pb^{2+} in both the seasons. Similar results have been reported by various authors in their studies, e.g., groundwater of Sialkot region of Pakistan (which is only 11kms from the Suchetgarh area of R.S.Pura, Jammu) is highly contaminated with Pb^{2+} because of leaching from contaminated soil (Baloch et al. 2021); concentration of Pb^{2+} also exceeds the permissible limits in El-Kharga oasis of Egypt (Abdelhafez et al. 2021); Lead concentration exceeded the set standard values in drinking water of ten cities in Saudi Arabia (Alidadi et al. 2019). Reasons for the enhanced concentration of Pb^{2+} in groundwater of study area might include geological composition of rocks, agricultural activities, non-point sources such as atmospheric deposition which later on settled down on soil and lead to leaching of Pb^{2+} and other heavy metals in the groundwater. In Fig. 22, comparison of pre-monsoon (PRM) and post-monsoon (POM), Pb^{2+} concentration is presented.

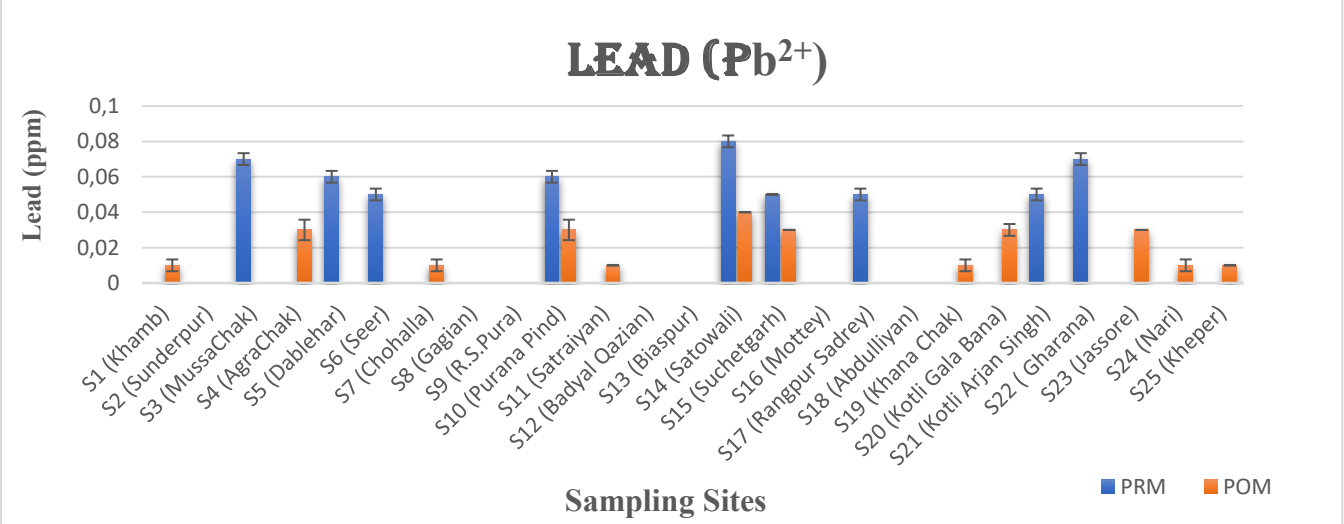

Fig.22: Lead (Pb^{2+}) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.2.5 Chromium (Cr^{3+}): Cr^{3+} is mainly associated with industrial discharges, anthropogenic activities, agricultural run-off, dust and gases released from chimney spread Cr^{3+} contaminants in all directions, diverse geology of an area, bedrock formations, other low- quality fuel used for combustion etc. (Kaur et al. 2019; Raja et al. 2021; Acharya et al. 2023). Hexavalent state of chromium can lead to lung tumours as it is cancerous, respiratory problems, ulcers, dermatitis (BIS- 10500 (2012); Sudan S, 2018; Alidadi et al. 2019). A study found that if a person is drinking 1 L/ day with Chromium dose of 8.3- 51 µg/L over one's lifetime then that person can suffer from lung, bladder, liver or kidney cancer (Alidadi et al. 2019). In present study, Cr^{3+} concentration ranged from 4.03-5.03 mg/L (av. 4.87 mg/L) for PRM and 2.31- 4.58 mg/L (av. 3.62 mg/L) for POM. However, the acceptable limit set by BIS-2012 and WHO-2011 for Cr^{3+} in drinking water is 0.05 mg/L. Chromium concentration is crossing the set standards at all sampling areas of study region in both the seasons. Probable causes of higher concentration of chromium in study area may include some natural sources and man-made sources such as domestic sewage, usage of inorganic fertilizers particularly phosphatic fertilisers which have chromium contamination. Ingestion of high chromium for longer duration can affect the health of local people as its high concentration can lead to cancer (lung and liver), respiratory problems, ulcers in mouth and skin related issues. Reporting of various studies where Cr^{3+} concentration (0.08 mg/L) exceeds the permissible limits includes Virudhunagar town of Tamil Nadu, India (Raja et al. 2021). Mean values of Cr^{3+} (Av. 4.94 mg/L) in drinking water exceeds the set standards in few cities of Thailand and Iran, probable reason of Cr^{3+} contamination was due to poor domestic treatment and pipeline corrosion (Alidadi et al. 2019). Also, Cr^{3+} concentration in drinking water was reported to be higher at many places such as Doosti dam water (present at the border of Iran and Turkmenistan), Lower Dir (northern Pakistan), China, Australia, Malaysia due to industrial and agricultural activities as they directly discharged their wastewaters into drinking water supply (Acharya et al. 2023; Baloch et al. 2021; Alidadi et al. 2019). Cr^{3+} concentrations in groundwater of study region for both seasons is given in Fig. 23.

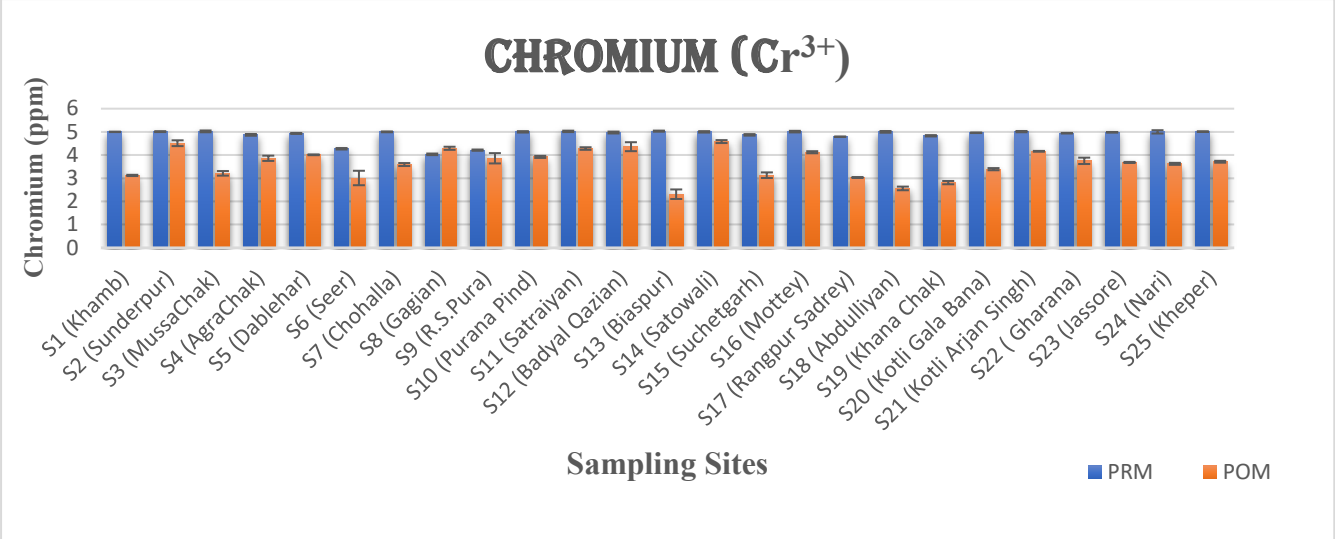

Fig. 23: Chromium (Cr^{3+}) concentration in study area for pre-monsoon (PRM) and post-monsoon (POM) season.

4.2.6 **Nickel (Ni^{2+}):** Nickel is a non-toxic element that has the potential to induce carcinogenic effects in animals and may interact with their DNA which results in changes in DNA structure (Sudan S, 2018). Various factors responsible for Ni^{2+} contamination in water includes poor purification system, pipeline corrosion and water dynamics (Baloch et al. 2021). Increased level of heavy metals like Ni^{2+} along with other metals (Cr^{3+}, Cd^{2+} and Pb^{2+}) in potable water can pile up in the tissues of human body and can cause health impacts like lung cancer by nickel etc. (Raja et al. 2021). According to USEPA, if concentration of the metals (Ni^{2+}, Pb^{2+}, Cr^{3+} and Hg^{2+}) in drinking water exceeds the permissible limits, then they have the ability to cause carcinogenic as well as non-carcinogenic risks in humans (Alidadi et al. 2019). In present study, concentration of Ni^{2+} in both the seasons was below the detection limits. Research studies conducted by Alidadi et al. 2019 in Ahvaz and Tehran cities of Iran, and by Acharya et al. 2023 in Dwarka region of New Delhi, India, reported that the concentration of nickel was not detected at ppm level.

4.2.7 **Arsenic (As^{3+}):** Arsenic (As^{3+}) occurs in groundwater due to the alkalization phenomenon, pesticide making industries, effluents form dyeing industries, geological composition of rocks, pharmaceutical industries, organic and inorganic chemical industries, nonpoint sources etc. (Sudan S, 2018; Khanoranga and Khalid, 2019; Alidadi et al. 2019). When the concentration of As^{3+} exceeds the permissible limits (0.01-0.05 mg/L) for drinking water, then it

will have adverse effects on the human health such as central nervous system, leading to coma, digestive infection, respiratory tract and even malignant tumours in vital organs (Sudan S, 2018; Khanoranga and Khalid, 2019). Arsenic concentration in study area ranged between 0.01-0.04 ppm with an average of 0.011 ppm in PRM. In POM season, As^{3+} ranged from 0.01-0.03 ppm with a mean of 0.016 ppm. 28% samples in PRM and 36% in POM of samples exceeds the acceptable limits of BIS-2012 and WHO-2011 standards (As^{3+} concentration in both season is represented in Fig. 24). Research findings where arsenic was exceeding its permissible limits include Baloch et al. 2021 conducted in Sindh province of Pakistan and in North East region of Iran by Alidadi et al. 2019 where average arsenic concentration was reported to be 1.52 mg/L and 0.18 mg/L respectively. It was also reported by Alidadi et al. 2019 that As^{3+} can lead to respiratory disorders as well as skin damage if its dose surpasses 0.0012 mg/kg/day in drinking water and in Bangladesh around 42% samples had Arsenic concentration above 50 µg/L. Abdelhafez et al. 2021 reported that in El-Kharga oasis of Egypt, arsenic concentration was found to be exceeding the permissible limits of set drinking water standards. Also, it has been reported by Alidadi et al. 2019 that Arsenic was the main pollutant in groundwater supplies of Mashhad city of Iran. In present study, long term arsenic risks have been reported and can lead to various respiratory disorders and skin related issues.

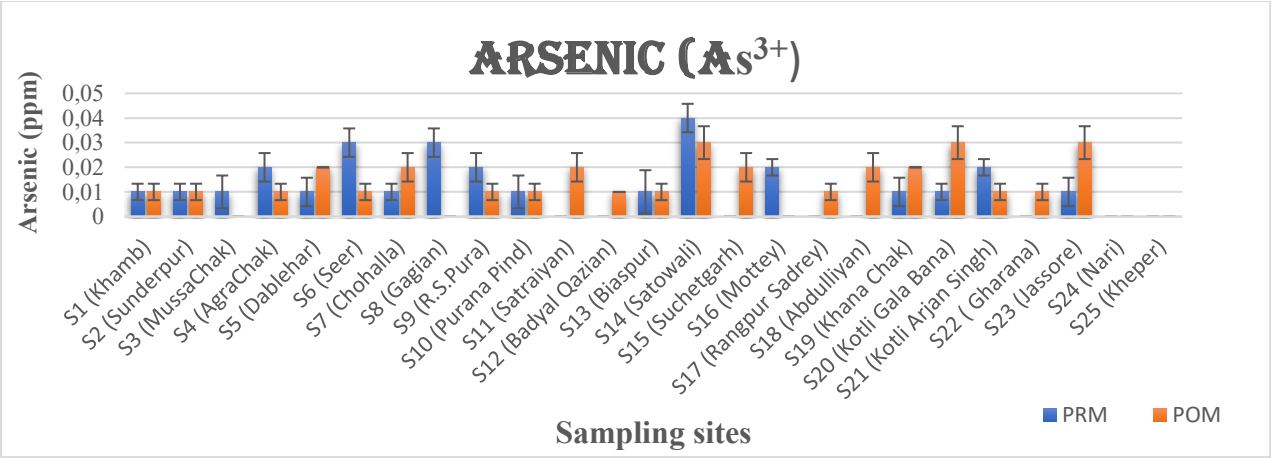

Fig.24: Arsenic (As^{3+}) concentration in groundwater of study area for pre-monsoon (PRM) and post-monsoon (POM) season.

Table 18: Physico-chemical parameters of water samples of study area with BIS-2012 and WHO-2011 drinking water standards for Pre-monsoon (PRM) and post-monsoon (POM) season.

Parameters	PRM Value range	Mean ± S.D.	% of samples exceeding the acceptable limits (PRM)	POM value range	Mean ± S.D.	% of samples exceeding the acceptable limits (POM)	Standard Permissible limits	
							BIS-2012	WHO-2011
pH	6.00-6.87	6.43 ± 0.030	52%-below the limits	6.12-7.13	6.57 ± 0.03	25%-below the limits	6.5-8.5	6.5-8.5
Electrical Conductivity (EC) (µS/cm)	356-1172	676.84 ± 1.22	4%	394-1037	622.37 ± 2.82	4%	500-1000	-
Temperature (ºC)	25.6-33.2	29.4 ± 0.02	-	24.5-34.4	29.45 ± 0.001	-	-	-
Turbidity (NTU)	0.0-0.3	0.15 ±0.001	0%	0.0-0.2	0.10 ± 0.001	0%	1-5	5
Total Dissolved Solids (TDS) (mg/L)	208-596	330.72 ± 1.14	12%	197-814	346.85 ± 2.36	12%	500-2000	1000
Total Alkalinity (TA) (mg/L)	100-250	162.88 ± 2.46	20%	65-185	104.11 ± 2.33	0%	200-600	1000
Total Hardness (TH) (mg/L)	200-560	305.88 ± 4.22	4%	183-520	299.32 ± 2.66	4%	200-600	100-500
Calcium (Ca^{2+}) (mg/L)	47.09-117.75	88.01 ± 2.47	72%	42.13-117.74	81.39 ± 1.18	72%	75-200	75
Magnesium (Mg^{2+}) (mg/L)	120.94-448.98	217.81 ± 3.05	100%	112.8-416.8	221.3 ± 2.81	100%	30-100	30
Sodium (Na^{+}) (mg/L)	23.02-46.71	35.56 ± 2.48	0%	11.63-45.21	29.82 ± 1.20	0%	200	200
Potassium (K^{+}) (mg/L)	12.21-15.01	13.74 ± 0.34	100%	0.19-4.29	1.37 ± 0.02	0%	12	-

Chloride (Cl^-) (mg/L)	8.52-113.6	32.52 ± 2.07	0%	11.4-99.4	37.24 ± 0.72	0%	250-1000	250
Nitrate (NO3-) (mg/L)	0.94-4.56	2.46 ± 0.031	0%	0.78-4.5	2.28 ± 0.05	0%	45	50
Fluoride (F-) (mg/L)	0.12-0.9	0.56 ± 0.035	0%	0.1-0.76	0.44 ± 0.02	0%	1-1.5	1.5
Sulphate (SO42-) (mg/L)	15.09-49.12	30.03 ± 1.11	0%	11.65-46.15	26.66 ± 1.21	0%	200-400	250-400
Iron (Fe^{2+}) (mg/L)	0.3-0.94	0.57 ± 0.017	96%, 100%	0.01-0.53	0.25 ± 0.01	48%, 68%	0.3	0.1
Zinc (Zn^{2+}) (mg/L)	0.11-0.25	0.17 ± 0.010	0%, 100%	0.05-0.16	0.09 ± 0.011	0%, 100%	5-15	0.05
Copper (Cu^{2+}) (mg/L)	0.04-0.25	0.098 ± 0.011	76%, 0%	0.01-0.19	0.08 ± 0.014	64%, 0%	0.05-1.5	2
Lead (Pb^{2+}) (mg/L)	BDL-0.07	0.017 ± 0.001	32%, 68%-BDL	0.01-0.03	0.02 ± 0.001	20%, 52%-BDL	0.01	0.01
Nickel (Ni^{2+}) (mg/L)	(BDL)*	-	BDL	(BDL)	-	BDL	0.02	0.07
Chromium (Cr^{3+}) (mg/L)	4.03-5.03	4.87 ± 0.026	100%	2.31-4.58	3.62 ± 0.089	100%	0.05	0.05
Arsenic (As^{3+}) (mg/L)	BDL-0.04	0.01 ± 0.003	28%, 32%-BDL	0.01-0.03	0.02 ± 0.002	36%, 20%-BDL	0.01-0.05	0.01

*-BDL stands for Below detection limits

4.3 Water Quality Index (WQI): WQI is a valuable tool for assessing the quality of drinking water and provides a single value, based on that value, water is classified into different categories as mentioned in Table 16. This classification has been used by different researchers to classify the drinking water of their study areas (Acharya et al. 2018; Ahada and Suthar, 2018; Shil et al. 2019; Kumari and Rai, 2020). In PRM, WQI of groundwater of study area ranged from 76.34 – 239.35 with an average of 128.18. Out of total 25 samples, 36% samples fall under 'Good category', 60% samples under 'Poor category' and 4% samples under 'Very poor category' of water quality

classification during PRM season. Only one groundwater sample i.e., S-14 (Satowali) was reported under very poor category (WQI=239.35). Lalitha et al. 2017 also reported similar results for PRM, where they classify the drinking water of Vuyyuru area of Andhra Pradesh, India under 40% each under Good & Poor and 20 % under Very Poor category. WQI in POM season ranged from 68.53- 133.01 with a mean of 96.96, maximum water samples (52%) fall under 'Good category' and rest (48%) under 'Poor category' of WQI classification. Results of present study are in accordance with studies where they classified the drinking water of Pandameru river basin of Anantapur district of A.P, India and Bangladesh into Good and Poor category of WQI classification (Pappaka et al. 2024; Akter et al. 2016). Also, results are similar with the results of study conducted by Ishaku, J M, 2011, where WQI value for POM season for the groundwater of Jimeta Yola area of Nigeria was found to be 96.4. Classification of groundwater of study area for both seasons is presented in Table 19 and is graphically presented in Fig. 25.

Table 19. Classification of groundwater samples of study area as per WQI.

WQI VALUE	CLASSIFICATION	%. OF SAMPLES	
		PRM	POM
Less than 50	Excellent	-	-
50 to 100	Good	36%	52%
100 to 200	Poor	60%	48%
200 to 300	V. Poor	4%	-
Greater than 300	Unsuitable for drinking	-	-

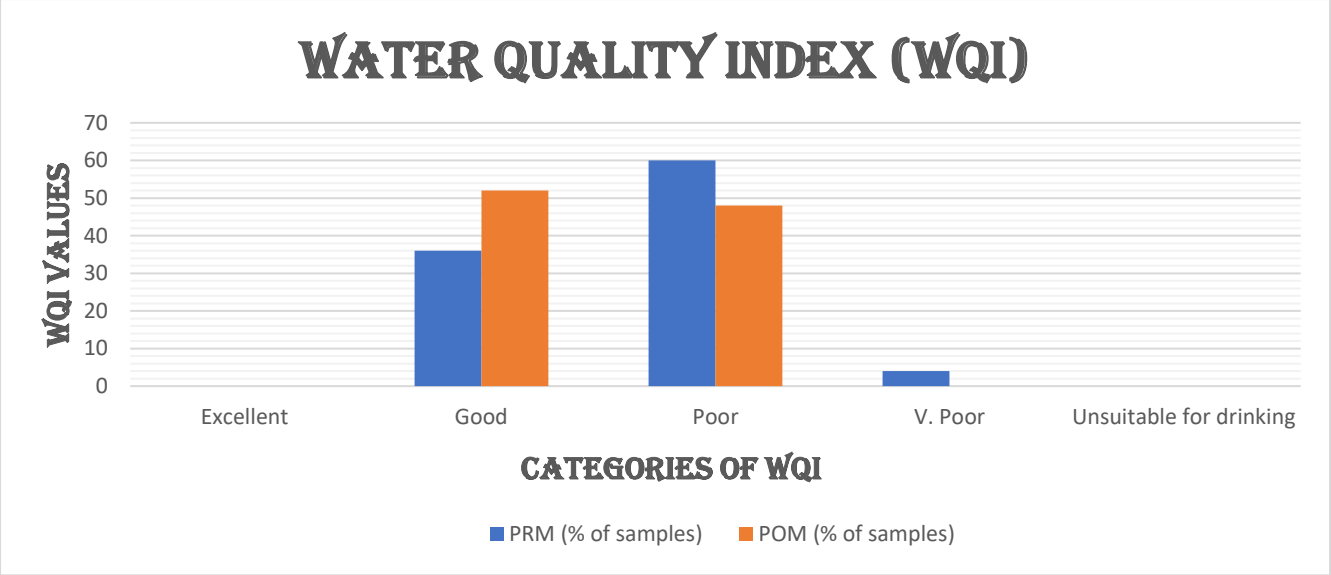

Fig. 25. Classification of water samples of study area as per WQI for Pre-monsoon (PRM) and post-monsoon (POM) season.

4.4 **Assessment of groundwater quality for irrigation purpose:** Evaluation of irrigation water quality is primarily done because it can have negative impact on crop production as well as on the health of soil (Mjemah and Mariki, 2021; Adimalla et al. 2020; Beyene et al. 2019; Chen et al. 2019; Zaman et al. 2018; Houatmia et al. 2016). Generally, irrigation water suitability is evaluated using indices such as Irrigation Water Quality Index (IWQI), Sodium Absorption Ratio (SAR), Percent Sodium (Na%), Residual Sodium Carbonate (RSC), Kelly's Index (KI), Permeability Index (PI) (Ayyandurai et al. 2022; Rao et al. 2021; Elumalai et al. 2020; Chen et al. 2019; Abbasnia et al. 2018; Saraswat et al. 2019; Shil et al. 2019). Suitability of water for irrigation purposes can be studied with the help of various parameters and indices which are discussed as under:

4.4.1 **Irrigation Water Quality Index (IWQI):** IWQI assesses the quality of groundwater for irrigation usage and classify the waters for irrigation depending upon the salinity of the soil and classification of groundwater samples of study area is given in Table 18 (Abbasania et al. 2018; Asadi et al. 2019; Baterseh et al. 2021; Osta et al. 2022; Tegegne et al. 2023). In present study, IWQI for PRM season ranged from 42.36- 89.77 with a mean of 70.14. Maximum water samples were reported under 'Moderate restriction' category (52%) and rest under 'No restriction' (12%) [S1 (Khamb), S5 (Dablehar, S-22(Gharana)], 'Low restriction' (32%), 'High restriction' (4%) whereas no sample was found under

'Severe restriction' category (0%) of IWQI classification. Only 1 sample was found under 'High restriction' category i.e., S-14 (Satowali) (IWQI=42.36) for PRM season. For POM season, IWQI value ranged from 48.48- 87.65 with a mean of 71.06. 12% of samples were found under 'No restriction' category [S1 (Khamb), S4 (Agra Chak), S-11 (Satrayian)], 28% of samples under 'Low restriction' category, 48% of samples under 'Moderate restriction' category, 12% of samples under 'High restriction' category [(S9 (R.S. Pura, S-14 (Satowali), S-25 (Kheper)] and no sample under 'Severe restriction' category of IWQI classification. S-9 (R. S. Pura), S-14 (Satowali) and S-25 (Kheper) were reported under high restriction category of IWQI for POM season. Results for IWQI for both seasons is presented graphically in Fig. 26. Results of our study are in accordance with study conducted in groundwater of Gunabay watershed of upper Blue Nile basin of Ethiopia where groundwater was classified into no restriction, low restriction, moderate and high restriction category of IWQI classification (Tegegne et al. 2023). Overall, the groundwater of the study area was found suitable for irrigation usage according to IWQI as maximum groundwater samples were falling under 'No to Moderate' category of IWQI classification.

Table 20. Groundwater samples classification of study area as per IWQI.

IWQI value	Water Restriction Category	% of Water samples	
		PRM	POM
85 to 100	No	12%	12%
70 to 85	Low	32%	48%
55 to 70	Moderate	52%	28%
40 to 55	High	4%	12%
0 to 40	Severe	-	-

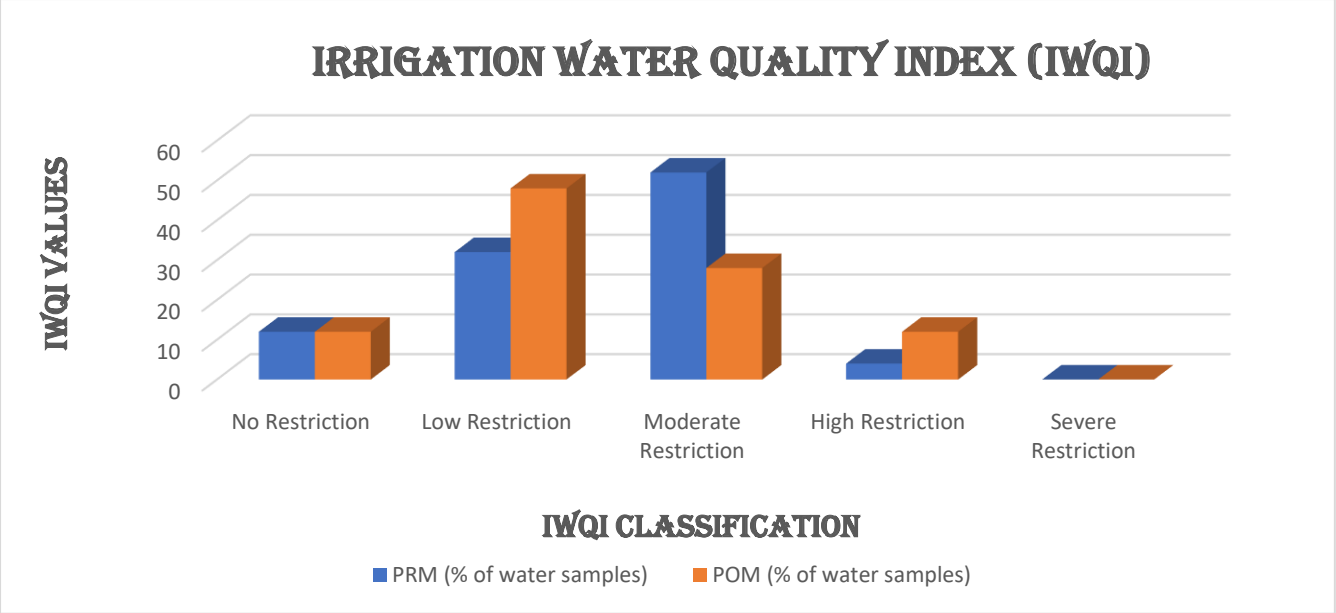

Fig. 26. Classification of water samples of study area as per IWQI for Pre-monsoon (PRM) and post-monsoon (POM) season.

4.4.2 **Sodium Absorption Ratio (SAR):** SAR indicates concentration of sodium in irrigation waters. Higher amounts of sodium in groundwater effects the soil and is harmful for crop production (Tegegne et al. 2023; Raheja et al. 2024). SAR evaluates the effect of Na^+ on soil which is represented in terms of alkalinity. If SAR concentration increases, then soil permeability decreases, which further adversely effects the growth of crops (Houatmia et al. 2016; Kaur et al. 2017; Gugulothu et al. 2022). In present study, SAR index of S-22 (Gharana) and S-5 (Dablehar) sampling sites fall under best quality of irrigation water. SAR values for PRM season fall in the range 0.19-0.51 having mean value 0.36 while for POM season, its range fall within 0.18-1.06 with mean of 0.44 for POM season. Cent percent samples of the study region were reported falling in the 'excellent category' of SAR classification in both the seasons. So, no sodium hazard was reported in the study region. The findings of present study have been witnessed by result of various studies where 100% of samples were found under 'excellent category' of SAR categorization in both pre-monsoon (PRM) and post-monsoon (POM) seasons (Gautam et al. 2023; Ibrahim et al. 2023; Kouser et al. 2022; Zafar et al. 2022; Sharma et al. 2021; Soleimani et al. 2018; Singha D, 2017). Representation of SAR values for both seasons is presented in Fig. 27 and values are represented in Table 21.

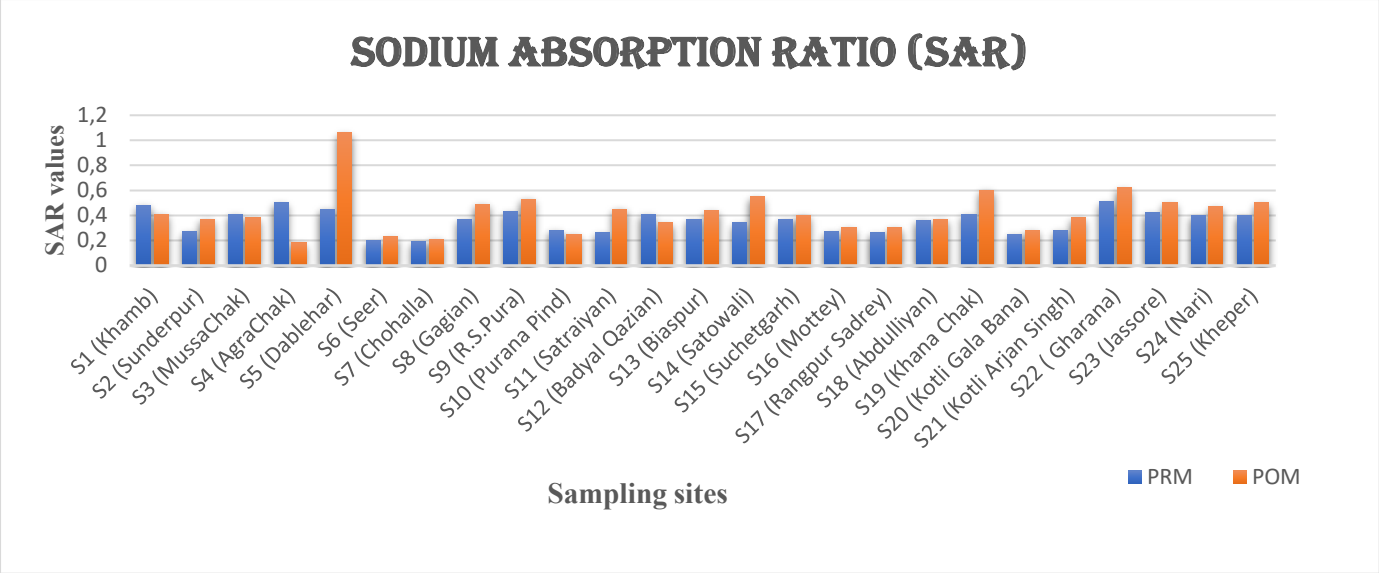

Fig. 27. Water samples classification of study area as per SAR classification for Pre-monsoon (PRM) and post-monsoon (POM) season.

4.4.3 **Percent Sodium (Na%):** If there is high sodium content in irrigation water, then it may get adsorbed by the clay particles present in soil which leads to exchange of Na^{+} in water and can displace Mg^{2+} and Ca^{2+} from soil. Thus, tend to change the soil properties, increases infiltration problem and effects the soil permeability (Houatmia et al. 2016; Kaur et al. 2017; Singha D, 2017; Gugulothu et al. 2022). Sodium percent value for PRM season ranged from 4.16-13.05 with a mean of 8.37 while it ranged from 2.69-13.33 with an average of 6.68 for POM season. Totality of water samples (100%) were under the safe category in terms of Sodium percentage classification in both the seasons. Soleimani et al. 2018 and Singha D, 2017 reported that 100% of water samples were falling under the safe zone of irrigation according to Na%. Groundwater classification of study area as per sodium percent for pre-monsoon (PRM) and post-monsoon (POM) seasons is presented in Fig. 28 and values are represented in Table 21.

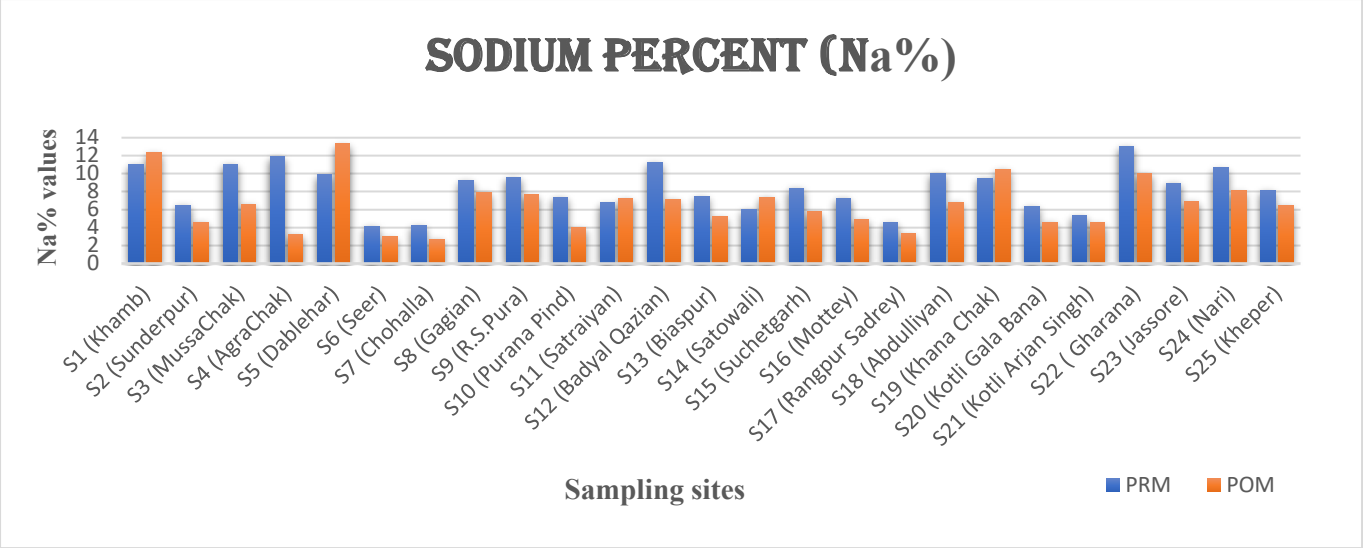

Fig. 28. Water samples classification of study area as per Na% classification for Pre-monsoon (PRM) and post-monsoon (POM) season.

4.4.4 **Residual Sodium Carbonate (RSC):** The purpose of RSC determination is to understand the detrimental impacts of bicarbonate and carbonate on the grade of groundwater for agricultural implementation (Mahaqi et al. 2018; Houatmia et al. 2016). If irrigation water is enriched with carbonates and bicarbonate, then calcium and magnesium start precipitating due to the concentrated water in the soil. As a result, it leads to increase in direct proportion of sodium in the water and forms sodium carbonate which effects the soil structure as well as crop production (Sadashivaiah et al. 2008; Ibrahim et al. 2023). RSC values in the study area varied from -39.2 to -12.13 having average of -20.31 for PRM season while for POM season RSC values ranged from -38.48 to -11.1 with a mean value of -20.71. Study area's groundwater was reported safe for irrigation according to this index because all the groundwater samples fall under the safe category of RSC classification for irrigation waters. Results of present study are also supported by the results of studies conducted by Ayyandurai et al. 2022; Singh et al. 2020; Soleimani et al. 2018 where they also found all samples under safe category of RSC classification for both pre-monsoon (PRM) and post-monsoon (POM) seasons. Results of study for RSC classification is presented in Fig. 29 and values are represented in Table 21.

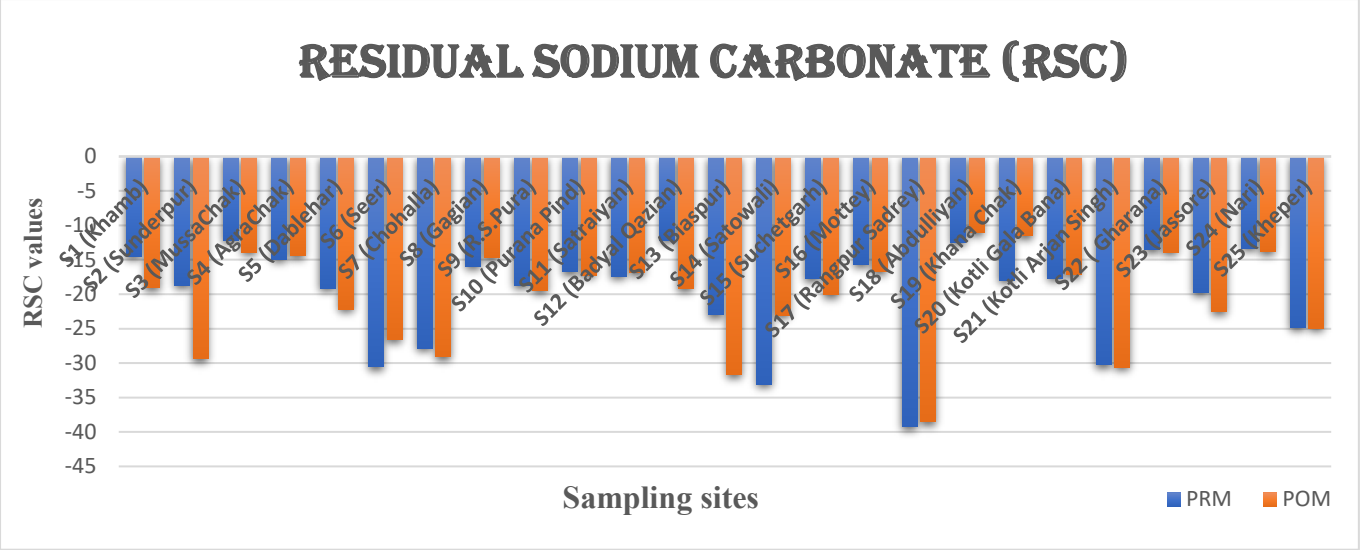

Fig. 29. Classification of samples in study area according to RSC classification for Pre-monsoon (PRM) and post-monsoon (POM) season.

4.4.5 **Kelly's Index (KI):** Irrigation water suitability is determined using Kelly's Index. KI values in the groundwater of study area ranged from 0.03-0.13 having average of 0.08 for PRM season while KI values ranged from 0.03-0.15 with a mean of 0.06 for POM season. Values of KI for both the season indicated that the groundwater of the study area is found fit for irrigation usage. Similar conclusions have also been published by various research studies, accomplished in various regions of India and across the world, where KI values for both Pre- and Post-monsoon seasons are less than 1 and reported the groundwater of their respective study region quite fit for irrigation purpose (Sharma et al. 2021; Shil et al. 2019; Veeraswamy et al. 2019; Soleimani et al. 2018). Values of KI are listed in Table 21 and KI water classification for both seasons are presented in Fig. 30.

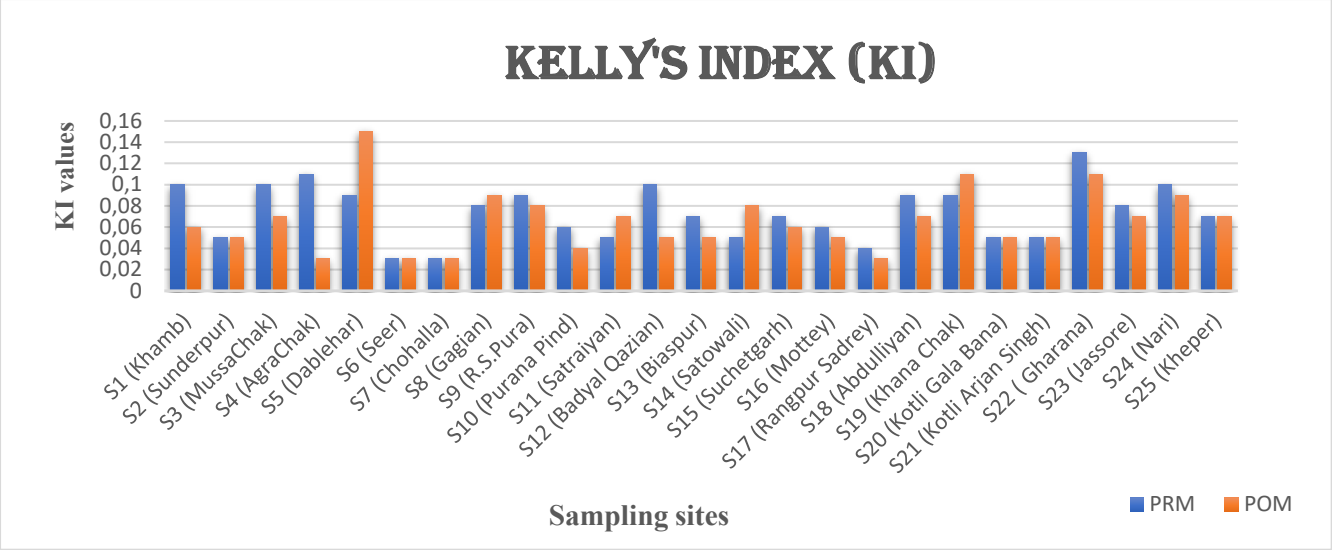

Fig. 30. Water samples classification of study area as per KI classification for Pre-monsoon (PRM) and post-monsoon (POM) season.

Table 21. Water classification of water samples in study area for Pre-monsoon (PRM) and post-monsoon (POM) season values based on various irrigation indices.

S. No.	Irrigation Index	Water Classification	Classification of irrigation water of study area	
			(PRM value range)	(POM value range)
1.	Sodium Absorption Ratio (SAR)	> 26- Poor 18 - 26- Fair 10 - 18- Good < 10- Excellent	Excellent (0.25-0.69)	Excellent (0.18- 1.06)
2.	Percent Sodium (%Na)	Greater than 80- Unsuitable 60 to 80- Doubtful 40 to 60-Permissible 20 to 40- Good Less than 20- Excellent	Excellent (4.14-13.05)	Excellent (2.69-13.33)

3.	Residual Sodium Carbonate (RSC)	< 2.5- Safe = 2.5- Marginal quality > 2.5- Not appropriate	Safe [-39.18-(12.11)]	Safe [-38.48- (-11.1)]
4.	Kelly's Index (KI)	Greater than 1- surplus sodium Less than 1- suitable Less than 2- deficiency of sodium	Suitable (0.03-0.13)	Suitable (0.03-0.15)

4.4.6 Permeability Index (PI): This index classifies the water for irrigation purposes. PI values in the groundwater of study area ranged from 8.04-18.51 having average of 13.75 for PRM season while for POM season PI values ranged from 1.23-39.44 with a mean of 23.93. Our results are in accordance with study conducted by Sarkar et al. 2022 in Malda district of Eastern India, where the groundwater is also classified into moderately suitable and unsuitable category of PI water classification. Classification of groundwater samples of the study area for pre-monsoon (PRM) and post-monsoon (POM) seasons on the basis of PI is given in Table 22 and graphically presented in Fig. 31.

Table 22: Classification of groundwater samples of study area based on PI.

PI Value	Classification	% of water samples	
		PRM	POM
>75	Suitable	-	-
25-75	Moderately Suitable	68%	40%
<25	Unsuitable	32%	60%

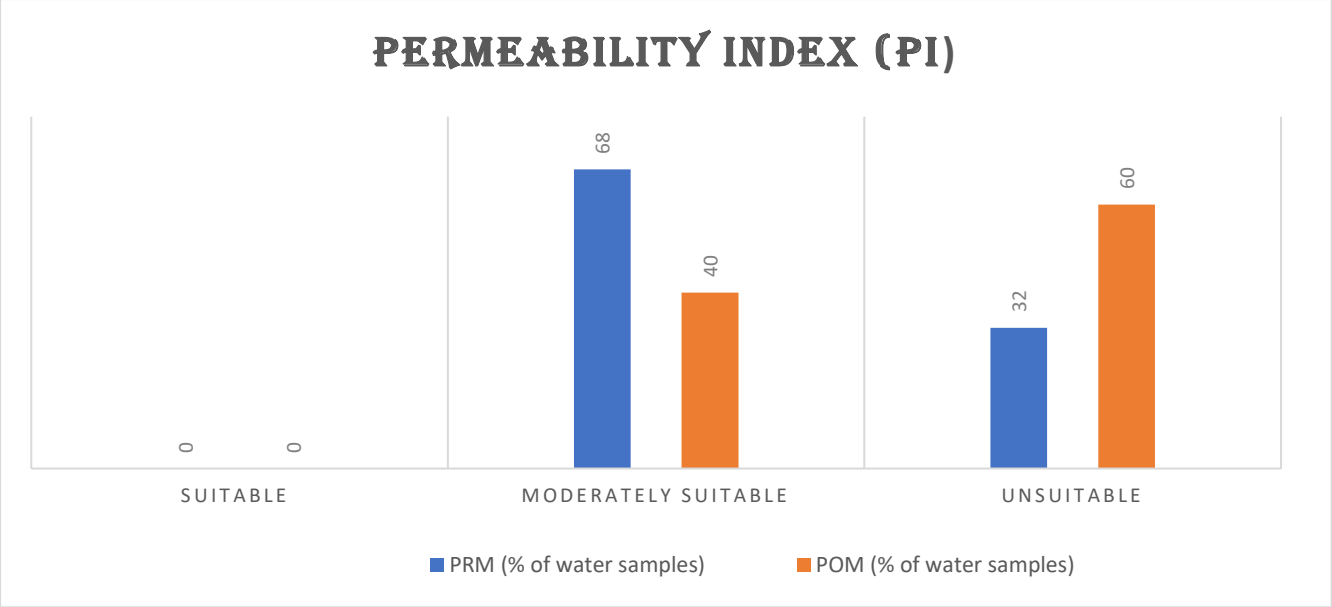

Fig. 31. Water samples classification of study area as per PI classification for Pre-monsoon (PRM) and post-monsoon (POM) season.

4.4.7 **Wilcox Diagrams:** Wilcox classified the irrigating groundwater on the basis of percent sodium (%Na) and Electrical Conductivity (EC) into 'excellent to good' category, 'good to permissible' category, 'permissible to doubtful' category, 'doubtful to unsuitable' category and 'unsuitable' category (Jude et al. 2023; Ayyandurai et al. 2022). This diagram indicates that the grade of groundwater for irrigation declines with the rise in the content of EC and Na% (Kauser et al. 2022). During Pre-monsoon season, 80% of groundwater samples of the study area was found under 'Excellent to Good' and 20% under 'Good to Permissible' category of Wilcox classification (Fig. 32) while in post-monsoon season, maximum water samples (76%) were classified under the 'Excellent to Good' category and remaining (24%) under "Good to Permissible' category of Wilcox classification (Fig. 33). Thus, according to these diagrams, study area's groundwater was reported suitable for irrigation usage. Results of our study are in accordance with the results reported by study which was carried out in Kathua area of Jammu, India where the groundwater samples were classified under only two categories i.e., 'excellent to good' category and 'good to permissible' category for both seasons (Kouser et al. 2022).

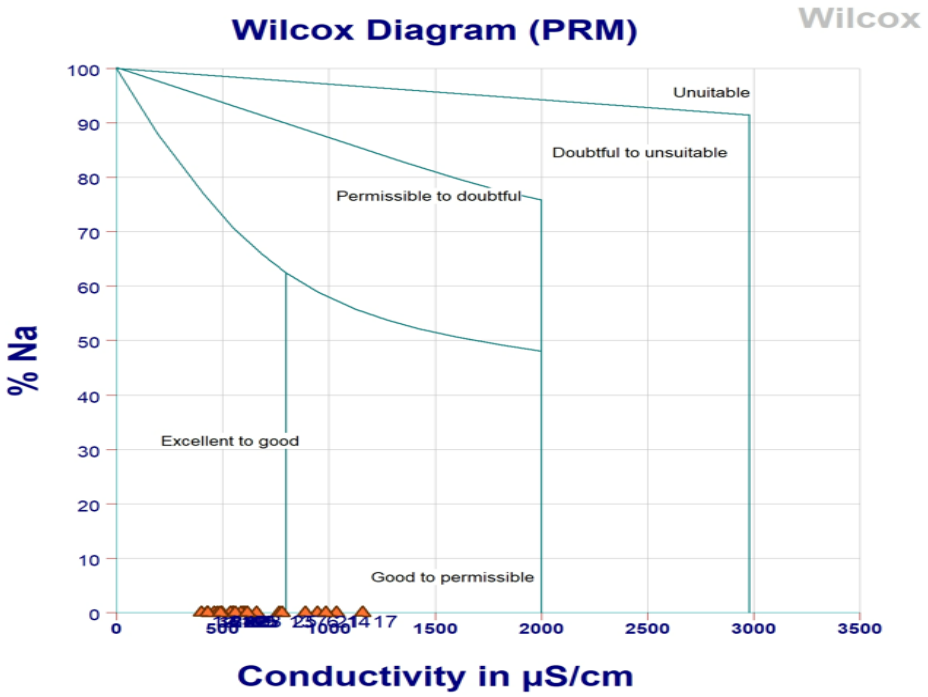

Fig. 32. Wilcox classification of groundwater in study area for Pre-monsoon season (PRM).

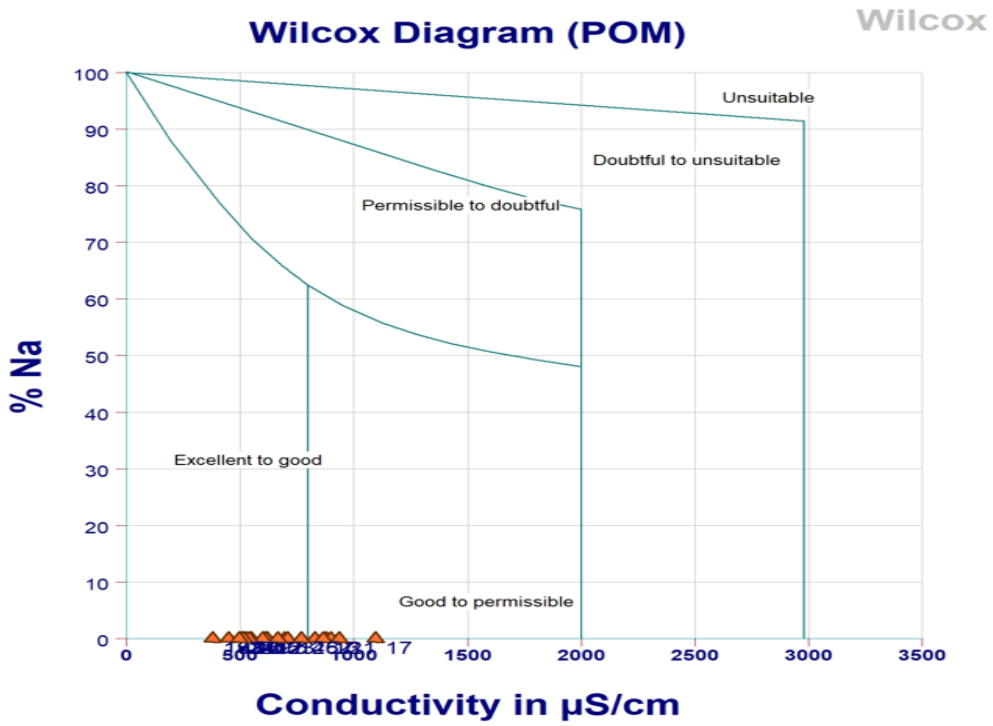

Fig. 33. Wilcox classification of groundwater in study area for post-monsoon season (POM).

4.4.8 Piper-Trilinear Plots: Piper plots are generally used to study the composition of waters in terms of ions and to classify the waters into different classes. These plots are used to understand the hydrochemistry of the groundwater. In piper diagram hydrogeochemical facies and water types is determine by major anions and cations (Acharya et al. 2023; Jude et al. 2023). Anionic triangle highlights the dominance of bicarbonate ions and absence of carbonates ions in the groundwater of study area. Cationic triangle shows the abundance of Magnesium ions while sodium and potassium ions were scarcely available in the groundwater of study area. Piper trilinear plot revealed that Mg $(HCO_3)_2$ is the dominant hydro-chemical facies followed by Mg-SO_4-Cl type facies for the PRM season. This indicate that the strong acids (SO_4^{2-} and Cl^-) and alkaline earth (Mg^{2+} and Ca^{2+}) dominated over the alkalis (Na^+ and K^+). The results of our study are in accordance with the study done by Jasrotia et al. 2018 where it was reported that the alkaline earth metals exceed the alkalis in the groundwater of Western Doon valley of Uttarakhand, India. For the POM season, Mg^{2+} was reported as dominant cation while SO_4^{2-} followed by HCO_3^- found to be the dominant anions. $MgSO_4$ is the dominant hydro-chemical facies followed by Magnesium sulphated chlorides (Mg-SO_4-Cl) type facies for the POM season. Fig. 34 and Fig. 35 shows the Piper plots of 25 groundwater samples of study area during Pre-monsoon season (PRM) and Post-monsoon (POM) respectively.

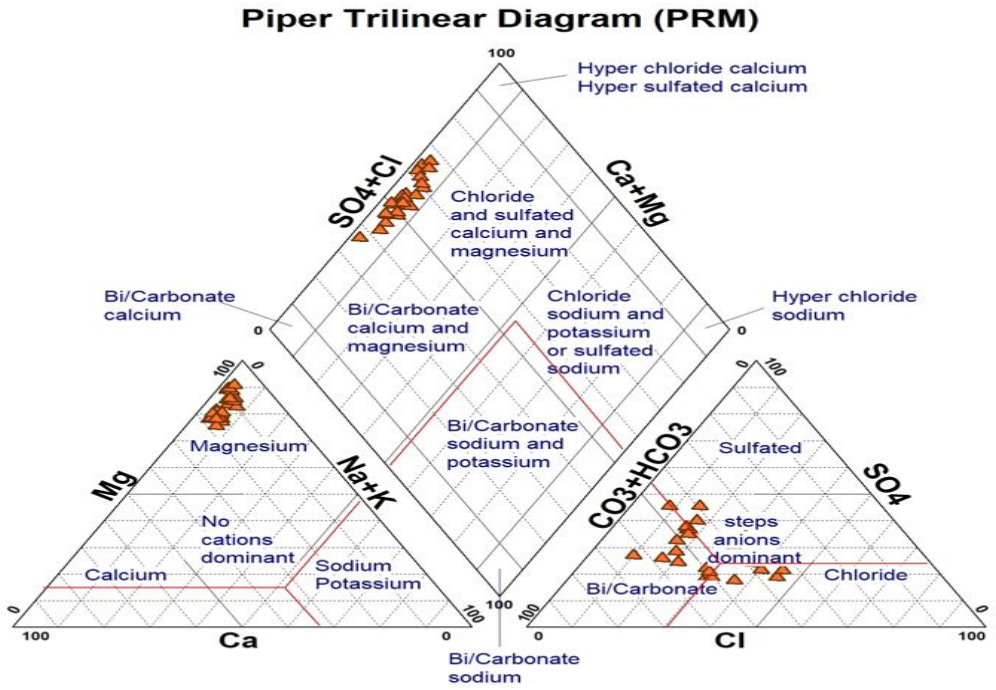

Fig. 34. Piper Trilinear plot for groundwater samples in study area for Pre-monsoon (PRM) season.

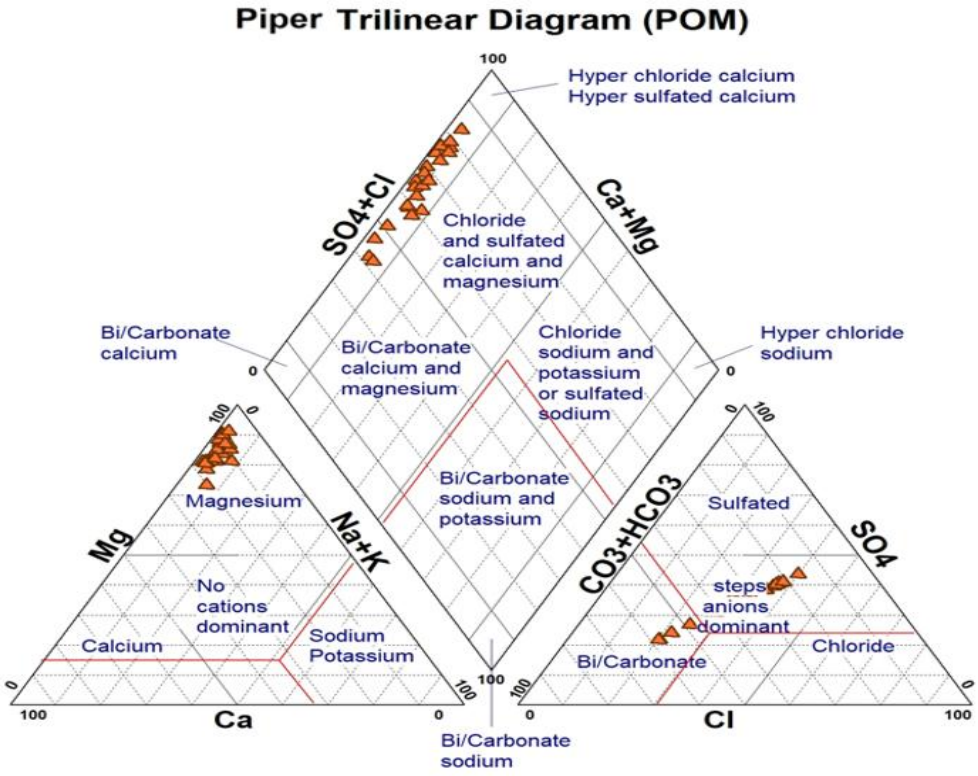

Fig. 35. Piper Trilinear plot for groundwater samples in study area for Post-monsoon (POM) season.

4.5 Health Risk Assessment: Health risk assessment is done to determine the potential hazards of toxic metals in groundwater and also assess the ability of heavy metals to cause ill impacts on the human health (Tokatli C, 2021; Baloch et al. 2021; Paneerselvam et al. 2020). It was reported by Kaur et al. 2019 that the carcinogenic risks caused due to ingestion of heavy metals through drinking groundwater in Reasi region of Jammu, India was found to be 7.6×10^{-6}–1.1×10^{-4}. A study conducted by Paneerselvam et al. 2020 on groundwater assessment of Yercaud region in Tamil Nadu, India, where children were found with greater health risks on comparison with adults. Results of study carried out by Raja et al. 2021 showed that Cr^{3+} and Pb^{2+} pose higher health risks, as compared to other heavy metals, in the residents of Virudhunagar region of Tamil Nadu, India. The study in Khorramabad, Iran done by Mohammadi et al. 2019 revealed that the carcinogenic risk for Cr^{3+}, Pb^{2+}, Ni^{2+} and Cd^{2+} were higher than the acceptable limit (1×10^{-6}). 20 out of 95 samples pose greater health risks in children than adults in Sindh, Pakistan. Carcinogenic risks from drinking water for adults and children were 7.38×10^{-5} and 1.33×10^{-4} respectively and exceeded the permissible safety limits of USEPA risks. These groups were reported at risk due to high Hazard Index (Baloch et al. 2021). Thus, in order to assess the risks by heavy metals, various indices such as Heavy metal pollution index (HPI), Heavy metal evaluation index (HEI), Target Hazard quotient (THQ), Average daily dose (ADD), Carcinogenic risks (CR), Non-carcinogenic risks etc. have been used (Abdelhafez et al. 2021; Baloch et al. 2021; Raja et al. 2021; Kaur et al.2019; Panneerselvam et al. 2020; Alidadi et al. 2019).

4.5.1 Nitrate Pollution Index (NPI): NPI is used to measure the contamination of nitrate in the groundwater and then classify the water on the basis of NPI values given in Table 23. (Paneerselvam et al. 2020). If nitrate concentration in drinking water exceeds the permissible limits (45 mg/L), then it can lead to blue baby syndrome in children, hypertension, thyroid, diabetes in adults etc. (Wagh et al. 2020; Abbasnia et al. 2018(a)) In present study, NPI value for PRM season ranges from -0.95 to -0.77 with a mean of -0.88, whereas for the POM season, its values ranged from -0.96 to -0.78 with a mean value of -0.89. Results indicate that the groundwater of the study region is under clean category of NPI classification for both the seasons and comparison of pre-monsoon (PRM) and post-monsoon (POM) values of NPI is given in Fig. 36.

Table 23. Water classification on the basis of NPI values for pre-monsoon (PRM) and post-monsoon (POM) season.

NPI Value	Classification	NPI value range	
		PRM	POM
less than 0	Clean water	[-0.953- (-0.772)]	[-0.961-(-0.775)]
0 to 1	Light water	-	-
1.1 to 2	Moderate water	-	-
2.1 to 3	Significant water	-	-
greater than 3	very significant water	-	-

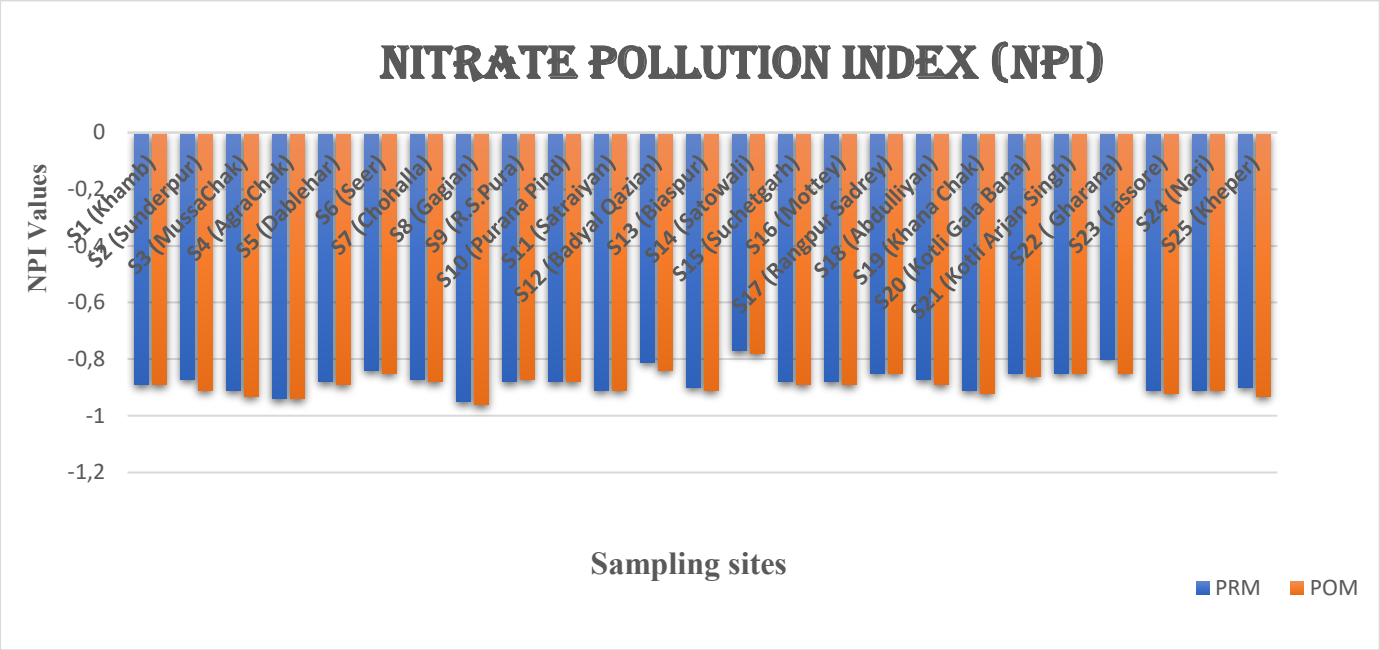

Fig. 36. NPI values of groundwater in study area for Pre-monsoon (PRM) and post-monsoon (POM) season.

4.5.2 **Heavy Metal Pollution Index (HPI):** This index is calculated to assess the groundwater contamination with heavy metals. If the value for HPI > 100, then the groundwater is contaminated with heavy metals. Classification of groundwater of study area based on HPI is given in Table 24 (Horton, 1965; Wagh et al. 2018; Raja et al. 2021). In present study, for PRM season, HPI

values of Chromium was found as 9740.8 and for Lead as 188, which point towards the contamination of these metals in the groundwater of study area however the values of HPI for Copper, Zinc and Arsenic were 2.73, 48.38 and 16.97 respectively, which implies that the groundwater of the study area doesn't pose any contamination for these heavy metals during PRM season. While for POM season, HPI index for Iron and Chromium was found above 100 with HPI 120.45 and 7240.8 for Fe^{2+} and Cr^{3+} respectively. Results showed that the Iron and Chromium are major contaminant during POM season. For another metals, HPI values were reported below 100 [Cu^{2+} (HPI=1.99), As^{3+} (HPI=19.97), Zn^{2+} (HPI= 49.08) and Pb^{2+} (HPI=88)]. The results of our study are similar with the results of studies done by Wagh et al. 2018 in Nashik, India and by Raja et al. 2021 in Virudhunagar, Tamil Nadu, India where they also reported higher HPI values of Cr^{3+} (HPI=1833.65) and Cr^{3+} (HPI=3232) respectively in groundwater.

Table 24. HPI classification of groundwater samples in study area.

Heavy Metals	HPI Values and classification (PRM)		HPI Values and classification (POM)	
	HPI values	**Classification**	**HPI values**	**Classification**
Chromium (Cr^{3+})	9740.8	Contaminated	7240.8	Contaminated
Lead (Pb^{2+})	188	Contaminated	88	Non-contaminated
Zinc (Zn^{2+})	48.38	Non-contaminated	49.08	Non-contaminated
Arsenic (As^{3+})	16.97	Non-contaminated	19.97	Non-contaminated
Copper (Cu^{2+})	2.73	Non-contaminated	1.99	Non-contaminated

4.5.3 Heavy Metal Evaluation Index (HEI): HEI basically gives the overall status of groundwater quality with respect to heavy metal contamination. The classification of Heavy Metal Evaluation Index (HEI) is low (<10), medium

(10-20) and high (>20) contamination (Raja et al. 2021; Rajkumar et al. 2020). In the study region, groundwater was found to be highly contaminated with the Iron (HEI= 47.5), Copper (HEI= 48.4), Lead (HEI= 49) and Chromium (HEI= 2435.2) metal contamination as values of HEI was greater than 20 whereas for Zinc (HEI= 0.83) and Arsenic (HEI= 2.6), indicating low contamination of these metals. For POM, In the study region, groundwater was found to be highly contaminated with the Arsenic (HEI=32), Copper (HEI=1817.4), Lead (HEI=22) and Chromium (HEI=39.4) metal contamination as values of HEI for these metals found greater than 20. Medium contamination of Iron (HEI=20) and low contamination of Zinc (HEI=0.46) was reported in the groundwater of study area. Overall, the groundwater of the study area was found to be contaminated with Copper, Lead and Chromium. Classification of HEI is given in Table 25.

Table 25. Classification of groundwater in the study area based on HEI.

S. No.	HEI Value	Water contamination	Metals classification as per HEI of study area	
			PRM	POM
1.	Less than10	Least/ low	Zn^{2+} and As^{3+}	Zn^{2+}
2.	10 to 20	Moderate/ Medium	-	Fe^{2+}
3.	Greater than 20	Greater/ High	Cu^{2+}, Fe^{2+}, Cr^{3+} and Pb^{2+}	As^{3+}, Cr^{3+}, Pb^{2+} and Cu^{2+}

4.5.4 Human Health Risk Assessment (HHRA): This evaluation method determines the potential health risks of consuming contaminated water with heavy metals on human health (Alidadi et al. 2019; Paneerselvam et al. 2020). These effects can be categorized as carcinogenic risks and non-carcinogenic risks (Baloch et al. 2019; Kaur et al. 2020). Average daily dose (ADD)/ Chronic daily intake (CDI) is the amount of contaminant consumed through ingestion, dermal or inhalation route per day by an individual (Alidadi et al. 2019; Baloch et al. 2019). In the present study, ADD (ingestion) is calculated for different age

groups (Men, women and children) in the study area. For PRM, maximum ADD were observed for Cr^{3+} in all three population groups with range of 15.5 x 10^{-2}-26.1 x 10^{-2}; 18.3× 10^{-2} –22.8× 10^{-2} and 20.9× 10^{-2} –26.1× 10^{-2} for Men, Women and Children respectively. For POM season, maximum values were observed for Cr^{3+} for Men, Women and Children were 8.8 × 10^{-2} – 17.6 × 10^{-2}; 10.5 × 10^{-2} – 20.8 × 10^{-2} and 12 × 10^{-2} – 23.8 × 10^{-2} respectively followed by Zn^{2+}, Fe^{2+}, Cu^{2+}, As^{2+} and Pb^{2+} in all three population groups and the CDI (Chronic daily intake) values for these heavy metals are mentioned in Table 26. Higher Cr^{3+} contamination was also reported by a study done by Kaur et al. 2019 in Reasi district of Jammu and Kashmir, India, where combusting gases, dust from brick kiln chimney, surrounding geology and bedrock geology were found to be the main causes for higher Cr^{3+} contamination in groundwater of study region. Higher concentration of Cr^{3+} was also reported to be higher in Thailand, China, Australia by Alidadi et al. 2019. Probable causes of Cr^{3+} contamination include release of chemicals from the factories and industries, water and wastewater treatment methods and also natural sources (Tumolo et al. 2020; Tucker D T, 2018). The higher values of Chromium indicate the groundwater contamination of study region and can pose various health impacts on humans such as skin irritation, skin and nasal ulcers, gastrointestinal effects, DNA damages and even stomach and intestinal cancer (BIS-10500; Kaur et al. 2019).

Table 26. Average Chronic Daily Intake (CDI) values in different age groups for Pre-monsoon (PRM) and Post-monsoon (POM) season.

Heavy Metals	CDI value for Men		CDI value for Women		CDI value for Children	
	PRM	POM	PRM	POM	PRM	POM
Iron (Fe^{2+})	1.1×10^{-2} - 3.6× 10^{-2}	3.8 × 10^{-4} - 20.3 × 10^{-4}	1.3×10^{-2}- 4.2× 10^{-2}	4.5 × 10^{-4} – 24.1× 10^{-4}	1.5×10^{-2}- 4.8×10^{-2}	5.2 × 10^{-4} – 27.6 × 10^{-4}
Zinc (Zn^{2+})	4.2 × 10^{-3} – 9.6× 10^{-3}	1.9 × 10^{-3} – 6.2 × 10^{-3}	5 × 10^{-3} – 11.3× 10^{-3}	2.3 × 10^{-3} – 7.3 × 10^{-3}	5.7× 10^{-3} – 13× 10^{-3}	2.6 × 10^{-3} – 8.3 × 10^{-3}
Lead (Pb^{2+})	1.9× 10^{-3} – 3.1× 10^{-3}	3.8 × 10^{-4} -11.5 × 10^{-4}	2.3× 10^{-3} – 3.6 × 10^{-3}	4.5 × 10^{-4} – 13.6 × 10^{-4}	2.6× 10^{-3} – 4.2× 10^{-3}	5.2 × 10^{-4} – 15.6 × 10^{-4}

Copper (Cu^{2+})	1.5×10^{-3} – 9.6×10^{-3}	3.9×10^{-4} – 73.1×10^{-4}	1.8×10^{-3} – 11.3×10^{-3}	4.6×10^{-4} – 86.4×10^{-4}	2.08×10^{-3} – 13×10^{-3}	5.2×10^{-4} – 98.8×10^{-4}
Arsenic (As^{3+})	3.8×10^{-4} – 15.3×10^{-4}	3.9×10^{-4} -11.5×10^{-4}	4.5×10^{-4} – 18.2×10^{-4}	4.6×10^{-4} – 13.6×10^{-4}	5.2×10^{-4} – 20.8×10^{-4}	5.2×10^{-4} – 15.6×10^{-4}
Chromium (Cr^{3+})	15.5×10^{-2} – 19.3×10^{-2}	8.8×10^{-2} – 17.6×10^{-2}	18.3×10^{-2} – 22.8×10^{-2}	10.5×10^{-2} – 20.8×10^{-2}	20.9×10^{-2} – 26.1×10^{-2}	12×10^{-2} – 23.8×10^{-2}

4.5.5 Carcinogenic Risks (CR): Carcinogenic risks/ Cancer Risks are the capacity of a person to develop chances of cancer over his/her lifetime due to exposure of a potential carcinogen (Kaur et al. 2019). The intake of drinking water contaminated with heavy metals can increase the chances of developing carcinogenic as well as non-carcinogenic risks in humans (Alidadi et al. 2019). CR value in the range of 10^{-6} to 10^{-4} are considered as safe for drinking (Alidadi et al. 2019; Baloch et al. 2021; Raja et al. 2021). During Pre-monsoon (PRM) and post-monsoon (POM) seasons, significant carcinogenic risks were observed for Lead (Pb^{2+}), Chromium (Cr^{3+}) and Arsenic (As^{3+}), as the CR values for these heavy metals were surpassing the limit i.e., 10^{-4}. For different age groups, CR values for children in the study area were found high during PRM season. CR caused by As^{3+}, Cr^{3+} and Pb^{2+} for various age groups i.e., Children, Women and Men are listed in Table 27. Study found that the average CR values for Pb^{2+} in Men, in Women and in Children found to be 5.9×10^{-3}, 7.1×10^{-3} and 8.1×10^{-3} respectively. Average CR values for Cr^{3+} in Men, in Women and in Children found to be 57.3×10^{-1}, 67.7×10^{-1} and 77.5×10^{-1} respectively. 9.2×10^{-1}, 10.9×10^{-1} and 12.5×10^{-1} are the average CR values reported in case of Arsenic for men, women & children in the study area. Results of CR for Pb^{2+}, Cr^{3+} and As^{3+} in all age groups are surpassing the limits set by USEPA and are posing threats to the human health. CR values are exceeding in all age groups but highest risk was observed for children as compared to adults (Men and Women). Reason for higher CR in case of children were reported because of their weak immunity, unhygienic habits, hand to mouth activities and lack of awareness (Alidadi et al. 2019; Raja et al. 2021).

Table 27: Cancer Risk (CR) range for heavy metals in different age groups of study area.

Heavy Metals	CR Values for Men		CR values for women		CR Values for children	
	PRM	POM	PRM	POM	PRM	POM
Lead (Pb^{2+})	$1.6 \times 10^{-2} - 2.6 \times 10^{-2}$	$3.3 \times 10^{-3} - 9.8 \times 10^{-3}$	$1.9\times 10^{-2} - 3.1 \times 10^{-2}$	$3.9\times 10^{-3} - 11.6 \times 10^{-3}$	$2.2 \times 10^{-2} - 3.5 \times 10^{-2}$	$4.4 \times 10^{-3} - 13.2 \times 10^{-3}$
Chromium (Cr^{3+})	$0.063 \times 10^{2} - 0.079 \times 10^{2}$	$36.4 \times 10^{-1} - 72.2 \times 10^{-1}$	$0.076 \times 10^{2} - 0.093 \times 10^{2}$	$43.1 \times 10^{-1} - 85.4 \times 10^{-1}$	$0.086 \times 10^{-2} - 0.112 \times 10^{-2}$	$49.2 \times 10^{-1} - 97.6\times 10^{-1}$
Arsenic (As^{3+})	$57 \times 10^{-2} - 231 \times 10^{-2}$	$5.8 \times 10^{-1} - 17.3 \times 10^{-1}$	$68 \times 10^{-2} - 272 \times 10^{-2}$	$6.8 \times 10^{-1} - 20.5 \times 10^{-1}$	$78 \times 10^{-2} - 312 \times 10^{-2}$	$7.8 \times 10^{-1} - 23.4\times 10^{-1}$

4.5.6 Non-Carcinogenic Risks: It is calculated in terms of Target Hazard Quotient (THQ) and Hazard Index (HI). THQ is the ratio between the reference dose (RfD) and ADD of each heavy metal (Alidadi et al. 2019; Baloch et al. 2021; Paneerselvam et al. 2020; Raja et al. 2021). For PRM season, groundwater of the study area was found contaminated with concentrations of Zn^{2+}, Fe^{2+}, Cu^{2+} and Pb^{2+}. Among different age groups, it was observed that Men and Women were found safe but children were found under risks. HQ value for Men, Women and Children in case of Zinc was found safe while HQ values for all population groups were found at risk for copper and lead. Average Hazard Index (HI) values during PRM for Men, Women and Children are 64.07, 75.78 and 86.71 respectively. For POM season, contamination of Cu^{2+}, As^{3+} and Pb^{2+} was reported in groundwater of study area as their concentration were exceeding the limits in all age groups. However, it was observed that the values for HQ in case of children were found to be higher, which indicates that children were under risks because of their low immunity and unhygienic drinking water habits. HQ value for Men, Women and Children in case of Zinc and Iron was found safe while HQ values for Copper, Lead and Arsenic in all population groups were found at risk. Similar results have been reported by Baloch et al. 2021 where the concentration of heavy metals in the groundwater of Sindh, Pakistan exceed the limits and were posing health impacts. Average values for Hazard Index (HI) in Male, female and children were observed to be 48.32, 56.99 and 65.32 respectively in the study area. Sampling Site S-14 (Satowali) was found at

higher risk as per the THQ values in both the seasons. Probable causes of Cu^{2+} and Pb^{2+} in the groundwater of the study area include domestic waste, plumbing, pesticides and can have serious health impacts such as stomach, intestine, liver and kidney damage, increases blood pressure in adults etc. (BIS-10500; Baloch et al. 2021). Thus, water of the study area needs some sort of treatment. RfD and values of HQ for different population groups of study area are mentioned in Table 28 (Kaur et al. 2019; Lanjwani et al. 2020; Raja et al. 2021).

Table 28: RfD and HQ values for men, women and children of study area.

Heavy Metal	RfD	HQ (Men)		HQ(Women)		HQ (Children)	
		PRM	POM	PRM	POM	PRM	POM
Iron (Fe^{2+})	0.7	0.78	0.34	0.93	0.41	1.06	0.47
Zinc (Zn^{2+})	0.3	0.53	0.30	0.63	0.35	0.72	0.40
Copper (Cu^{2+})	0.04	2.32	1.89	2.75	2.24	3.15	2.56
Lead (Pb^{2+})	0.0035	5.38	2.42	6.36	2.86	7.28	3.27
Arsenic (As^{3+})	0.0003	35.89	41.03	42.42	48.48	48.53	55.47
Chromium (Cr^{3+})	0.003	1561	1165	1844	1376	2110	1575

4.6 Statistical Analysis:

4.6.1 Pearson's Correlation: Correlation matrix is used to explain the relationship among different parameters. Statistically, it helps us to understand how two variables are closely associated (Jude et al. 2023; Singh et al. 2012). The relationship among different physico-chemical parameters for Pre-monsoon (PRM) and post-monsoon (POM) season is presented in Fig. 37. In the Maximum parameters in the groundwater of the study area are positively correlated with one another. For PRM season, positive correlation was found among EC, TDS, TA, TH, Cl^- and Mg^{2+}. Strong positive correlation of 0.97 was reported for Mg^{2+} and TH indicating the significant relationship and influences the groundwater quality the most as compared to other parameters. Negative correlation was seen for pH with EC, TDS, TA, TH, Mg^{2+}, NO_3^- and Fe^{2+}. In the

study area, hardness was reported in the form of $MgCl_2$, $CaCl_2$ and $MgCO_3$. For POM season, perfect positive correlation was reported for Cl^- with SO_4^{2-} which indicates that Cl^- is significantly related with SO_4^{2-} in the water of the study region. Positive correlation was observed between different parameters such as EC, TDS, TH, TA, Cl^-, Mg^{2+}, NO_3^- and SO_4^{2-} while strong negative correlation was observed for pH with EC, TDS, Cu^{2+}, TH, Cl, Mg^{2+}, NO_3^- and SO_4^2. During POM season, insignificant correlation of Cu^{2+} with K^+ was observed indicating the increase of one parameter with the decrease in another.

	pH	EC	TDS	TA	TH	Cl	Ca	Mg	Na	K	NO3-	F-	SO42-	Fe	Zn	Cu	Cr
pH	1																
EC	-0,81428	1															
TDS	-0,80165	0,889735	1														
TA	-0,6173	0,784923	0,722279	1													
TH	-0,67115	0,794399	0,849549	0,778194	1												
Cl	-0,46371	0,753058	0,674745	0,593315	0,569679	1											
Ca	-0,1215	0,289973	0,286233	0,522513	0,392443	0,172035	1										
Mg	-0,68867	0,783097	0,842749	0,716102	0,979772	0,569284	0,200491	1									
Na	0,061374	0,02277	0,047591	0,164986	0,102799	-0,02317	-0,07696	0,125253	1								
K	-0,21543	0,151811	0,177226	0,048005	0,260162	-0,00833	0,173506	0,238594	0,275896	1							
NO3-	-0,55414	0,448151	0,582463	0,348952	0,367873	0,447973	-0,03225	0,39955	0,032001	0,147443	1						
F-	-0,18744	-0,03097	0,001352	-0,08775	-0,15063	0,058704	0,002322	-0,16178	-0,03074	-0,12984	0,28271	1					
SO42-	-0,04971	0,186119	0,201634	0,200769	0,339209	0,279741	0,158244	0,32564	0,290999	0,264709	0,296523	0,218163	1				
Fe	-0,41619	0,450273	0,258388	0,236073	0,274643	0,410019	-0,15841	0,326451	0,0577	0,313568	0,336813	-0,06032	0,278089	1			
Zn	-0,25074	0,223142	0,446523	0,074643	0,197253	0,363164	-0,334	0,283367	0,039406	0,043671	0,569744	-0,15894	0,058316	0,12814	1		
Cu	-0,15085	0,381982	0,410109	0,361138	0,252354	0,430077	0,006518	0,268228	0,368146	0,381638	0,399569	-0,09499	0,354961	0,187484	0,363614	1	
Cr	0,086822	-0,01481	-0,12823	0,035551	-0,09306	-0,00513	-0,00091	-0,09951	-0,02061	-0,30685	0,184773	0,18375	0,12026	0,062082	0,013703	-0,12459	1

	pH	EC	TDS	TA	TH	Cl	Ca	Mg	Na	K	NO3	F	SO42-	Fe	Zn	Cu	Cr
pH	1																
EC	-0,6511	1															
TDS	-0,60873	0,8006	1														
TA	-0,32771	0,332727	0,396814	1													
TH	-0,39152	0,659956	0,612284	0,127279	1												
Cl	-0,40024	0,671642	0,56836	0,553623	0,334115	1											
Ca	-0,14707	0,465793	0,298047	0,380907	0,49363	0,485097	1										
Mg	-0,39375	0,60955	0,59885	0,045209	0,976357	0,246636	0,293968	1									
Na	-0,17959	0,21664	-0,02494	0,221257	0,244973	0,040276	0,06152	0,253947	1								
K	0,047951	0,100492	0,053106	0,551051	0,003451	0,264379	0,335989	-0,07972	0,27314	1							
NO3	-0,57871	0,655983	0,470792	0,517596	0,396647	0,449577	0,370044	0,343959	0,13018	0,339256	1						
F	-0,2472	0,177072	-0,06467	0,09664	0,217715	0,191802	0,099206	0,214622	0,25095	0,280762	0,313615	1					
SO42-	-0,40024	0,671642	0,56836	0,553623	0,334115	1	0,485097	0,246636	0,040276	0,264379	0,449577	0,191802	1				
Fe	-0,28692	0,094995	0,102921	-0,1181	0,173119	0,000972	-0,03169	0,198144	0,012757	-0,26121	-0,13217	-0,31803	0,000972	1			
Zn	-0,26637	0,137504	0,187617	0,231715	-0,01327	0,367705	0,109722	-0,04186	-0,04026	-0,12565	0,101445	-0,2976	0,367705	0,297776	1		
Cu	-0,35164	0,334816	0,238471	-0,17411	0,200496	-0,1324	0,062522	0,204816	-0,01007	-0,56021	0,147572	-0,20072	-0,1324	0,133194	-0,0705	1	
Cr	-0,29723	0,220188	0,130308	0,069945	0,039675	0,153986	0,17229	0,000781	0,091437	0,337431	0,143919	0,329616	0,153986	0,090946	-0,08483	-0,18358	1

Fig. 37: Pearson correlation matrix of physico-chemical parameters for Pre-monsoon (PRM) and post-monsoon (POM) season.

Negative correlation Moderate correlation Positive correlation

4.6.2 Principal Component Analysis (PCA): PCA was carried out to analyze the compositional pattern of the variables on the entire dataset to some influencing factors by avoiding some insignificant data (Shil et al. 2019; Tajwar et al. 2023). In the present study, first two principal components (PCs) were chosen for both seasons to explain variances. For pre-monsoon season, 33.4% and 10.85% variances are explained by PC1 and PC2 respectively, and in post-monsoon season, 28.61% and14.61% variances are explained by PC1 and PC2 respectively (Table 29). The factor loadings are classified based on absolute loading values, loading values > 0.75, 0.75–0.50 and 0.50‑0.30 are categorised as 'strong', 'moderate' and 'weak' respectively (Boateng et al. 2016; Shil et al. 2019). It was found that PC1 of PRM season dominantly contains EC, TDS, TA, TH, Cl^-, Mg^{2+}, NO_3^-, Cu^{2+}, Pb^{2+} and PC1 of POM contains EC, TDS, TA, TH, Cl^-, Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-} as dominant variables (Table 30). Hence, it can be concluded that these variables are hydro-chemical and are supposed to be originated from geogenic sources or from geological processes. High factor loadings of Mg^{2+} and Cl^- during PRM depicts that ion-exchange process is dominant in the study area, which affects the chemistry of the groundwater. PC2 of PRM season contains Zn^{2+} and Pb^{2+} and for POM season PC2 contains K^+ and Pb^{2+} indicating the usage of fertilisers and pesticides in the agricultural fields and also pressure of anthropogenic sources. During POM season, high factor loadings of NO_3^-, SO_4^{2-}, Cl^- confirmed that anthropogenic activities are hampering the groundwater of the study area. In present study, the loadings of PC1 and PC2 are accounted for 44.26% of pre-monsoon and 49.23% of post-monsoon of total variances are explained and are presented in the form of biplots (Fig. 38). Scree plots of Pre-monsoon (PRM) and post-monsoon (POM) seasons (Fig. 39) are also used to represent the change in eigen values of all the components.

Table 29: Eigenvalues, Variability and cumulative percentage for Pre-monsoon (PRM) and Post-monsoon (POM) season.

Eigenvalues (PRM)

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21
Eigenvalue	7,014	2,280	1,872	1,829	1,770	1,176	1,062	0,948	0,724	0,672	0,449	0,383	0,270	0,245	0,114	0,096	0,054	0,021	0,016	0,006	0,000
Variability (%)	33,402	10,859	8,914	8,707	8,426	5,598	5,057	4,514	3,447	3,202	2,138	1,826	1,285	1,165	0,544	0,459	0,256	0,101	0,075	0,027	0,000
Cumulative %	33,402	44,261	53,175	61,883	70,309	75,907	80,963	85,477	88,924	92,126	94,263	96,089	97,374	98,539	99,083	99,541	99,797	99,898	99,973	100,000	100,000

Eigenvalues (POM):

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19
Eigenvalue	6,009	3,070	2,322	1,869	1,404	1,291	1,148	0,924	0,655	0,594	0,497	0,366	0,255	0,185	0,160	0,134	0,059	0,033	0,026
Variability (%)	28,614	14,617	11,059	8,900	6,684	6,147	5,469	4,398	3,118	2,829	2,365	1,741	1,215	0,882	0,762	0,636	0,282	0,158	0,125
Cumulative %	28,614	43,230	54,289	63,189	69,873	76,020	81,489	85,887	89,005	91,835	94,200	95,941	97,155	98,037	98,799	99,435	99,717	99,875	100,000

Table 30: Factor loading values of physico-chemical parameters for Pre-monsoon (PRM) and Post-monsoon (POM) season.

Variables	Pre-monsoon season (PRM)			Post-monsoon season (POM)		
	Factor loading values			Factor loading values		
	F_1	F_2	F_3	F_1	F_2	F_3
pH	-0,758	0,176	0,200	-0,627	0,415	-0,044
EC	0,893	-0,252	-0,063	0,885	-0,264	0,084
TDS	0,926	-0,118	-0,133	0,777	-0,340	-0,089
Temp.	0,095	-0,003	-0,127	-0,462	-0,053	-0,158
Turbidity	0,296	-0,017	0,652	-0,098	0,052	0,794
TA	0,791	-0,368	0,023	0,619	0,376	-0,154
TH	0,871	-0,319	-0,087	0,686	-0,402	0,233
Cl^-	0,782	-0,019	0,208	0,805	0,168	-0,317
Ca^{2+}	0,245	-0,696	0,134	0,641	0,294	-0,045
Mg^{2+}	0,875	-0,188	-0,123	0,595	-0,514	0,267
Na^+	0,160	0,266	0,202	0,223	0,031	0,409
K^+	0,271	0,141	-0,193	0,343	0,702	-0,074
NO_3^-	0,635	0,359	0,259	0,738	0,091	0,195
F^-	-0,051	-0,083	0,606	0,273	0,220	0,443

SO_4^{2-}	0,379	0,100	0,606	0,805	0,168	-0,317
Fe	0,460	0,220	-0,029	0,020	-0,603	-0,429
Zn	0,464	0,714	-0,153	0,221	-0,161	-0,686
Cu	0,525	0,408	0,112	0,115	-0,531	0,397
Pb	0,558	0,671	-0,117	0,175	0,696	0,045
Cr	-0,077	0,050	0,561	0,223	0,148	-0,134
As	0,443	0,052	-0,204	0,402	0,518	0,238

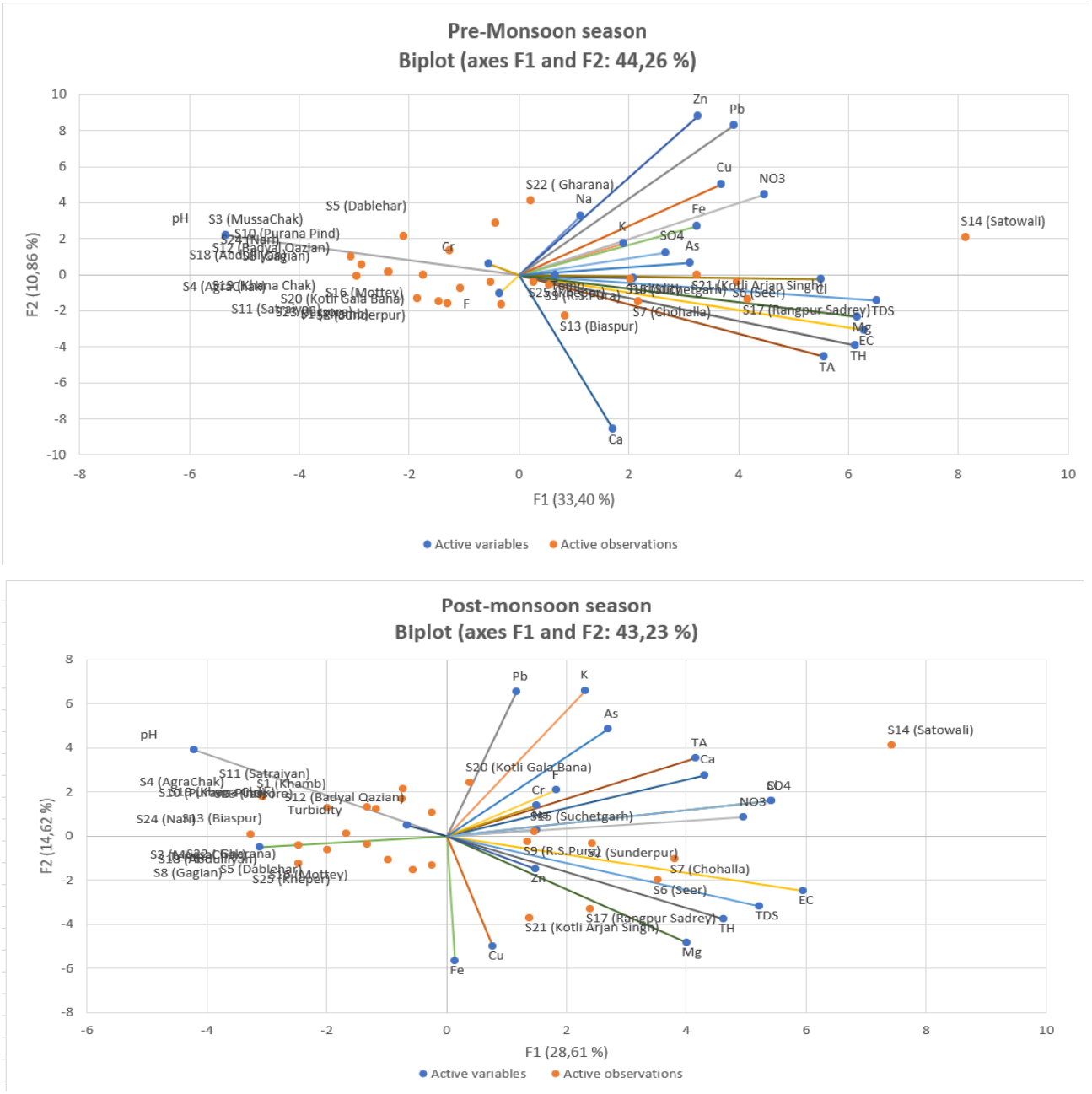

Fig. 38. Biplots of water quality parameters for Pre-monsoon (PRM) and post-monsoon (POM) season.

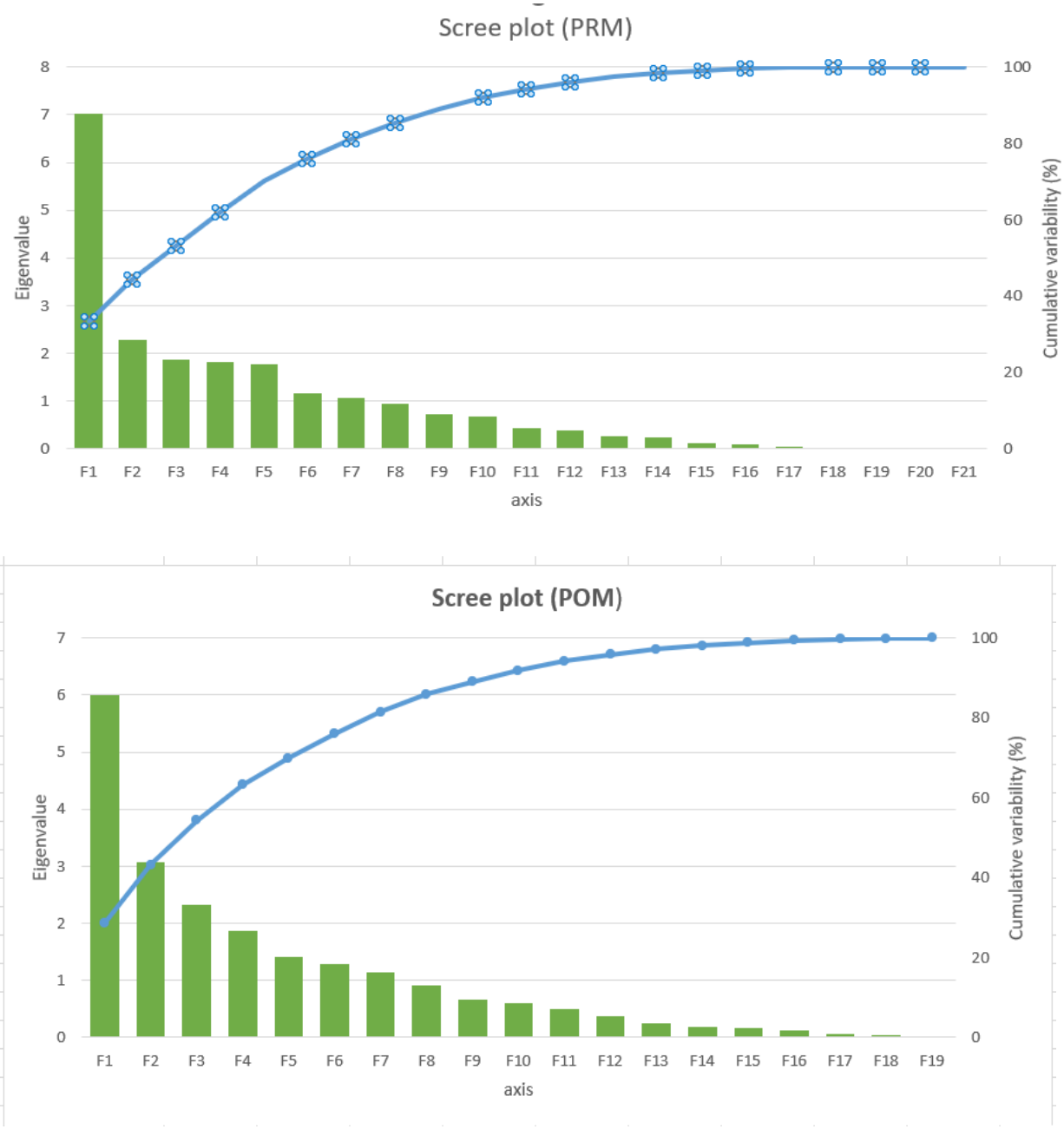

Fig. 39. Scree plots for Pre-monsoon (PRM) and post-monsoon (POM) season.

4.6.3 Descriptive Statistics: Various statistical tools such as mean, standard deviation and standard error for the physico-chemical parameters of the groundwater of study area has been calculated for the Pre-monsoon (PRM) and Post- monsoon (POM) season and their corresponding results for both the seasons have been listed in Table 31.

Table 31: Descriptive Statistics for physico-chemical parameters in study area for Pre-monsoon (PRM) and post-monsoon (POM) season. (all values are represented in mg/L except for pH, EC (µS/cm))

Parameter	Pre-monsoon (PRM)					Post- monsoon (POM)				
	Min.	Max.	Mean	S.D.	SEM	Min.	Max.	Mean	S.D.	SEM
pH	6	6.87	6.43	0.052	0.030	6.12	7.13	6.57	0.05	0.03
EC	356	1172	676.84	2.1	1.22	394	1037	622.37	4.88	2.82
TDS	208	596	330.72	2.28	1.32	197	814	346.85	4.08	2.36
TA	100	250	162.88	4.27	2.46	65	185	104.11	4.04	2.33
TH	200	560	305.88	7.32	4.22	183	520	299.32	4.62	2.66
Ca^{2+}	47.09	117.75	88.01	4.29	2.47	42.13	117.74	81.39	2.05	1.18
Mg^{2+}	120.94	448.98	217.81	5.28	3.05	112.8	416.8	221.3	4.86	2.81
Na^{+}	23.02	46.71	35.56	4.30	2.48	11.63	45.21	29.82	2.08	1.20
K^{+}	12.21	15.01	13.74	0.59	0.34	0.19	4.29	1.37	0.04	0.02
Cl^{-}	8.52	113.6	32.52	3.6	2.07	11.4	99.4	37.24	1.24	0.72
NO_3^{-}	0.94	4.56	2.46	0.054	0.031	0.78	4.5	2.28	0.08	0.05
F^{-}	0.12	0.9	0.56	0.061	0.035	0.1	0.76	0.44	0.03	0.02
SO_4^{2-}	15.09	49.12	30.03	1.93	1.11	11.65	46.15	26.66	2.1	1.21
Fe^{2+}	0.3	0.94	0.57	0.03	0.017	0.01	0.53	0.25	0.02	0.01

Zn^{2+}	0.11	0.25	0.17	0.02	0.010	0.05	0.16	0.09	0.02	0.011
Cu^{2+}	0.04	0.25	0.098	0.02	0.011	0.01	0.19	0.08	0.02	0.014
Pb^{2+}	*BDL	0.08	0.017	0.0018	0.001	BDL	0.04	0.02	0.002	0.001
Cr^{3+}	4.03	5.03	4.87	0.046	0.026	2.31	4.58	3.62	0.16	0.089
As^{3+}	BDL	0.04	0.01	0.007	0.004	BDL	0.03	0.02	0.004	0.002

*BDL-below detection limits

Chapter 5

SUMMARY AND CONCLUSION

5.1 Summary

The present study has been carried out in the Ranbir Singh Pura (R.S. Pura) tehsil of Jammu and Kashmir, India with an area of 245 Km^2 and a population of 1,97,739 (2011 census). Groundwater served as a unique source utilized for a wide range of applications in the study area. Study has been conducted during Pre-monsoon (PRM) and post-monsoon (POM) season of year 2022 with the objectives-assessment of groundwater quality for drinking and irrigation purposes, analysis of physico-chemical parameters of groundwater and assessment of health impacts on humans and on soil, calculation of water quality index for drinking usage. To achieve the above-mentioned objectives, the methodology has been followed which includes collection of groundwater samples, analysis of samples and then interpretation of results.

To determine the groundwater quality of study area, 25 groundwater samples were collected from different sites (handpumps, borewells, tubewells) of the study area according to the standard procedures of APHA (1999). To carried out the study, groundwater samples were examined for 22 parameters viz, pH, Electrical Conductivity (EC), Temperature, Turbidity, Total Alkalinity (TA), Total Dissolved solids (TDS), Magnesium (Mg^{2+}), Total Hardness (TH), Calcium (Ca^{2+}), Potassium (K^{+}), Fluoride (F^{-}), Nitrates (NO_3^{-}), Sodium (Na^{+}), Chloride (Cl^{-}), Sulphate (SO_4^{2-}), Iron (Fe^{2+}), Arsenic (As^{2+}), Zinc (Zn^{2+}), Nickel (Ni^{2+}), Lead (Pb^{2+}), Chromium (Cr^{2+}), Copper (Cu^{2+}). Water quality index (WQI) has been applied to categorize groundwater based upon its drinking water suitability.

Average pH of the groundwater samples during PRM was found below the permissible limits of BIS-2012 drinking water standards indicating slight acidic nature of the groundwater. Satowali (S-14) sampling site was reported with elevated levels of EC in groundwater of study area for both seasons. Enhanced concentration of EC in groundwater can be due to occurrence of dissolved salts and minerals in the groundwater. Few samples (12%) were exceeding TDS standard limits of BIS-2012 in both the seasons. Sampling sites Satowali (S-14), Rangpur Sadrey (S-17) were found with highest TDS concentration for PRM and POM season. Groundwater samples of the study area were observed within safe limits of BIS-

2012 for TA, TH and Na^+. Only HCO_3^- ions were found to be present while OH^- and CO_3^{2-} were found to be absent in the groundwater of study area. Most samples (72%) of groundwater were reported with high Ca^{2+} concentration, where Khamb (S-1), Satowali (S-14) and Jassore (S-23) were reported with highest Ca^{2+} concentration. All the sampling sites of the study area exceeded the permissible limits of Mg^{2+} laid by BIS-2012 and WHO-2011. High content of Mg^{2+} in the study region was reported due to mineral and salt dissolution, limestone hardness. K^+ concentration was found higher during PRM but found safe in POM season. High concentration of K^+ in groundwater of study area includes application of K^+ rich fertilizers and natural factors like weathering of rocks. Chloride (Cl^-), Nitrate (NO_3^-), Fluoride (F^-), Sulphate (SO_4^{2-}) were reported within safe limits of BIS-2012 for pre-monsoon (PRM) and post-monsoon (POM) season.

Water quality index classified the groundwater into various classes based on the suitability of water for drinking. For PRM season, WQI classified groundwater samples under good (36%), poor (60%) and very poor (4%) category. Only sampling site S-14 (Satowali) was reported under Very poor category (WQI-239.35) for PRM season. For POM season, WQI classified groundwater samples under good (52%) and poor (48%) category. In the study region, higher WQI values was reported during POM, which was due to effective leaching of ions, over exploitation of groundwater and anthropogenic activities.

Irrigation water suitability has been analyzed with the help of IWQI (Irrigation water quality index), SAR (Sodium absorption ratio), PI (Permeability index), RSC (Residual sodium carbonate), Na% (Sodium percent) and KI (Kelly's Index). Wilcox diagrams were plotted to classify groundwater samples for irrigation usage. Different hydrogeochemical facies were depicted using Piper-trilinear diagrams. IWQI classified 96% and 88% samples under 'No to moderate' restriction category during PRM and POM season respectively, indicating water suitability for irrigation purposes. Sampling site S-14 (Satowali) was reported unfit for agricultural use as per IWQI in both the seasons, thus restricting its use for irrigation. Results of the present research indicated that the groundwater is safe for agrarian sector according to Na%, SAR, KI and RSC water classification. 68% and 40% samples have been classified suitable/safe for irrigation during PRM and POM season respectively as per PI classification. Wilcox diagrams reported maximum samples under 'Excellent-good' category of Wilcox classification. Piper plots revealed $MgCO_3$

followed by Mg-SO_4-Cl be the prominent hydro chemical species in the groundwater of study area. Study also revealed that the groundwater contains more strong acids and alkaline earth metals as compared to alkalis.

For pre-monsoon (PRM) and post-monsoon (POM) season, 100% and 40% of the water samples reported beyond the safer limits of Fe^{2+} respectively. Gharana (S-22) was found with highest Fe^{2+} concentration for both the seasons. 76% and 68% samples were exceeding the BIS-2012 limits of Cu^{2+} during PRM and POM respectively. Satowali (S-14) and Suchetgarh (S-15) were reported with highest Cu^{2+} concentration in both the seasons. Pb^{2+} was below the detection limits at many sits at ppm level. Satowali (S-14) sampling site followed by Suchetgarh (S-15) found with highest Pb^{2+} concentration in both the season. Cr^{3+} concentration was exceeding the set limits at all the sampling sites of study area in both the seasons. Concentration of Ni^{2+} in both the seasons was below the detection limits (at ppm levels). No zinc contamination was observed for PRM and POM season as the concentration of Zn^{2+} was found within the permissible limits. 28% samples in PRM and 36% samples in POM exceeds the permissible limits of As^{3+} according to BIS-2012 and WHO-2011 standards.

Evaluation of health impacts using health indices, such as Heavy metal pollution index (HPI), Heavy metal evaluation index (HEI), Carcinogenic risks (CR), Hazard quotient (HQ), have been done to assess the health hazards caused by drinking contaminated water. No nitrate contamination was reported in the study area for both the seasons. Pb^{2+} and Cr^{3+} contamination was reported as per HPI. In the study area, high contamination of Cu^{2+}, Cr^{3+} and Pb^{2+} was found according to HEI. High Carcinogenic risks for Pb^{2+}, Cr^{3+} and Cu^{2+} (for women, men and children) were reported. Children were found more susceptible to carcinogenic risks as compared to adults. Non-carcinogenic risks in the form of HQ were calculated and results revealed that the groundwater was found contaminated with high concentrations of Zn^{2+}, Fe^{2+}, Cu^{2+} and Pb^{2+} during PRM season. Overall, the study area was found with Cu^{2+}, Cr^{3+} and Pb^{2+} contamination. Domestic waste, agricultural activities such as excessive usage of pesticides and fertilizers and plumbing could be the causes of high concentration of these heavy metals in the study area and can lead to severe health impacts of locals such as stomach ache, liver and kidney damage, enhanced blood pressure in adults etc. PCA carried out to assess the dominant species in the groundwater in which first principal component (PC1) indicates EC, TDS, TA, TH,

Cl^-, Mg^{2+}, Pb, NO_3^- as the loading factor and can be concluded that these variables were totally hydro-chemical and were supposed to be originated from geogenic sources. Second Principal component (PC2) of PRM contains Zn^{2+} and Pb^{2+} while of POM contains K^+ and Pb^{2+} depicting the use of agricultural fertilizers and pesticides and interference of human activities.

5.2 Conclusion

Some of the important conclusions drawn from the present study are mentioned below:

- No nitrate contamination has been reported in all the sampling sites of the study area.
- Sampling Site S-14 (Satowali) exceeds the permissible limits of EC, Cu^{2+}, Pb^{2+}, Ca^{2+}, Mg^{2+}, K^+ TDS in PRM and POM season and hence groundwater of this site found unfit for drinking usage.
- Turbidity found to be enhanced during POM season due to flooding of groundwater during monsoon.
- Low pH and higher HCO_3^- indicates chemical weathering in the study area.
- HCO_3^- dominance can lead to alkalinity of groundwater and thus supporting the alkaline pH of study area.
- High Mg^{2+} concentration than Ca^{2+} indicates carbonate weathering in the study area.
- WQI value was higher in POM due to effective leaching of ions, over exploitation and anthropogenic activities.
- Heavy metal contamination of Cr^{3+}, Cu^{2+} and Pb^{2+} was found and carcinogenic risks from these metals were reported as per HPI, HEI and CR.
- Chromium concentration was above the permissible limits at all sampling sites. Consumption of water with higher Cr^{3+} concentration can lead to skin allergy and rashes but is very harmful for aquatic ecosystem.
- HQ values indicated that children were more vulnerable to cancer risks when compared to men and women, due to their weakened immune systems and poor sanitation practices related to drinking water.

- Concentration of Mg^{2+}, K^{+}, Fe^{2+}, Pb^{2+}, Cr^{3+} was found present at all sampling sites above the permissible limits and can be due to agricultural activities, human activities and improper disposal of domestic waste.
- Concentration of Na^{+}, TA, TH, Zn^{2+}, Cl^{-}, NO_3^{-}, F^{-}, SO_4^{2-} was observed within the safe limits of drinking water standards.
- Groundwater was found suitable for irrigation usage according to IWQI, Na%, SAR, KI and RSC but found unsuitable according to PI.
- Groundwater of sampling sites Agra Chak (S-4), Seer (S-6), Chohalla (S-7) and R.S. Pura (S-17) found to have cleanest waters for irrigation purpose while Khana Chak (S-19) and Satowali (S-14) were reported to be moderately unsuitable and unsuitable for irrigation usage respectively.
- Piper trilinear plots revealed the dominance of $MgCO_3$ species followed by Mg-SO_4-Cl species in the water of study region, indicating the dominance of strong acids and alkaline earth elements over alkalis in the groundwater.
- Overall, quality of groundwater has been found to be of high grade during post-monsoon season when compared to Pre-monsoon. This is due to dilution of groundwater after monsoon.

5.3 Recommendations

On the basis of findings of the present research work, following suggestions are recommended:

- Usage of organic fertilizers instead of chemical fertilizers are recommended.
- Groundwater used for drinking must be treated before use.
- Continuous monitoring and groundwater suitability assessment should be carried out on a regular basis to combat the pollution problem in the study area.

5.4 Expected outcomes of the present study

The possible outcomes of the present study are as follows:

- The present work will be helpful in assessing the quality of groundwater and its suitability for domestic, drinking and irrigation use.

- Present study will be beneficial for the local people about the health hazards caused by the ingestion of contaminated groundwater of the study area.
- The results of this study will assist stakeholders and decision makers in formulating effective policies and managing the groundwater resources in the area.

REFERENCES

- Abbasnia, A., Radfard, M., Mahvi, A. M., Nabizadeh, R., Yousefi, M., Soleimani, H., and Alimahommadi, M. (2018), Groundwater quality assessment for irrigation purposes based on irrigation water quality index and its zoning with GIS in the villages of Chabahar, Sistan and Baluchistan, Iran, *Data in Brief*, Vol. 19, pp: 623-631.
- Abbasnia, A., Yousefi, N., Mahvi, A. H., Nabizadeh, R., Radfard, M., Yousefi, M., and Alimohammadi, M. (2018), Evaluation of groundwater quality using water quality index and its suitability for assessing water for drinking and irrigation purposes: Case study of Sistan and Baluchistan province, Iran. *Human and Ecological Risk Assessment: An International Journal*, Vol. *25*(4), pp: 988–1005.
- Abbulu, Y., and Rao, G. V. R. S. (2013), A Study on Physico-Chemical Characteristics of Groundwater in the Industrial Zone of Visakhapatnam, Andhra Pradesh, *American Journal of Engineering Research,* Vol. 2 (10), pp:112-116.
- Abdelhafez, A. A, Abbas, M. H. H., Kenawy, M. H. M., Noureldeen, A., Darwish, H., Ewis, A. M. G., and Hamed, M. H. (2021), Evaluation of underground water quality for drinking and irrigation purposes in New Valley Governorate, Egypt*, Environmental Technology and Innovation*, Vol. 22, pp: 1-15.
- Acharya, S., Sharma, S. K., and Khandegar, V. (2018), Assessment of groundwater quality by water quality indices for irrigation and drinking in South West Delhi, India, *Data in Brief*, Vol. 18, pp: 2019-2028.
- Acharya, S., Khandegar, V., and Sharma, S. K. (2023), Hydrochemistry and groundwater quality assessment of newly developed Dwarka region, New Delhi, India, *Research Square,* pp:1-26.
- Adimalla, N., Li, P., and Venkatayogi, S. (2018), Hydrogeochemical Evaluation of Groundwater Quality for Drinking and Irrigation Purposes and Integrated Interpretation with Water Quality Index Studies, *Environmental Processes*, pp: 1-22.
- Adimalla, N., Dhakate, R., Kasarla, A., and Taloor, A. K. (2020), Appraisal of groundwater quality for drinking and irrigation purposes in Central Telangana, India, *Groundwater for Sustainable Development*, Vol. 10, pp: 1-15.
- Ahada, S. P. C., and Suthar, S. (2018), Assessing groundwater hydrochemistry of Malwa Punjab, India, *Arabian Journal of Geosciences*, Vol. 11(17), pp: 1-15.

- Ajmal, P. R., Babar, M. M., Gul, N., and Jokhio, R. (2022), Assessment of Groundwater Quality using Water Quality Index, and Geo-Spatial Tools, *Neutron*, Vol. 22(1), pp: 65-74.
- Akter, T., Jhohura, F. T., Chowdhary, T. R., Dey, D., and Rahman, M. (2016), Water Quality Index for measuring drinking water quality in rural Bangladesh: a cross-sectional study, *Journal of Health, Population and Nutrition,* Vol. 35 (4), pp: 1-12.
- Alidadi, H., Sany, S. B. T., Oftadeh, B. Z. G., Md. T., Shamszade, H., and Fakhari, M. (2019), Health risk assessments of arsenic and toxic heavy metal exposure in drinking water in northeast Iran, *Environmental Health and Preventive Medicine*, Vol. 24 (59), pp: 1-17.
- American Public Health Association (1999), Standards methods for the examination of water and wastewater, Water Environment Federation, pp: 1-541.
- Asadi, E., Isazadeh, M., Samadianfard, S., Ramil, M. F., Mosavi, A., Nabipour, N., Shamshirband, S., Hajnal, E., and Chau, K. W. (2019), Groundwater Quality Assessment for Sustainable Drinking and Irrigation, *Sustainability,* Vol. 12 (177), pp: 1-13.
- Aslam, Z. and Raina, M. Y. (2016), Study of Physico Chemical Parameters of Basantar River and Impact of Industrial Waste on Groundwater Quality in Vicinity of Dumping Site in Samba Town, Jammu & Kashmir, India, *International Journal of Engineering Research & Technology*, Vol. 5 (3), pp: 327-332.
- Ayyandurai, R., Vanketeswaran, S. and Karunanidhi, D. (2022). Hydrogeochemical assessment of groundwater quality and suitability for irrigation in the coastal part of Cuddalore district, Tamil Nadu, India. *Marine Pollution Bulletin*, Vol. 174, pp: 1-15.
- Baloch, M., Zhang, W., Chai, J., Li, S., Alqurashi, M., Rehman, G., Tariq, A., Talpur, S. A., Iqbal, J., Munir, M. and Hussein, E. (2021), Shallow groundwater quality assessment and its suitability analysis for drinking and irrigation purposes, *Water*, Vol. 13 (3361), pp:1-25.
- Bansal, J. and Dwivedi, A. K. (2018), Assessment of ground water quality by using water quality Index and physico chemical parameters: review paper, *International Journal of Engineering Sciences & Research Technology,* Vol. 7(2), pp: 170-175.
- Batarseh, M., Imreizeeq, E., Tilev, S., Alaveen, A., Suleiman, W. and Remeithi, A. (2021). Assessment of groundwater quality for irrigation in the arid regions using

irrigation water quality index. *Groundwater for Sustainable Development*, Vol. 14, pp: 1-17.

- Bernard, E. and Ayeni, N. (2012), Physicochemical Analysis of Groundwater Samples of Bichi Local Government Area of Kano State of Nigeria, *World Environment*, Vol. 2 (6), pp: 116-119.
- Beyene, G., Aberra, D. and Fufa, F. (2019), Evaluation of the suitability of groundwater for drinking and irrigation purposes in Jimma Zone of Oromia, Ethiopia*, Groundwater for Sustainable Development,* Vol. 9, pp: 01-08.
- Bhunia, G. S., Keshavarzi, A., Shit, P. K., Omran, E. S. E. and Bagherzadeh, A. (2018), Evaluation of groundwater quality and its suitability for drinking and irrigation using GIS and geostatistics techniques in semiarid region of Neyshabur, Iran, *Applied Water Science*, Vol. 8 (168), pp: 01-16.
- BIS (2012), Indian Standards Specifications for Drinking Water (second revision), *Bureau of Indian Standards*, New Delhi. IS: 10500 -2012.
- Boateng, T. K., Opoku, F., Acquaah, S. O. and Akoto, O. (2016), Groundwater quality assessment using statistical approach and water quality index in Ejisu-Juaben Municipality, Ghana, *Environmental Earth Science*, Vol. 45 (489), pp: 1-14.
- Chakraborti, D., Rahman, M. M., Mukherjee, A., Alauddin, M., Hassan, M., Dutta, R. N., Pati, S., Mukherjee, S. C., Roy, S., Quamruzzman, Q., Rahman, M, Islam T, Sorif S, Selim Md, Islam MR, Hossain MM (2015), Groundwater arsenic contamination in Bangladesh—21 years of research, *Journal of Trace Elements in Medicine and Biology*, Vol. 3 (1), pp: 37–248.
- Chaudhary, V. and Satheeshkumar, S. (2018), Assessment of groundwater quality for drinking and irrigation purposes in arid areas of Rajasthan, India, *Applied Water Science,* Vol. 8 (218), pp: 1-18.
- Chen, J., Huang, Q., Lin, Y., Fang, Y., Qian, H., Liu, R. and Ma, H. (2019), Hydrogeochemical Characteristics and Quality Assessment of Groundwater in an Irrigated Region, Northwest China, *Water*, Vol. 11 (96), pp: 1-18.
- Chidambaram, S., Prasanna, M.V., Venkatramanan, S., Nepolian, M., Pradeep, K., Banajarani, Panda., Thivya, C. and Thilagavathi, R. (2021), Groundwater quality assessment for irrigation by adopting new suitability plot and spatial analysis based on fuzzy logic technique, *Environmental Research,* Vol. 204 (2022), pp: 1-16.

- Dhakshinamoorthy R and Selvarajan G. (2025), Comprehensive evaluation of groundwater quality in Mayiladuthurai district, Tamil Nadu: Physico-chemical and heavy metal analysis, Ecology, Environment and Conservation, Vol. 31(2), pp: 865-868.
- De. A. K., Environmental Chemistry, seventh edition, 2010, New Age International Ltd. Publishers.
- Dogra, S., Sharma, K. and Singh, N. (2023), Water quality and health risk assessment of heavy metals in groundwater of Ranbir Singh Pura tehsil of Jammu and Kashmir, India, *Environmental monitoring and assessment*, Vol. 195 (1026), pp: 1-19.
- Doneen, L. D. (1964). Notes on Water Quality in Agriculture; Published as a Water Science and Engineering Paper 4001; *Department of Water Science and Engineering*, University of California: Oakland, CA, USA.
- Elumalai, V., Vhonani, G., Nethononda, V., Manivannan, N., Rajmohan., Li P. and Elango, L. (2020), Groundwater quality assessment and application of multivariate statistical analysis in Luvuvhu catchment, Limpopo, South Africa, *Journal of African Earth Sciences*, Vol. 171, pp: 1-14.
- Gabr, M. E., Soussa, H. and Fattouh, E. (2020), Groundwater quality evaluation for drinking and irrigation uses in Dayrout city Upper Egypt, *Ain Shams Engineering Journal,* Vol. 12 (2021), pp: 327-340.
- Gagandeep., Prakash, R., Kumar, S., Satyavan., Rajpaul. and Sharma, S. K. (2016), Assessment of groundwater quality for irrigation in Hodal Block of Palwal district, Haryana*, Journal of Soil Salinity and water quality,* Vol. 8 (1), pp: 30-36.
- Gautam, D., Vaid, U. and Khaki, Q. Z. (2023), Suitability evaluation of groundwater for drinking and agriculture purpose in Una District, Himachal Pradesh, India, *IOP Conference Series: Earth and Environmental Science*, Vol. 1110, pp: 1-13.
- Gugulothu, S., Subbarao, N., Das, R. and Dhakate, R. (2022), Geochemical evaluation of groundwater and suitability of groundwater quality for irrigation purpose in an agricultural region of South India, *Applied Water Science*, Vol. 12 (142), pp:1-13.
- Gulgundi, M. S. and Shetty, A. (2018), Groundwater quality assessment of urban Bengaluru using multivariate statistical techniques, *Applied Water Science*, Vol. 43, pp: 1-15.

- Guo, H., Li, M., Wang, L., Wang, Y., Zang, X., Zhao, X., Wang, H. and Zhu, J. (2021), Evaluation of Groundwater Suitability for Irrigation and Drinking Purposes in an Agricultural Region of the North China Plain, *Water*, Vol.13 (3426), pp: 1-22.
- Houatmia, F., Azouzi, R., Charef, A. and Bedir, M. (2016), Assessment of groundwater quality for irrigation and drinking purposes and identification of hydrogeochemical mechanisms evolution in Northeastern, Tunisia, *Environment Earth Science*, Vol. 75 (746), pp: 1-17.
- Ibrahim, H., Yaseen, Z, M., Scholz, M., Ali, M., Gad, M., Elsayed, S., Khadr, M., Hussein, H., Ibrahim, H, H., Eid, M. H. and Khalifa, M. M. (2023), Evaluation and Prediction of Groundwater Quality for Irrigation Using an Integrated Water Quality Indices, Machine Learning Models and GIS Approaches: A Representative Case Study, *Water*, Vol.15 (694), pp:1-26.
- Ishaku, J. M. (2011), Assessment of groundwater quality index for Jimeta Yola area, Northeastern Nigeria, *Journal of Geology and Mining Research,* Vol. 3(9), pp. 219-231.
- Jain, C. K., and Vaid, U. (2018), Assessment of groundwater quality for drinking and irrigation purposes using hydrochemical studies in Nalbari district of Assam, India, *Environmental Earth Sciences*, Vol. 77 (254), pp: 1-14.
- Jasrostia, A. S., Taloor, A. K., Andotra, U. and Bhagat, B. D. (2018), Geoinformatics based groundwater quality assessment for domestic and irrigation uses of the Western Doon valley, Uttarakhand, India, *Groundwater for Sustainable Development,* Vol. 6, pp: 200-212.
- Jasrotia, A. S., Taloor, A. K., Andotra, U. and Kumar, R. (2019), Monitoring and assessment of groundwater quality and its suitability for domestic and agricultural use in the Cenozoic rocks of Jammu Himalaya, India: A geospatial technology-based approach, *Groundwater for Sustainable Development*, Vol. 8, pp: 554-566.
- Jude, N. N., Wotany, E. R., Agyingi, C., Ghomsi, F. K., Aurore, M. K., Nelson, M. A. and Bessa, A. Z. (2023), Hydrogeochemical monitoring of groundwater and surface water quality of East of Mount Cameroon and West of the Penda Mboko River, suitability for drinking and irrigation, *Research Square*, pp: 1- 39.
- Kanga, I. S., Naimi, M. and Chikhaoui, M. (2020), Groundwater quality assessment using water quality index and geographic information system based in Sebou River

Basin in the North-West region of Morocco, *International Journal of Energy and Water Resources,* pp: 1-9.

- Kaur, T., Bhardwaj, R. and Arora, S. (2017), Assessment of groundwater quality for drinking and irrigation purposes using hydrochemical studies in Malwa region, southwestern part of Punjab, *India, Applied Water Science,* Vol. 7, pp: 3301-3316.
- Kaur, M., Kumar, A., Mehra, R. and Kaur, I. (2019), Quantitative Assessment of exposure of heavy metals in ground water & soil on human health in Reasi district, Jammu, *Environmental geochemistry & Health,* Vol. 42, pp: 77-94.
- Kelly W. P (1940) Permissible composition and concentration of irrigated waters. In: *Proceedings of the ASCF* 66, pp: 607.
- Khadse, K. G., Patni, M. P., & Labhasetwar, K. P. (2016). Water quality assessment of Chenab River and its tributaries in Jammu Kashmir (India) based on WQI. *Sustainable Water Resource Management*, Vol. 2, pp:121- 126.
- Khan, R. and Jhariya, D.C. (2017), Groundwater Quality Assessment for Drinking Purpose in Raipur City, Chhattisgarh Using Water Quality Index and Geographic Information System, *Journal of the geological society of India*, Vol. 90, pp: 69-76.
- Khanna. P. (2019), Groundwater quality assessment: Physico-chemical and statistical analysis of selected groundwater samples in district Samba, Jammu, Jammu and Kashmir, India, *International Journal of Global Science Research*, Vol. 6 (1), pp: 697-710.
- Khanoranga, and Khalid, S. (2019), An assessment of groundwater quality for irrigation and drinking purposes around brick kilns in three districts of Balochistan province, Pakistan, through water quality index and multivariate statistical approaches, *Journal of Geochemical Exploration,* Vol. 197, pp: 14-26.
- Kouser, B., Bala, A., Verma, O., Prashanth, M., Khosla, A. and Pir, R. A. (2022), Hydrochemistry for the assessment of groundwater quality in the Kathua region, Jammu and Kashmir, India, *Applied Water Science,* Vol. 12 (143), pp: 1-22.
- Kumar, S. K., Rammohan, V., Sahayam J.D. and Jeevanandam, M. (2009), Assessment of groundwater quality and hydrogeochemistry of Manimuktha River basin, Tamil Nadu, India, *Environmental Monitoring and assessment*, Vol. 159, pp: 341-351.
- Kumar, P. J. S. and James, E. J. (2013), Physicochemical parameters and their sources in groundwater in the Thirupathur region, Tamil Nadu, South India, *Applied Water Science*, Vol. 3, pp:219–228.

- Kumar, S.K., Logeshkumaran, A., Magesh, N. S., Prince, S., Godson, N. and Chandrasekar. (2015), Hydro-geochemistry and application of water quality index (WQI) for groundwater quality assessment, Anna Nagar, part of Chennai City, Tamil Nadu, India, *Applied Water Science*, Vol. 5, pp: 335-343.
- Kumar, A., Kaur, M., Mehra, R. and Kumar, D. (2017), Comparative study of Radon concentration with two techniques & environmental analysis in drinking water samples of Jammu district, J&K, India, *Health Physics,* Vol. 113, pp: 271-281.
- Kumar, H. V., Patil, N.S. and Prabhu, N. (2020), Analysis of water quality parameters of groundwater near Ranebennur Industrial Area, Haveri district, Karnataka, India, *AIP Conference Proceedings* 2204, 020025. P. no. 1-8.
- Kumar, S. K., Logeshkumaran, A., Magesh, N. S., Godson, P. S. and Chandrasekar, N. (2022), Hydro-geochemistry and application of water quality index (WQI) for groundwater quality assessment, Anna Nagar, part of Chennai City, Tamil Nadu, India, *Applied Water Science,* Vol. 5, pp: 335-343.
- Kumari, M. and Rai, S.C. (2020), Hydrogeochemical Evaluation of Groundwater Quality for Drinking and Irrigation Purposes Using Water Quality Index in Semi-Arid Region of India*, Geological society of India*, Vol. 95, pp: 159-168.
- Lanjwani, M. F., Khuhawar, M. Y. and Khuhawar, T. M. J. (2020), Groundwater quality assessment of Shahdadkot, Qubo Saeed Khan and Sijawal Junejo Talukas of District Qambar Shahdadkot, Sindh, *Applied Water Science,* Vol. 26, pp: 1-18.
- Li, P., Karunanidhi, D., Subramani, T. and Srinivasamoorthy, K. (2021), Sources and Consequences of Groundwater Contamination, *Archives of Environmental Contamination and Toxicology*, Vol. 80, pp: 1-10.
- Loh Y. S. A, Akurugu B. A, Manu E, Aliou A. S (2020), Assessment of groundwater quality and the main controls on its hydrochemistry in some Voltaian and basement aquifers, northern Ghana, *Groundwater for Sustainable Development,* Vol. 10, pp:1-13.
- Lorestani, B., Merrikhpour, H. and Cheraghi, M. (2020), Assessment of heavy metals concentration in groundwater and their associated health risks near an industrial area. Environmental *Health Engineering and Management* Journal; Vol. 7(2): pp: 67–77.
- Madhav, S., Ahamad, A., Kumar, A., Kushawaha, J., Singh, P. and Mishra, P. K. (2018), Geochemical assessment of groundwater quality for its suitability for drinking and irrigation purpose in rural areas of Sant Rsavidas Nagar (Bhadohi), Uttar Pradesh, *Geology, Ecology, and Landscapes*, Vol. 2, pp: 127-136.

- Maglangit, F. (2014), Physicochemical-assessment of the Water Quality of Buhisan River, Cebu, Philippines, *International Journal of Research in Environmental Science and Technology*, Vol. 4 (2), pp: 83-87.
- Mahaqi A, Moheghi M. M, Mehiqi M, Mohegy M. A (2018), Hydrogeochemical characteristics and groundwater quality assessment for drinking and irrigation purposes in the Mazar-i-Sharif city, North Afghanistan, *Applied Water Science*, Vol. 8 (133), pp: 1-10.
- Mallick J, Singh C. K, Almesfer M. K, Kumar A, Khan R. A, Islam S and Rahman A (2018), Hydro-Geochemical Assessment of Groundwater Quality in Aseer Region, Saudi Arabia, *Water*, Vol. 10, pp: 1- 14.
- Matta, G., Gautam, R., Kumar, A. and Kumar, P. (2018), Monitoring and assessment of ground water quality in rural area of Haridwar district, Uttarakhand, *Dissertation,* pp: 1-17.
- Mjemah, I. C. and Mariki, E. E. (2021), Hydrochemical Characteristics of Groundwater and its Suitability for Drinking and Irrigation Uses in Makutupora Sub-basin, Tanzania, *8th Brunei International Conference on Engineering and Technology,* AIP Conf. Proc. 2643, 030014-1–030014-8.
- Mohammadi, A. A., Ahmad, Z., Majidic, S., Ghaderpoury, A., Hashempour D., Saghi, M. H., Alinejad, J., Yousefi, M., Hosseingholizadeh, N. and Ghaderpoori, M. (2019), Carcinogenic and non-carcinogenic health risk assessment of heavy metals in drinking water of Khorramabad, Iran, *MethodsX*, Vol. 6, pp: 1642-1651.
- Murtaza, K. O., Romhoo, S. A., Rashid, I. and Shah, W. (2019), Geospatial assessment of groundwater quality in Udhampur district, Jammu and Kashmir, India, *Proceedings of National Academy of Sciences, India, Section A: Physical Sciences,* pp: 1-15.
- Naidu, S., Gupta, G., Singh, R., Tahama, K. and Erram, V. C. (2021), Hydrogeochemical Processes Regulating the Groundwater Quality and its Suitability for Drinking and Irrigation Purpose in Parts of Coastal Sindhudurg District, Maharashtra, *Journal Geological Society of India*, Vol. 97, pp: 173-185.
- National Institute of Hydrology, Jalvigyan Bhawan, Roorkie (1996-97), Ground water Quality studies in Jammu & Kathua district (J&K), Vol. 37, pp:1-62.
- Osta, M. E., Masoud, M., Alqarawy, A., Elsayed. and Gad, M. (2022), Groundwater suitability for drinking and irrigation using water quality indices and multivariate

modeling in Makkah Al-Mukarramah province, Saudi Arabia, *Water,* Vol. 14 (483), pp: 1-23.

- Paliwal, K.V., 1972. Effect of gypsum application on the quality of irrigation water. *Madras Agriculture Journal,* Vol. 59, pp: 646–647.
- Palmajumder, M., Chaudhuri, S., Das, V. K. and Nag, S. K. (2021), An appraisal of geo-hydrological status and assessment of groundwater quality of Indpur Block, Bankura District, West Bengal, India, *Applied Water Science,* Vol. 11 (59), pp:1-21.
- Paneerselvam, B., Karuppannan, S. and Muniraj, K. (2020), Evaluation of drinking and irrigation suitability of groundwater with special emphasizing the health risk posed by nitrate contamination using nitrate pollution index (NPI) and human health risk assessment (HHRA), *Human and Ecological Risk Assessment: An International Journal,* Vol. 27 (3), pp: 1-25.
- Pappaka, R. K., Somagouni, S. G., Chinthala, K. and Nakkala, A. B. (2024), Appraisal of groundwater quality for suitability of drinking and irrigation purposes of pandameru river basin, anantapur district, AP, India, *Arabian Journal of Geosciences,* Vol. 17 (23), pp: 1-16.
- Prakash, K. L. and Somashekhar, R. K. (2006), Groundwater quality - Assessment on Anekal Taluk, Bangalore Urban district, India, *Journal of environmental biology*, Vol. 27(4), pp: 633-637.
- Raheja, H., Goel, A. and Pal, M. (2024), Assessment of Groundwater Quality for Drinking and Potential Health Risks of Nitrate Pollution, *World Environmental and Water Resources Congress*, pp: 473-485.
- Raja, V., Laxmi, R. V., Sekar, C. P., Chidambaram, S. and Neelakantan, M. A. (2021), Health risk assessment of heavy metals in groundwater of industrial township Virudhunagar, Tamil Nadu, India*, Archives of Environmental Contamination and Toxicology*, Vol. 80, pp:144–163.
- Rajkumar, H., Naik, P. K. and Rishi, M. S. (2020), A new indexing approach for evaluating heavy metal contamination in groundwater, *Chemosphere,* Vol. 245, pp: 1-55.
- Ramakrishnaiah, C.R., Sadashiviah, C. and Ranganna, G. (2009), Assessment of Water Quality Index for the Groundwater in Tumkur Taluk, Karnataka State, India, *E-Journal of Chemistry*, Vol. 6 (2), pp: 523-530.

- Rao, G.S. and Nageswararao, G. (2013), Assessment of Groundwater quality using Water Quality Index, *The journal of Archives of Agriculture and Environmental Science*, Vol. 7, pp: 1-5.
- Rao, N. S., Dinakar, A., Sravanthi, M. and Kumari, B. K. (2021), Geochemical characteristics and quality of groundwater evaluation for drinking, irrigation, and industrial purposes from a part of hard rock aquifer of South India, *Environmental Science and Pollution Research,* Vol. 28, pp: 31941–31961.
- Rao, N. S. (2006), Seasonal variation of groundwater quality in a part of Guntur District, Andhra Pradesh, India, *Environmental Geology,* Vol. 49, pp: 413-429.
- Rather, I. A. and Dar, A. Q. (2019), Forecasting Past and Future Trend of Physio-Chemical Parameters in Dal Lake, Srinagar Kashmir, India using Statistical Analysis and Modelling, *International Journal of Engineering and Advanced Technology*, Vol. 9 (2), pp: 1043-1051.
- Ravikumar, P., Somashekhar, R. K. and Prakash, K. L. (2015), A Comparative study on the usage of Durov and Piper Diagrams to interpret hydrochemical processes in groundwater from SRLIS River basin, Karnataka, India, *Elixir International Journal*, Vol. 80, pp: 31073-31077.
- Rawat, K. S., Singh, S. K. and Gautam, S. K. (2018), Assessment of groundwater quality for irrigation use: a peninsular case study. *Applied Water Sci*ence, Vol. 8 (233), pp: 1-24.
- Rawy, M. E., Ismail, E. and Abdalla, O. (2019), Assessment of groundwater quality using GIS, hydrogeochemistry and factor statistical analysis in Qena governorate, Egypt, *Desalination and Water Treatment*, Vol. 162, pp: 14-29.
- Reza, G. and Singh, G. (2010), Assessment of Ground Water Quality Status by Using Water Quality Index Method in Orissa, India, *World Applied Sciences Journal*, Vol. 9 (12), pp: 1392-1397.
- Saad, A. S., Massoud, M. D., Amder, R. A. and Ghorab, M. A. (2017), Assessment of the Physico-chemical Characteristics and Water Quality Analysis of Mariout Lake, Southern of Alexandria, Egypt, *Journal of Environmental & Analytical Toxicology,* Vol. 7 (1), pp: 1-19.
- Sadashivaiah, C., Ramakrishnaiah, C.R. and Ranganna, G. (2008), Hydrochemical Analysis and Evaluation of Groundwater Quality in Tumkur Taluk, Karnataka State,

India, *International Journal of Environmental Research and Public Health*, Vol. 5 (3), pp: 158-164.

- Saleem, M., Hussain, A. and Mahmood, G. (2016), Analysis of groundwater quality using water quality index: A case study of greater Noida (Region), Uttar Pradesh (U.P), India, *Cogent Engineering*, Vol. 3, pp: 1-11.
- Saraswat, C., Kumar, P., Dasgupta, R., Avtar, R. and Bhalani, P. (2019), Sustainability assessment of the groundwater quality in the Western India to achieve urban water security, *Applied Water Sciences*, Vol. 73, pp: 1-17.
- Sarkar, M., Pal, S. C. and Islam, A. R. (2022), Groundwater quality assessment for safe drinking water and irrigation purposes in Malda district, Eastern India, *Environmental Earth Sciences*, Vol. 81 (52), pp: 1-20.
- Shil, S., Singh, U. K. and Mehta, P. (2019), Water Quality assessment of a tropical river using water quality index (WQI), multivariate statistical techniques and GIS, *Applied Water Science,* Vol. 9 (168), pp: 1-21.
- Sharma, N., Vaid, V., Sharma, S. K. (2021), Assessment of groundwater quality for drinking and irrigation purpose using hydrochemical studies in Dera Bassi town and it surrounding agricultural area of Dera Bassi Tehsil of Punjab, India, *Springer Nature Applied Sciences*, Vol. 3 (245), pp: 1-13.
- Singha, D. (2017), A Study on Ground Water Quality Analysis in the District of Idukki, Kerala, *International Journal of Scientific and Engineering Research,* Vol. 8 (3), pp: 842-858.
- Singh, V. K., Bikundia, D. S., Saraswat, A. and Mohan, D. (2012), Groundwater quality assessment in the village of Lutfullapur Nawada, Loni, District Ghaziabad, Uttar Pradesh, India, *Environmental Monitoring and Assessment,* Vol. 184, pp: 4473-4488.
- Singh, G., Singh, D. and, Sharma, S. K. (2013), Effect of Polluted Surface Water on Groundwater: A Case Study of Budha Nullah, *IOSR Journal of Mechanical and Civil Engineering,* Vol. 5, pp: 01-08.
- Singh, K. K., Tewari, G. and Kumar, S. (2020), Evaluation of groundwater quality for suitability of irrigation purposes: A case study in the Udham Singh Nagar, Uttarakhand, *Journal of Chemistry*, Vol. 2, pp: 1-15.
- Soleimani, H., Abbasnia, A., Yousefi, M., Mohammadi, A. A. and Khorasgani, F. C. (2018), Data on assessment of groundwater quality for drinking and irrigation in rural

area Sarpol-e Zahab city, Kermanshah province, Iran, *Data in Brief*, Vol. 17, pp: 148-156.

- Subramaniyan, A., Karthikeyan, B. and Lakshmanan, E. (2022), Geochemical evaluation of fluoride and groundwater quality for drinking and irrigation purposes in a weathered gneissic rock aquifer of southern peninsular India, *Environmental Earth Sciences*, Vol. 81 (273), pp: 1-18.
- Sudan, S. (2018), Assessment of Ground water quality: A Case Study of Jammu District, *International Journal of Science & Research,* Vol. 7, pp: 1151- 1162.
- Tajwar, M., Uddin, A., Lee, M. K., Nelson, J., Zahid, A. and Sakib, N. (2023), Hydrochemical Characterization and Quality Assessment of Groundwater in Hatiya Island, Southeastern Coastal Region of Bangladesh, *Water*, Vol. 15 (905), pp: 1-21.
- Tegegne, A. M., Lohani, T. K. and Eshete, A. A. (2023), Evaluation of groundwater quality for drinking and irrigation purposes using proxy indices in the Gunabay watershed, Upper Blue Nile Basin, Ethiopia, *Heliyon*, Vol. 9, pp: 1-16.
- Tokatli, C. (2021), Health risk assessment of toxic metals in surface and groundwater resources of a significant agriculture and industry zone in Turkey, *Environmental Earth Sciences,* Vol.80 (156), pp: 1-14.
- Tumolo, M., Ancona, V., Paola, D. D., Lossacco, D., Campanale, C., Massarelli, C. and Uricchio, V. F. (2020), Chromium Pollution in European Water, Sources, Health Risk, and Remediation Strategies: An Overview, *International Journal of Environmental Research and Public Health,* Vol. 17 (5438), pp: 1-24.
- Tucker, D. T. (2018), Natural chromium sources threaten California groundwater, Stanford News.
- Uqab, B., Singh, A. and Mudasir, S. (2017), Impact of sewage on physico-chemical water quality of Tawi River in Jammu city, *Environment Risk Assessment and Remediation*, Vol. 1(2), pp: 56-61.
- US Salinity Laboratory Staff (1954), Diagnosis and improvement of saline and alkali soils, *US Department of Agriculture Handbook* 60, Washington, DC.
- Vardhan, H., Verma, A. K., Allayie, S. A, and Mushtaq, R. (2015), Assessing variations in physico-chemical paramters of Tatapani spring of district Rajouri- Jammu, *International Journal of Science and Research*, Vol. 11(1), pp: 133-138.
- Vasanthavigar, M., Srinivasamoorthy, K., Vijayaragavan., Ganthi, R., Chidambaram, S., Anandhan, P., Manivannan, R. and Vasudevan, S. (2010), Application of water

quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India, *Environmental Monitoring and Assessment*, Vol. 171, pp: 595-609.

- Veeraswamy, G., Balaji, E. and Rao, M. S. (2019), Groundwater quality assessment for drinking and irrigation in Yerpedu area Chittoor district, Andhra Pradesh, South India, *International Journal of Technical Innovation in Modern Engineering & Science,* Vol. 5 (2), pp: 43-49.
- Wagh, V., Panasakar, D., Mukate, S., Gaikvaid, S. K., Muley, A. and Varade, A. (2018), Health risk assessment of heavy metal contamination in groundwater of Kadava River Basin, Nashik, India, *Modeling Earth Systems and Environment*, Vol. 4, pp: 969-980.
- Wagh, V., Mukate, S., Muley, A., Kadam, A. K., Panasakar, D. and Varade, A. (2020), Study of groundwater contamination and drinking suitability in basaltic terrain of Maharashtra, India through PIG and multivariate statistical techniques, *Journal of Water Supply: Research and Technology—AQUA*, Vol. 69 (4), pp: 398-414.
- Wilcox L. V. (1955). Classification and use of irrigation Waters, United States Department of Agriculture (USDA), Washington DC, USA
- WHO (2004), *Guidelines for Drinking Water Quality*: Vol.1 Recommendations (4th edition). Geneva: World Health Organization.
- Yadav, B.K. and Kumar, D. (2020), Assessment of groundwater quality for drinking and irrigation purposes in Bathinda and Mansa districts of Southwest Punjab, India, *Journal of Environmental Biology*, Vol. 42, pp: 388-395.
- Zafar, M. M., Sulaiman, M. A., Prabhakar, R. and Kumari, A. (2022), Evaluation of the suitability of groundwater for irrigational purposes using irrigation water quality indices and geographical information systems (GIS) at Patna (Bihar), India, *International Journal of Energy and Water Resources,* Vol. 2, pp: 1-15
- Zaman, M., Shahid, S. A. and Heeng, L. (2018), *Chapter-5* Irrigation Water Quality, Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques, Vol. 5, pp: 112-131.