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Assessment of groundwater quality and irrigation suitability in the Doodhganga Catchment, Kashmir Valley

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ABSTRACT

This study evaluates groundwater quality in the Doodhganga catchment area, located in the Kashmir Valley, for its suitability for agricultural use. A comprehensive analysis of 66 groundwater samples collected over two years (2022–2023) assessed physico-chemical parameters, including pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), hardness, and concentrations of major ions like calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^{-}), and bicarbonate (HCO^{3-}). Results indicated that groundwater falls within the "fresh water" category, adhering to both WHO and ISI standards, ensuring suitability for agriculture irrigation. Key indices such as Residual Sodium Carbonate (RSC), Kelley's Index (KI), and Permeability Index (PI) were calculated to assess irrigation quality. The findings underscore the groundwater's general potability and suitability for irrigation, with minor hardness concerns, linked to geological formations, which may affect industrial applications. This study supports sustainable groundwater management in the Kashmir Valley, vital for agricultural productivity and water security.

Key words: Groundwater quality, Doodhganga catchment, Irrigation suitability, Water hardness, Physico-chemical analysis, Kashmir valley

INTRODUCTION

Groundwater is a critical natural resource, underpinning socioeconomic, agricultural, and industrial development worldwide (Bouslah *et al*., 2017). It contributes approximately 40% of the water required for food production and 30% for drinking water globally (Amiri *et al*., 2021; Chowdhury *et* al., 2021). However, the ever-increasing reliance on groundwater has led to its over-extraction and quality deterioration, driven by rapid urbanization, population growth, and agricultural intensification (Jasrotia *et al*., 2019; Adimalla and Taloor, 2020). The introduction of the Green Revolution in the 1970s further escalated groundwater use for irrigation, facilitated by year-round cropping and the extensive use of chemical fertilizers. While this revolution significantly increased agricultural output, it also resulted in unintended consequences such as groundwater depletion and soil degradation (Suhag, 2016).

Groundwater quality is a key determinant of its usability for irrigation and drinking purposes. Poor water quality, characterized by high salinity, elevated ion concentrations, or excessive hardness, adversely affects soil health, crop productivity, and human health (Singh *et al*., 2023). Parameters like Electrical Conductivity (EC), Total Dissolved Solids (TDS), and pH influence soil salinity and alkalinity, directly impacting plant water absorption and soil structure (Mills, 2003). Indices such as Residual Sodium Carbonate (RSC), Kelley's Ratio (KR), and Permeability Index (PI) provide insights into the suitability of groundwater for irrigation and its potential impact on soil health (Estefan *et al*., 2013; Singh *et al*., 2021). Long-term use of poor-quality irrigation water can lead to soil salinization, declining fertility, and reduced agricultural productivity.

The Kashmir Valley, known for its abundant natural water resources and agricultural productivity, is experiencing significant challenges due to unregulated urban expansion, deforestation, and pollution. Many water bodies have been reduced to a fraction of their original size, with the most notable impacts seen in Srinagar, where half of the water bodies in and around the city have disappeared over the past century due to rising water demand and the unsustainable management of vital resources in the face of urban growth and

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modernization (Kumar *et al.*, 2020). The Doodhganga catchment, a vital water source in this region, is no exception. Over the years, declining water quality, wetland encroachment, and reduced flows have degraded the region's water resources, impacting agricultural practices and overall ecological balance (Kumar *et al.*, 2012; Romshoo *et al.*, 2015; Rashid *et al.*, 2017). Despite its importance, groundwater quality in the Doodhganga catchment remains inadequately studied, with limited data available to guide sustainable water resource management.

This study evaluates groundwater quality in the Doodhganga catchment by analyzing key physico-chemical parameters such as pH, EC, TDS, bicarbonates, sulfates, nitrates, and hardness. These parameters are assessed against national (ISI) and international (WHO) standards to determine their suitability for irrigation. Additionally, indices such as RSC, KR, and PI are calculated to assess the implications of groundwater quality on soil health and crop productivity. By addressing these aspects, the study aims to provide a comprehensive understanding of groundwater quality and its potential to support sustainable agricultural practices in the Kashmir Valley.

MATERIALS AND METHODS

Study area

Doodhganga originates from the eastern slopes of the Pir Panjal mountain range in the Himalayas, beneath the Tatakuti peak at an elevation of approximately 4500 meters above mean sea level. The stream is fed by various sources, including snowfields, springs, and small lakes. It serves as an essential water source for the residents of the Budgam and Srinagar districts. Doodhganga catchment of Kashmir Valley (Fig. 1), located in the northern part of India between 33°42′ to 34°50′ N and 74°24′ to 74°54′ E, covers an area of 655 km². The area supports a varied topography exhibiting altitudinal extremes of 1557 to 4663 m above mean sea level. Water is fed to this stream by variety of sources such as snow fields, springs and small lakes (Iqbal and Sajjad, 2014). The stream is important source of water for residents of district Budgam and Srinagar (Hussain, 2011).

Sampling and Analysis

During the years 2022 and 2023, a total of 66 groundwater samples were collected from tube wells, bore wells, and springs across various locations within the study area for a comprehensive physio-chemical analysis. To ensure the accuracy of the results, clean 50 ml HDPE sample bottles were employed, which were pre-rinsed with the groundwater samples prior to collection. Samples were drawn after ten minutes of pumping from the wells to obtain water that accurately represented the quality of the source.

Once the samples were collected, they were carefully sealed, labelled, and key parameters such as pH, temperature, electrical conductivity (EC), and total dissolved solids (TDS) were measured on-site using portable EC and pH meters. Using standard methods (APHA, 1998) the samples were

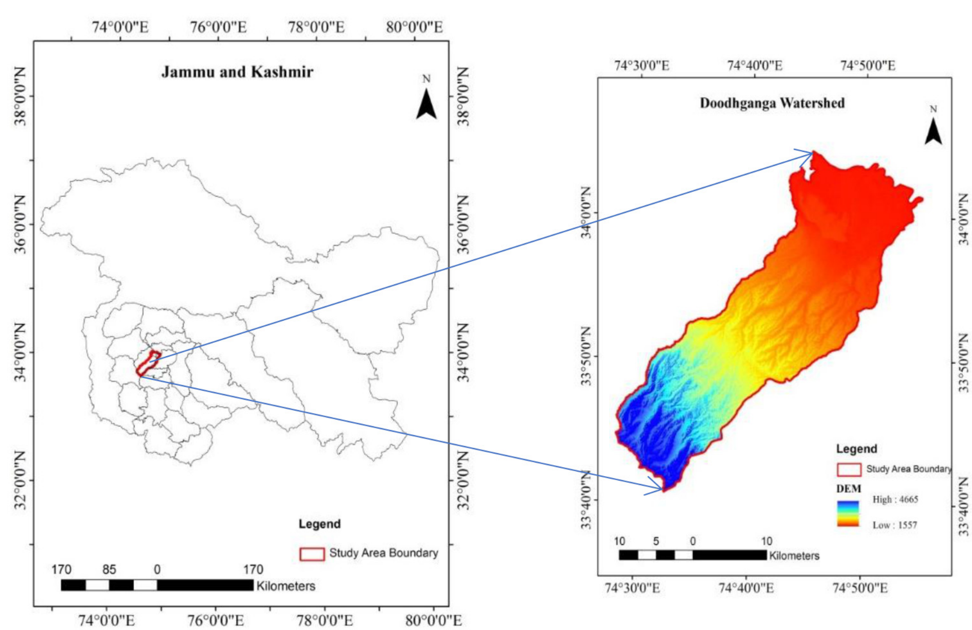

Fig. 1. Location map of Doodhganga watershed

filtered through 0.45 µm membranes and collected in acid-washed, thoroughly rinsed polyethylene bottles. For the analysis of major cations, the filtered samples were acidified with 1% v/v HNO_3, while the filtered, unacidified samples were reserved for anion analysis. The major cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and anions (Cl^{-}, SO_4^{2-}, and NO_3^{-}) were analyzed using ion chromatography at the National Institute of Hydrology (NIH) in Roorkee (ICS 5000). This method ensured a precise and reliable determination of the ion concentrations in the groundwater samples. HCO_3^{-} was determined by titration of the water sample against HCl (0.01N) in which methyl orange was used as an indicator. During the analytical procedures, blanks and standards were used to verify the reliability of the adopted methods. For most of the groundwater samples, the total cation charge ($TZ^{+} = Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}$, in meq/L) closely matches the total anion charge ($TZ^{-} = HCO_3^{-} + Cl^{-} + SO_4^{2-} + NO_3^{-} + F^{-}$, in meq/L) within the limits of analytical uncertainties. The normalized inorganic charge balance (NICB), calculated as: $NICB=(TZ^{+}-TZ^{-})/TZ^{+}\times100\%$ is found to be within ±5%.

Groundwater quality assessment indices for evaluating irrigation suitability

Determination of Residual sodium content (RSC)

Residual Sodium Carbonate (RSC) is also one of the most important parameters for evaluating irrigation water quality and was used in this study to assess its impact on soil structure and suitability for sustainable agriculture and was calculated using the standard formula (Eaton,1950). Irrigation water was then classified based on RSC values according to the USSL (Richards, 1954). Water with RSC values below 1.25 meq/L was categorized as safe for agricultural use, water with RSC values between 1.25 and 2.5 meq/L was deemed unsuitable for irrigation, and water with RSC values greater than 2.5 meq/L was classified as harmful for plant growth.

Determination of Kelly's Ratio (KR)

Kelly's Ratio was also used in this study to assess irrigation water quality by evaluating the ratio of sodium to calcium and magnesium. This parameter helped identify potential sodium hazards and its impact on soil structure and crop productivity. Kelley (1940) and Paliwal (1967) introduced a key parameter for assessing irrigation water quality through the use of formula as follows

$$KR= \frac{Na^{+}}{Ca^{2+} + Mg^{2+}} *100 \qquad (2)$$

Where,

Na^{+} is the concentration of sodium in meq/L, Ca^{2+} is the concentration of calcium in meq/L, and Mg^{2+} is the concentration of magnesium in meq/L.

According to Kelly's classification (Kelly, 1957), water with a Kelly's Ratio (KR) of less than 1 is considered suitable for irrigation, while water with a KR greater than 1 is classified as unsuitable due to high sodium levels. Based on this criterion, groundwater in this study were classified to evaluate their irrigation suitability.

Determination of Permeability Index (PI)

The Permeability Index (PI), introduced by Doneen (1964), was used in this study to evaluate the suitability of both surface water and groundwater for irrigation. The PI assesses the impact of ion concentrations (Na^{+}, Ca^{2+}, Mg^{2+} and HCO_3^{-}) on soil permeability. Based on Doneen's classification, water was categorized into three groups: good (PI >75), fair (75 ≥ PI > 25), and poor (PI < 25). This analysis provided insights into the long-term suitability of surface and groundwater for maintaining soil structure and fertility in agricultural applications. The PI was calculated using the following formula

$$PI = \frac{(Na^{+} + \sqrt{HCO_3^{-}})}{(Ca^{2+} + Mg^{2+} + Na^{+})} *100 \qquad (3)$$

All concentration of ions is expressed in meq/l.

Calculation for the Total Hardness

Water hardness, primarily driven by concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}), is a critical factor in evaluating water's applicability in industrial, domestic, and agricultural contexts. Hard water is often associated with increased detergent consumption and scaling in heating equipment, leading to inefficiencies and higher operational costs. While hardness lacks direct adverse health impacts, its correlation with cardiovascular conditions has been a subject of scientific investigation (WHO, 2017).

Hardness in this study was calculated using the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, expressed in milligrams per liter (mg/L). The total hardness (TH), expressed as calcium carbonate ($CaCO_3$), was determined using the formula (Sawyer and McCarty, 1967):

$$TH \text{ (mg/L as } CaCO_3) = 2.5 \times [Ca^{2+} \text{ (mg/L)}] + 4.1 \times [Mg^{2+} \text{ (mg/L)}]$$

Where,

Ca^{2+} = Concentration of calcium ions in mg/L and Mg^{2+} = Concentration of magnesium ions in mg/L.

The constants 2.5 and 4.1 are conversion factors based on the molecular weights of calcium and magnesium and their equivalent weights in terms of calcium carbonate ($CaCO_3$).

RESULTS AND DISCUSSION

Water quality assessment

The physico-chemical parameters of groundwater in the Doodhganga catchment area, as summarized in Table 1, reveal critical insights into its quality and potential applications. To further assess the groundwater's potability, we compared major ion concentrations against WHO (2006) and ISI (1993) standards as shown in Table 1. All tested chemical parameters, including calcium, magnesium, nitrate, and chloride, conformed to acceptable limits, confirming the groundwater's suitability for domestic and agricultural use. The pH values ranged from 7.0 to 8.4, with an average of 7.71, positioning the water in a slightly acidic to slightly alkaline range. This alkalinity is attributed to the dissolution of carbonate and bicarbonate minerals prevalent in the region's carbonate-rich lithology (Jiang YongJun *et al*., 2006). Such pH stability supports the water's suitability for both domestic consumption and irrigation, as values align with WHO and ISI permissible limits (6.5 - 8.5). Minor fluctuations in pH could be indicative of localized geological interactions or minor anthropogenic influences.

Electrical Conductivity (EC) values varied from 157 μS/cm to 789 μS/cm, with a mean of 508.42 μS/cm. This slight exceedance suggests a localized increase in dissolved ions, from the upland areas by rainwater and leaching of dissolved solids from effluents through the alluvial deposits (Ravindra and Garg, 2007). Although there is no specific WHO guideline for EC, ISI suggests a desirable limit of 750 μS/cm. Higher EC values can indicate increased salinity, which may affect soil structure and plant growth, but the majority of samples here remain within acceptable limits. EC levels, closely associated with Total Dissolved Solids (TDS), which ranged from 81 to 396 mg/L (mean: 251.79 mg/L), suggest a predominantly "fresh water" category, as per Freeze and Cherry's classification (1979). None of the groundwater samples exceeded the 1000 mg/L threshold required to classify water as

Table 1. Summary statistics of major ion concentrations of the analyzed groundwater samples.

Parameters	Measured Range	Mean	Minimum	Maximum	Standard Deviation	WHO Standards (mg/L)	ISI Standards (mg/L)
pH	7.5 - 8.4	7.7109375	7	8.4	0.287913781	6.5 - 8.5	6.5 - 8.5
EC	157-789	508.421875	157	789	141.4701499	No specific guideline	750 μS/cm (Desirable)
T	6.1-19.8	12.3875	6.1	19.8	3.068503591	-	-
TDS	77 - 275	251.7903125	81	396	71.41813342	<1000	<500
Total Hardness	8.7948-286.8827	179.5584135	8.7948	286.8827	70.86911433	200 (Desirable)	300 (Acceptable)
CO_3^{2-} (mg/L)	0.116322542-0.32556449	0.187328808	0.116322542	0.32556449	0.043294523	-	-
HCO_3^- (mg/L)	7.9-321.756	197.5692031	7.9	321.756	76.16376706	-	-
SO_4^{2-} (mg/L)	0.419-33.124	12.77500359	0.419	33.124	8.48018891	250	200
NO_3^- (mg/L)	0.212-50.235	10.63852563	0.212	50.235	11.60133572	50	45
NO_2^- (mg/L)	0-1.935	0.3369375	0	1.935	0.550692144		
Cl^- (mg/L)	0.574-38.224	13.73986063	0.574	38.224	12.0767978	250	250
Ca^{2+} (mg/L)	2.652-96.021	56.37841875	2.652	96.021	23.31146294	75	75
K^+ (mg/L)	0-9.088	1.855797656	0	9.088	1.961656044	12	12
Mg^{2+} (mg/L)	0.005-28.3012	9.435452813	0.005	28.3012	6.67895577	<30	30
Na^+ (mg/L)	0.321-30.4705	10.79972953	0.321	30.4705	6.412262087	200	200
NH_4^+ (mg/L)	0-2.136	0.264860313	0	2.136	0.427901402	1.5	0.5
Li (mg/L)	0-0.31172	0.01049875	0	0.31172	0.042567347	-	-
F (mg/L)	0-0.289	0.087118844	0	0.289	0.060612929	1.5	1

"brackish." Maintaining TDS within this limit is crucial, particularly for irrigation, as high salinity levels can impede soil structure and osmotic balance, adversely affecting plant health and crop yield. These findings underscore the groundwater's suitability for agricultural use.

TDS values ranged from 77 to 275 mg/L, with a mean of 251.79 mg/L. This falls within the WHO guideline (<1000 mg/L) and ISI desirable standard (<500 mg/L), indicating "fresh water". Building further upon the TDS classification by Davis and De Wiest (1966), all samples fall within the "desirable" category (<500 mg/L), reinforcing the water's favorable quality. The absence of high TDS levels also minimizes potential risks of soil salinization and ensures environmental sustainability. Consequently, the water is deemed suitable for both irrigation and domestic consumption, with quality controls ensuring it remains within the fresh water range to safeguard soil and crop health.

The groundwater temperature ranged from 6.1°C to 19.8°C, with a mean of 12.39°C, indicating an alignment with ambient conditions. While there are no specific WHO or ISI standards for water temperature, maintaining moderate temperatures is essential. Seasonal and depth variations may influence these temperatures, which are critical as elevated temperatures can enhance microbial activity, potentially altering water chemistry.

Hardness assessment

The analysis of total hardness (TH) in the groundwater samples provides critical insights into the water's quality and its suitability for various applications (Table 2). Hardness in water is primarily caused by the presence of dissolved calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, which are naturally derived from the dissolution of carbonate, bicarbonate, and sulfate minerals in the surrounding geology. Variability in TH levels across the study area reflects the heterogeneity in lithology, groundwater flow paths, and residence time, which influence the dissolution and accumulation of these minerals.

Table 2. Showing water hardness classes (Sawyer and McCarthy, 1967)

Category	Total hardness (TH) as $CaCO_3$	Total no. of samples
Soft Water	< 75 mg/L	5
Moderately Hard Water	75–150 mg/L	9
Hard Water	150–300mg/L	52
Very Hard Water	> 300 mg/L	-

The classification of 7.6% of the samples as soft water (TH < 75 mg/L) indicates limited mineral content, likely attributed to rapid recharge or shorter groundwater residence times in areas with less soluble lithological formations. Such water is ideal for domestic and industrial applications, as it poses minimal risks of scaling in pipelines, boilers, and other water systems. However, soft water may sometimes lack essential minerals required for certain agricultural and dietary needs.

Moderately hard water (13.6% of the samples, TH 75–150 mg/L) represents acceptable levels of hardness that are generally suitable for most uses, though some minor scaling could occur in domestic and industrial systems. This category highlights areas where groundwater quality is intermediate, benefiting from a balance of mineral dissolution and dilution processes.

The dominance of hard water (78.8% of the samples, TH 150–300 mg/L) underscores the significant influence of geological factors in the study area. Prolonged contact between groundwater and carbonate-rich rocks or other mineral-bearing formations leads to higher levels of dissolved calcium and magnesium (Qian *et al.*, 2024). Hard water, while not harmful to health, can pose challenges for domestic, industrial, and agricultural use. Scaling in pipes, reduced efficiency of water heaters, and the need for increased detergent usage are common issues associated with hard water. For irrigation, hard water may increase soil salinity and alkalinity over time, potentially affecting soil structure and crop productivity if not managed appropriately.

Advanced analysis of major ions and suitability for irrigation

An analysis of major ions, including Carbonate (CO_3^{2-}), bicarbonates (HCO_3^-), sulfates (SO_4^{2-}), and nitrates (NO_3^-), Nitrite (NO_2^-), Chloride (Cl^-), Calcium (Ca^{2+}), Potassium (K^+), Magnesium (Mg^{2+}), Sodium (Na^+), Ammonium (NH_4^+), Lithium (Li) and Fluoride (F^-) provides further insight into groundwater chemistry (Table 1). CO_3^{2-} concentrations ranged from 0.12 to 0.33 mg/L, with an average of 0.19 mg/L. No specific WHO or ISI limits are provided for carbonate, but high carbonate levels could contribute to soil alkalinity if used for irrigation over time. However, the low values observed suggest minimal impact on soil quality. HCO_3^- levels, ranged from 7.9 to 321.8 mg/L, with a mean of 197.57 mg/L, ensuring minimal risk of soil alkalinity issues. This is likely due to balanced hydrogeochemical conditions in the Doodhganga catchment, where natural buffering processes and the interaction of groundwater with carbonate-rich rocks effectively regulate bicarbonate levels, maintaining soil pH and nutrient availability. Although no specific limits for bicarbonate are provided by WHO (2006) or ISI (1993), elevated bicarbonate concentrations could potentially lead to soil alkalinity issues over prolonged irrigation use, affecting soil pH and nutrient availability. SO_4^{2-} concentrations varied from 0.42 to 33.12 mg/L, with an average of 12.78 mg/L. These levels are well within the WHO and ISI permissible limits (250 mg/L and 200 mg/L, respectively), indicating no significant risk to irrigation suitability. NO_3^- values ranged from 0.21 to 50.24 mg/L, with a mean of 10.64 mg/L. This is within the WHO standard (50 mg/L) and ISI limit (45 mg/L). Low nitrate levels are beneficial, as high concentrations can pose health risks and contribute to nitrogen leaching in agricultural settings. However, in some groundwater samples, the possible sources of elevated nitrates include intense leaching and surface runoff from agricultural fields, leakage from septic tanks, surface drains, and domestic sewage (Lone *et al*., 2021). NO_2^- levels were low, ranging from 0 to 1.94 mg/L, with an average of 0.34 mg/L. Although WHO and ISI do not set specific limits for nitrite, the low levels observed suggest minimal health and environmental risks. Cl^- levels ranged from 0.57 to 38.22 mg/L, averaging 13.74 mg/L, which is well within the WHO and ISI limit of 250 mg/L. Low chloride concentrations are favourable, as high levels can lead to soil salinization, affecting plant health and soil structure. Ca^{2+} concentrations varied from 2.65 to 96.02 mg/L, with a mean of 56.38 mg/L. The majority of groundwater samples remain within the WHO and ISI guideline of 75 mg/L, however, the upper limit exceeds this permissible threshold in certain locations. This elevated calcium concentration is likely attributed to the dissolution of carbonate and gypsum-bearing rocks prevalent in the region's geology (Barakat *et al*., 2018). Calcium is crucial for plant health, and these levels should be beneficial for irrigation purposes. K^+ levels ranged from 0 to 9.09 mg/L, with an average of 1.86 mg/L, within the WHO and ISI recommended limit of 12 mg/L. Potassium levels in this range support plant health without causing toxicity. Mg^{2+} values ranged from 0.005 to 28.30 mg/L, with a mean of 9.44 mg/L, which is below the ISI limit of 30 mg/L. This level is beneficial as magnesium is essential for plant growth and poses no risk at these concentrations. Na^+ concentrations ranged from 0.32 to 30.47 mg/L, with a mean of 10.80 mg/L, staying below the WHO and ISI limit of 200 mg/L. Low sodium is favorable for irrigation, as high sodium levels can cause soil structure degradation and reduce water infiltration. NH_4^+ values ranged from 0 to 2.14 mg/L, with a mean of 0.26 mg/L, exceeding the WHO and ISI limit suggesting possible localized contamination, as elevated ammonium levels can indicate the presence of organic pollution or agricultural runoff, sewage and animal waste pollution (Fahmi *et al*., 2023). Managing these elevated concentrations is essential to ensure the safety and potability of groundwater in affected areas. Li levels ranged from 0 to 0.31 mg/L, with a mean of 0.01 mg/L. Although there are no WHO or ISI guidelines, low lithium levels are generally safe and pose no immediate concern for agricultural irrigation. F^- concentrations were low, ranging from 0 to 0.29 mg/L, with an average of 0.09 mg/L, within the WHO and ISI limits of 1.5 mg/L. This low level of fluoride is suitable for agricultural irrigation, as it minimizes the risk of fluoride accumulation in soils.

Irrigation purposes

Groundwater quality assessment for irrigation is essential to ensure that the water meets the specific requirements needed for effective agricultural use. Critical parameters for evaluating irrigation water quality include pH, concentrations of specific ions such as sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and chloride (Cl^-) (Abdessattar *et al*., 2024). The interplay between water quality, soil characteristics, and cropping practices determines the suitability of irrigation and its potential impact on agricultural productivity. High levels of dissolved ions can affect plants and soils physically by reducing osmotic pressure within plant cells, limiting water uptake to branches and leaves, and chemically by disrupting plant metabolic processes.

Key irrigation water quality concerns include salinity, chlorinity, and alkalinity, which influence both soil structure and crop yield. High salinity, for instance, can degrade soil structure, while pH levels affect nutrient availability and microbial activity within the soil (Al-Aizari *et al*., 2024). Research underscores the importance of regular monitoring to ensure sustainable irrigation practices, especially in regions where water scarcity and quality degradation are prevalent.

In the Kashmir Valley, agriculture, horticulture, and allied sectors such as sericulture depend heavily on water availability. The region uses traditional systems like the Zamaindari kuhl network locally constructed canals to distribute water to fields. Additionally, the government has developed irrigation projects along the River Doodhganga and its tributaries, utilizing lift, diversion, and storage schemes to reach upland Karewas and other water-scarce areas. The effectiveness of these irrigation systems, however, relies on maintaining high water quality. Poor-quality irrigation water risks introducing excess harmful elements into the soil, which can reduce soil fertility and hinder crop productivity.

To evaluate irrigation suitability comprehensively, various indices and parameters were applied, including:

Residual Sodium Carbonate (RSC): Used to assess the carbonate and bicarbonate concent-ration's impact on water suitability. High RSC values indicate potential soil alkalinity issues, which can reduce soil permeability and hinder plant growth.

Kelley's Index (KI): An indicator that compares sodium to calcium and magnesium concentrations. KI values below 1 indicate suitable water for irrigation, as low sodium levels relative to calcium and magnesium prevent soil structure degradation.

Permeability Index (PI): This parameter evaluates the effects of water on soil permeability. Suitable irrigation water should support soil permeability and water infiltration, which are essential for root development and nutrient absorption.

These parameters provide a detailed understanding of water's impact on soil health and crop productivity, supporting informed decisions for sustainable agricultural practices in the Kashmir Valley.

Residual sodium content (RSC)

Residual sodium carbonate serves as an indicator for assessing the bicarbonate hazard, as the concentration of bicarbonate and carbonate determines the suitability of water for irrigation (McLean *et al*., 2000). When the concentration of carbonates and bicarbonates surpasses that of calcium and magnesium, it can lead to the complete precipitation of calcium and magnesium. This is detrimental to soil properties, as bicarbonates and carbonates cause the dissolution of organic matter, leaving a black residue on the soil surface once dried.

The hydrochemical analysis of groundwater in the study area revealed that all samples fell within the "suitable" category based on Residual Sodium Carbonate (RSC) values, with RSC levels below 1.25 meq/L (Fig.2). This indicates that 100% of the groundwater samples are appropriate for irrigation use. No samples were classified as "marginally unsuitable" (RSC: 1.25–2.5 meq/L) or "very harmful" (RSC > 2.5 meq/L), highlighting the absence of significant risks associated with RSC in the groundwater of the study area. Understanding

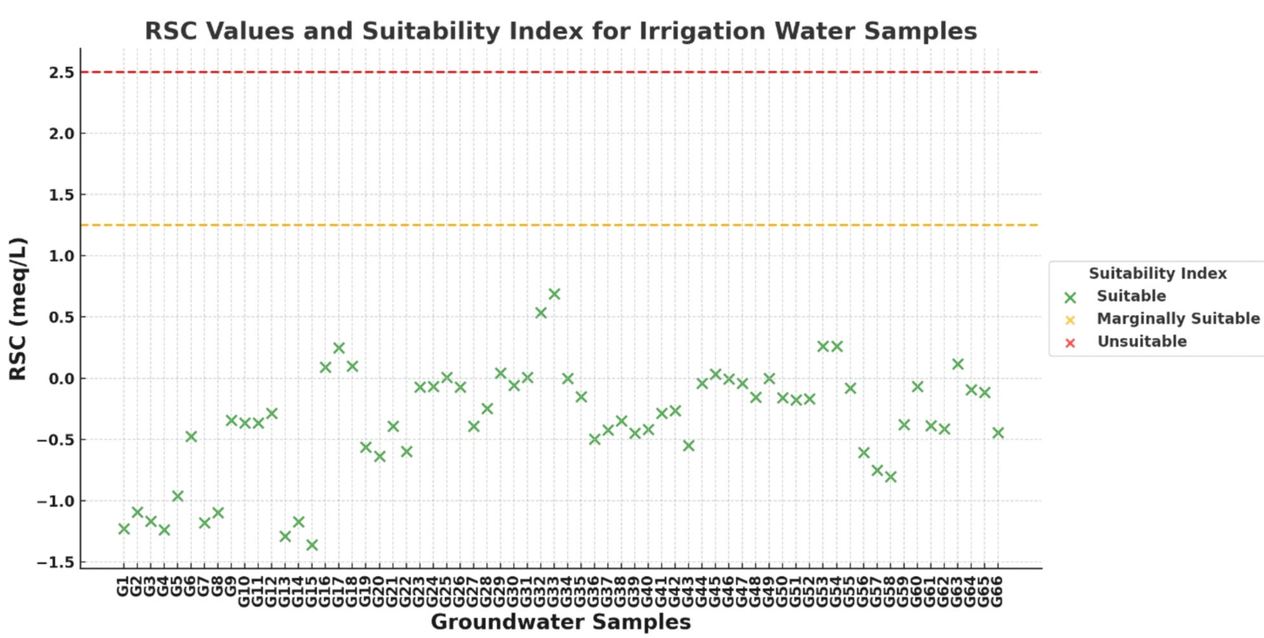

Fig. 2. Distribution of groundwater samples based on Residual Sodium Carbonate (RSC) values and irrigation suitability

RSC distribution is essential for assessing the suitability of water for irrigation, as elevated RSC levels can reduce soil productivity over time. Most of the samples have negative RSC values, indicating that the concentration of calcium and magnesium is higher than that of bicarbonate and carbonate, which is due to the alkaline earth exceeding the concentration of carbonates in the groundwater (Al-Aizari *et al*., 2024). This suggests that the water is safe for irrigation. A few samples have positive RSC values, but they are still below 1.25 meq/L, which is within the safe range. These favorable conditions can be attributed to several hydrogeological and environmental factors in the Doodhganga watershed. The interaction of groundwater with carbonate-rich rocks, such as limestone and dolomite, contributes to the presence of bicarbonates and carbonates. However, natural buffering mechanisms effectively regulate the dissolution process, preventing excessive accumulation of these ions. Additionally, groundwater benefits from natural filtration through sediments and rock formations, maintaining balanced ion concentrations and ensuring water quality. Similar results were observed by Mir and Jeelani, (2015); Saha *et al*. (2019); Yadav *et al*. (2024) who also reported that groundwater with negative and low RSC values is highly suitable for irrigation, with minimal risks of bicarbonate-induced soil sodicity. These findings confirm the excellent quality of groundwater in the study area, ensuring its suitability for sustainable agricultural practices without additional management interventions.

Kelley's Ratio (KR)

Kelly's ratio (KR) was used in the research region is a critical metric in evaluating irrigation water quality, particularly in agricultural contexts by analyzing the balance of sodium and calcium in water samples. The hydrochemical analysis of groundwater in the study area based on KR values indicates that all samples fall within the "suitable" category, with KR values less than 1 as illustrated in Fig. 3. This demonstrates that 100% of the groundwater samples are appropriate for irrigation purposes, reducing the risk of soil structure degradation. No samples were found to exceed a KR value of 1, which would classify them as "unsuitable," further confirming the irrigation suitability of the groundwater in the study area.. This balanced ionic composition of groundwater is likely a result of favorable aquifer mineralogy and effective recharge conditions, which prevent sodium accumulation. Recent studies, such as those by Mir and Jeelani (2015) and Moges and Dinka (2023) further highlight the role of balanced cation ratios in ensuring irrigation suitability and long-term soil fertility.

Permeability Index (PI)

The Permeability Index (PI) analysis for groundwater in the Doodhganga watershed confirms their overall suitability for irrigation, ensuring excellent soil permeability and productivity.

Of the 66 samples analyzed, 65 samples (98.48%) fall within Class I (PI > 75%), indicating

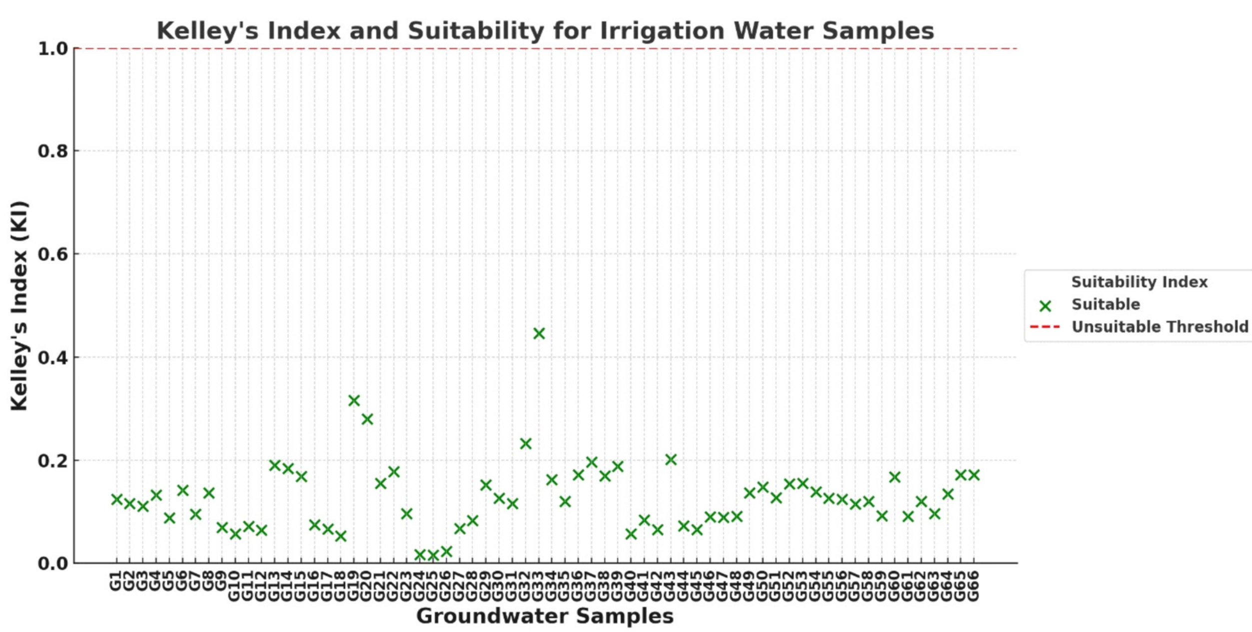

Fig. 3. Distribution of groundwater samples based on Kelley's Index for irrigation suitability

Table 3. Classification of groundwater samples based on Permeability Index (PI) for irrigation suitability

Class	Quality Category	Range of PI	No. of Samples	%age of Samples
Class I	Suitable	> 75%	65	98.48%
Class II	Marginally suitable	25% ≤ PI ≤ 75%	1	1.51%
Class III	Unsuitable	< 25%	-	-

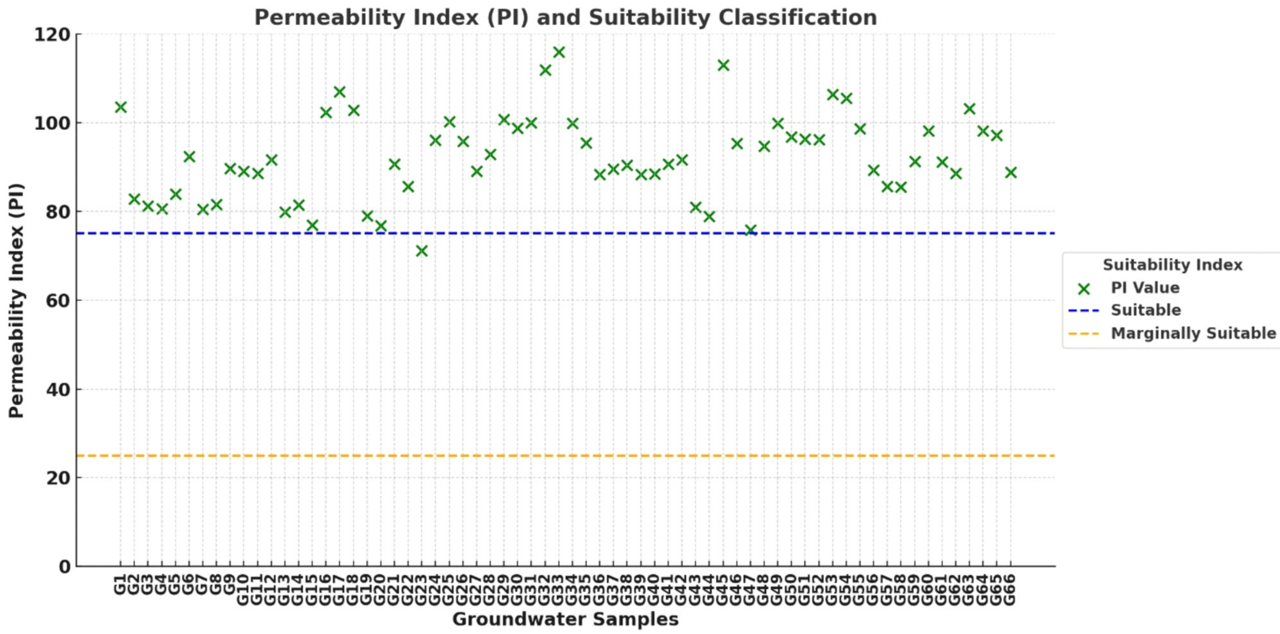

Fig. 4. Permeability Index (PI) of Groundwater Samples and Suitability for Irrigation

suitability for irrigation, as shown in Table 3 and illustrated in Fig. 4. One sample (1.51%) falls into Class II (25% ≤ PI ≤ 75%), categorized as marginally suitable for irrigation, likely due to localized variations in sodium or bicarbonate concentrations due to geological or anthropogenic activities. No groundwater samples fall into Class III (PI < 25%), indicating the overall high quality of groundwater for agricultural purposes in the study area.

Similar findings have been reported in previous studies, supporting the results of this analysis. Al-Aizari *et al.* (2024) found that most groundwater samples in their study area were suitable for irrigation-based PI values. Furthermore, Kouser *et al.* (2022) assessed groundwater quality in the Kathua region of Jammu and Kashmir and concluded that the majority of the samples analyzed were suitable for irrigation, consistent with the results presented in this study. These studies collectively affirm the suitability of groundwater for irrigation in various regions, corroborating the findings for the Doodhganga catchment.

CONCLUSION

This study comprehensively evaluated groundwater quality in the Doodhganga catchment, confirming its overall suitability for domestic consumption and agricultural irrigation. The physico-chemical analysis revealed that key parameters such as pH, TDS, and major ion concentrations fall within permissible limits set by WHO and ISI standards. The groundwater is classified as "freshwater," with low salinity and manageable hardness levels, making it ideal for sustaining soil health and crop productivity.

Indices such as Residual Sodium Carbonate (RSC), Kelley's Ratio (KR), and Permeability Index (PI) further validated the irrigation suitability of the groundwater, with no significant risks of salinity or sodicity observed. These findings underscore the high quality of groundwater in the region, supporting sustainable agricultural practices. Regular monitoring and effective groundwater management are recommended to maintain these standards, considering potential challenges from climate change and land-use dynamics.

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