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An Appraisal of Groundwater Chemistry, Quality and Its Assessment from Simlapal Block, Bankura District, West Bengal for Domestic and Agricultural Purposes

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Abstract:

Seventeen groundwater samples have been taken up from different locations within the Simlapal Block, Bankura district, West Bengal. These samples underwent analysis for several physical parameters, (pH, TDS, EC, and TH). Chemical analysis measured the concentrations of Ca, Mg, Na, K, SO_4, Cl, and HCO_3 ions. The results for all these parameters were then compared against water quality standards established by BIS and WHO.

The results indicated that the water samples are fresh**,** low conductivity and a neutral to weakly alkaline**.** The Piper diagram suggests Ca-HCO_3^- type chemical character and about 55% fall within the bicarbonate or fresh water zone. Besides this general classification, the Water Quality Index indicates that majority of the samples are "not suitable" for consumption due to the presence of very high to high levels of iron content in the water

The Gibbs diagram indicates that primary cations in the groundwater are calcium and magnesium, while the main anions are bicarbonate, chloride and sulfate**.** These findings strongly suggest rock weathering as the predominant natural mechanism controlling the groundwater's chemical composition.

From Schoeller diagram the trends of Ca>Mg>Na>K and HCO_3>Cl>SO_4>with total Fe>F (for mg/L) and Mg>Ca>Na>K and Cl>HCO_3>SO_4>F (for meq/L) have been established. Positive correlations found between F^- with pH and HCO_3^- , while showing negative pattern with Ca^{2+} suggesting fluoride bearing minerals are being dissolved in groundwater. Besides these, a good positive correlation between pH and HCO_3^- suggests an alkaline condition prevailing in the groundwater caused dissolution of mineral.

Keywords: Water chemistry, Groundwater quality, Water Quality Index (WQI), Gibbs' diagram and Schoeller diagram, Simlapal Block, Bankura district.

1. Introduction

Groundwater serves as an important freshwater source which meets a variety of human requirements globally amongst various types of available water. Approximately 43% of water which is being used for irrigation in agriculture globally is provided by groundwater [1] (Siebert et al. 2010). It also serves as a substantial resource for household chores, particularly as a potable water source, in many locations [2-5] (Zhang et al. 2021; Ram et al. 2021; Omonona and Okogbue 2021; Kawo and Karuppannan 2018). Groundwater forms to be an essential environmental component to various life forms. It serves as an important part in socioeconomic expansion of inhabitants [6] (Park 1997). Our life quality is also dependent with the quality of water used for meeting our drinking purposes [7 – 10] (Ali et al. 2022; Takdastan et al. 2018; Shams et al. 2012; Faraji et al. 2014). It is also acting as an important strategic resource for preserving ecological balance and fostering socioeconomic growth [11] (Meng et al. 2024). Groundwater happens to be the biggest representative of freshwater and forms an important component for whole livelihood around the globe [12-14] (Li et al.2021, Gleeson et al. 2020, Shekhar and Pandey 2015). But, owing to rapid increase of inhabitants, irrigational practices coupled with socio-developmental activities, it has become utmost essential for its sustainable utilization [12,15-17] (Li et al.2021, Morsy et al. 2018, Sun et al. 2016, Datta 2005). The main consequences of this are (i) the rapid declining of water tables [18,19] (Mays 2013, Reddy 1989) and (ii) deterioration of the water quality owing to unscientific disposal of anthropogenic waste along with increasing use of fertilizers [20-23] (Alao et al.2023, Srivastav 2020, Sinha Ray and Elango 2019, Vasanthi et al.2008) . The declining water level directly controls the water availability in one hand while on the other hand, the quality deterioration bears a distinct influence on our health as well as agricultural practices [12, 24-27] (Li et al. 2021, Baloch et al. 2021, Meena et al. 2020, Bagher and Rahnama 2010, Hildebrandt et al. 2008). The characteristics of groundwater primarily relies on the interactions between hydrogeological and anthropogenic activities which makes it susceptible to various geological and human induced contaminants [28 – 31] (Zhu et al. 2020, Li et al. 2018, Khatri and Tyagi 2015, Huang et al. 2014). Groundwater becomes unsuitable to be used for both agricultural and drink with increasing levels of such contaminants. A good number of studies have been reported globally over such adverse implications of using deteriorated groundwater on health and irrigational practices [12, 32 – 34] (Karunanidhi et al.2021, Li et al.2016; 2021, Srivastav 2020, Ahada and Suthar 2018) Therefore understanding and assessing the quality of groundwater has become inevitable for safeguarding the avoiding waterborne diseases and promoting sustainable agriculture.

The present study area has no commercial industries, wherefrom contaminated effluents can pollute the groundwater, but the partial use of chemical fertilizers, improper sewage disposal or geo-genic contaminants might be accountable for quality deterioration of groundwater. Present study is aimed for (a) delineating the groundwater chemistry of the study area (b) understanding the dominant activity governing the groundwater quality and (c) determining the suitability of this water to be used for agriculture and domestic uses [16,18,19,35] (Abbasnia et al. 2018, Sun et al. 2016, Mays 2013, Reddy 1989).

A popular way of evaluation of groundwater quality of is to compare each important parameter with the standard limits for drinking water. The variation which is noticed in groundwater causing chemical alteration as well as the physical characteristics owing to the minerals might have severe effects on quality of groundwater and its aesthetic value [36] (Rajmohan and Elango 2004).

Different methods like fuzzy comprehensive, the health risk weighting model (HRWM) and the ground water quality index (GWQI) are being used by researchers extensively in this context. International researchers have utilized the water quality index (WQI) more frequently than other approaches because of its ease of calculation, usefulness, and range of applications [37] (Zhai et al. 2022).

In GWQI, a mathematical formula is followed to measure the groundwater quality in various places throughout the world. The GWQI is a concept which is useful to evaluate the groundwater characteristics in several global areas [38 -40] (Dash and Kalamdhad 2021, Talpur et al. 2020, Zhang et al. 2018). It forms a crucial criterion for decision-makers to select the most effective approach for pre-remediation goals. It has consequently emerged as a key element in the assessment of water characteristics [41 – 46] (Baloch et al. 2022, Kamruzzaman et al. 2020, Dilpazeer et al. 2023, Singh et al. 2012, Ramakrishnaiah et al .2009, Abbasnia et al. 2019).

Fluoride (F^-) is a vital micronutrient that plays a critical role in strengthening the apatite matrix found in human bones and teeth [47 – 48] (Wang et al. 2022, Maithani et al. 1998). But tooth enamel loses its shine as a result of consuming too much fluoride. Excessive intake of fluoride may cause degeneration of muscle fiber, diminishing hemoglobin levels and thirstiness. It is also responsible for with headache, skin rashes, nervousness, depression, etc. [49 – 50] (Gibert et al 2022, Ayoob.and Gupta 2006[).

For the past 20 years, the groundwater situation in West Bengal's Bankura district has been concerning due to fluoride poisoning. While the characteristics of the Simlapal Block's ground water have been examined and analyzed in a few earlier studies, the nature of aquifers and the geochemical constituents which determine its suitability for drinking purposes have not been thoroughly examined. Recent studies have focused on evaluating drinking water safety regarding fluoride levels, using the specific geochemical characteristics of the local groundwater to determine contamination risk [51,52] (Rudra and Khan 2018,2019).

The current study involved a systematic analysis of various water quality measures, including the determination of fluoride levels. The other parameters measured were temperature, pH, EC, TDS, Alkalinity, Na^+, K^+), Ca^{2+}, Mg^{2+}, e (Cl^-, SiO_2, HCO_3^-, CO_3^{2-}), Fe^{2+}, and SO_4^{2-}. In 2023, a survey was carried out for groundwater in areas affected by high fluoride levels, specifically exploring potential relationships between fluoride concentration and other various parameters within those regions.

The primary objectives established for this investigation, considering the features outlined previously, were:

1. To assess and determine the current level of contamination within the Simlapal Block of the Bankura district, West Bengal, India.
2. To evaluate the quality of the local groundwater by analyzing relevant water quality parameters and calculating the Water Quality Index (WQI).
3. To utilize statistical analysis methods to identify the specific factors that influences the release of various hydrochemical constituents into the groundwater and
4. To analyze and understand the correlations and relationships present between the different hydrochemical parameters.

2. MATERIALS AND METHODOLOGY

2.1 *Study Area*

Simlapal block is occurring within the Khatra sub-division of Bankura district, West Bengal (Figure 1). The block **is** situated in the south-eastern part of its district within a hard rock area, spans a latitudinal extent of 22° 51' N to 23° 00' N and a longitudinal extent of 86° 55' E to 87° 13' E. It covers approximately 310.15 sq.km in area with an average height of 78 m (256 ft). Taldangra block lies to the north of this block, the Sarenga block on the south, the Khatra block on the west while Garhbeta II block of the Paschim Medinipur district to the east.

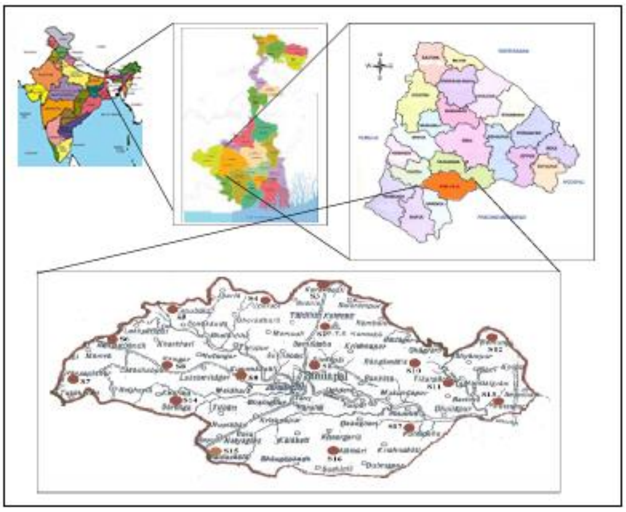


Figure 1: Map of the Study Area showing sampling locations

The Bankura district, which makes up 7.75% of the state of West Bengal, is separated into three topographical regions: i) an alluvial plain on the east side, where the Simlapal block is located; ii) a region with mountainous terrain on the west side; and iii) an undulating surface in the middle. Joypanda River and Shilabati cross the block. A large area of this block is covered by forest and marked as tribal habitation [53] (Mandal and Gupta 2016). The area's rural residents use groundwater-based tube wells for water as they have no other options.

2.2 *Climates*

The division undergoes humid and hot tropical climate. During middle of March the summer starts and it lasts until June. The area is characterized by intense heat with highs of 48°C. Rain precipitates from June to October due to winds carried by the south-west monsoon. Annual rainfall ranges between 1100 to 1400 mm. Aprroximately80 % of total annual rainfall takes place during this time. From November through February, there are dry, bitter winters with temperature lowering up to 4 to5°C.

2.3 *Geology and Soil Type*

Geographically the entire block is undulating. In contrast to the eastern portion, the western and southwestern regions are rougher. The area is characterized by elevated areas, ridges with frequently incised riverine network. The Archaean basement composed of granites, granitic gneiss, calc-granulites and biotite schist types of rocks. Flaggy shale, clay, and compact sandstone (Dubrajpur layers) of Lower Jurassic age are lying unconformably on top of it, followed by alluvium, lateritic gravel, and more recent laterites. Red coloured sandy and loamy soils, lateritic soils, and alluvial soils (both older and younger) are the main types of soil. Soil contains ferrugenous concretions called duricrusts [54 – 55] (Wang et al. 2023, NBSS and LUP 2016) (Fig. 2).

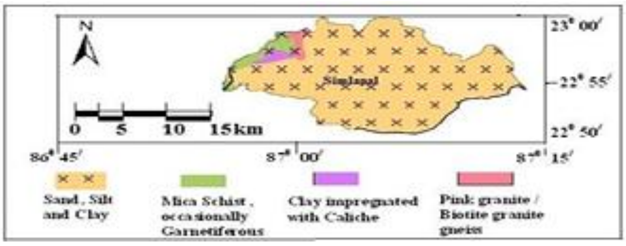


Figure 2. Map showing rock-types present in the Simlapal Block, Bankura District, West Bengal

2.4 *Sample Collection and Analysis*

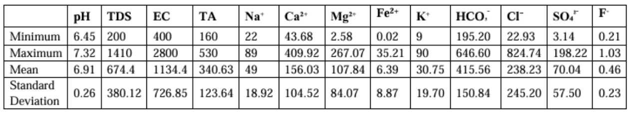
Seventeen (17) villages in the Block Simlapal, District Bankura in West Bengal, India, were chosen for this investigation and are shown in Fig. 1. The areas where from water samples have been collected were pre-determined so that the samples are well spread over the entire area. All these water samples, have been gathered following standard procedures (in previously sterilized Tarson-made polypropylene bottles). The bottles were kept in cold conditions (at or below 10 C). During the sample process, GPS readings were collected to capture exact geographic location of each sampling site.

The bottles were filled completely with water. Attention was given during sample collection to avoid any air trapped air bubble inside the bottle. Immediately after sample collection, all bottles have been then sealed with double plastic caps so that no evaporation can take place. While bringing these bottles to the laboratory with utmost cautions where chemical analyses for keeping the samples free from stirring. The samples were analysed as early as possible by employing standard methods [56-57] (APHA 1998, Das *et al*. 2016)

The summary statistics (minimum, maximum, mean and standard deviation for water samples is provided in Table-1. Analytical techniques used thrice for each collected water sample. The GPS (Garmin) was utilized to collect the geographical positions and elevations of the sample locations. The on-spot measurement of pH, TDS, EC, temperature and total alkalinity was performed using Portable Hanna Pen type pH, TDS-EC-TEMP meters and Aquasol Alkalinity test kit respectively. After that in laboratory, the parameters such as TA, TH, Ca, Cl and HCO_3 were determined by volumetric titration methods following Indian Standard (IS) analytical procedures. The concentrations of other parameters like Na, K and SO_4 were obtained by using flame photometer and UV-Spectrophotometer respectively. Concentration of Mg was estimated based on the equation 1.

$TH = 2.497\,(Ca^{+2}) + 4.118\,(Mg^{+2})$ … (1)

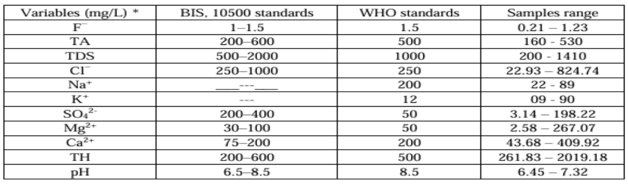
Table 1: Summarized values of collected samples showing Minimum, and Maximum values, Mean and Standard deviation. [Units: EC: µS/cm; All other parameters (except pH): mg/L]



	pH	TDS	EC	TA	Na^+	Ca^{2+}	Mg^{2+}	Fe^{2+}	K^+	HCO_3^-	Cl^-	SO_4^{2-}	F^-
Minimum	6.45	200	400	160	22	43.68	2.58	0.02	9	195.20	22.93	3.14	0.21
Maximum	7.32	1410	2800	530	89	409.92	267.07	35.21	90	646.60	824.74	198.22	1.03
Mean	6.91	674.4	1134.4	340.63	49	156.03	107.84	6.39	30.75	415.56	238.23	70.04	0.46
Standard Deviation	0.26	380.12	726.85	123.64	18.92	104.52	84.07	8.87	19.70	150.84	245.20	57.50	0.23

All constituent concentrations are measured in milligrams per litre (mg/L), except for electrical conductivity (EC), which is reported in micro-Siemens per centimeter ($\mu S/cm$). To estimate the ion-balance error and verify the accuracy of the results, the measurements originally in milligrams per liter (mg/L) were converted into milliequivalents per liter (meq/L). The concentration ranges for all parameters were compared against the drinking water standards established by the Bureau of Indian Standards [58] (BIS 2012), and WHO as presented in Table-2.

Table 2: Comparison with the BIS,10500 and WHO drinking water guidelines. [TH: Total hardness; TA: Total alkalinity. pH: no units.]



Variables (mg/L) *	BIS, 10500 standards	WHO standards	Samples range
F^-	1–1.5	1.5	0.21 – 1.23
TA	200–600	500	160 - 530
TDS	500–2000	1000	200 - 1410
Cl^-	250–1000	250	22.93 – 824.74
Na^+	___---___	200	22 - 89
K^+	---	12	09 - 90
SO_4^{2-}	200–400	50	3.14 – 198.22
Mg^{2+}	30–100	50	2.58 – 267.07
Ca^{2+}	75–200	200	43.68 – 409.92
TH	200–600	500	261.83 – 2019.18
pH	6.5–8.5	8.5	6.45 – 7.32

Irrigational water quality was determined by using key chemical indicators like Sodium Adsorption Ratio (SAR), Soluble Sodium Percent (SSP), Magnesium Adsorption Ratio (MAR), Permeability Index (PI), and Kelly's Ratio (KR) to determine its suitability and potential hazards for crops and soil health, with these indices revealing different levels of good, permissible, or unsuitable water quality.

Irrigation water suitability was assessed using standard indices (SAR, SSP, MAR, PI and KR) to evaluate sodium, magnesium and permeability hazards followed by classifying the water's quality for agricultural use. The [59] Gibbs(1970) diagram has been used to determine the dominant mechanisms (like precipitation, rock-water interaction, or evaporation/crystallization) that control groundwater chemistry. The trilinear diagram proposed by Piper was used to identify the hydrochemical facies of the water samples.

2.5 *Quality control assurance*

Groundwater quality is being induced by geology of the underground reservoir, rock–water interactions, mineral dissipation and geochemical activity [60] (AI-Futaisi *et al*. 2007). The anthropogenic activities like discharge from industry, runoff from cultivated lands, infiltration of polluted water into the underground reservoir, are also the factors controlling differences in groundwater quality [61] (Jalali 2007). The evaluation of groundwater quality relies on these factors [62] (Pritchard 2008), that acts as the fundamental insights into the groundwater suitability for domestic life, crop production, and manufacturing processes**.**

To evaluate the dependability and contamination of data under analysis, quality control procedures were implemented. Every experimental procedure included careful sample collection and preservation for quality control considerations. Three replicate samples were used for each assay in order to ensure precision of analysis. All glassware has been cleaned thoroughly before use. Double-distilled, deionized water was used exclusively throughout the experiment. Standards (E-mark, AR grade) were used for preparing the standard curve concurrently with sample analysis. The experimental outcomes were improved by utilizing the mean values and standard deviation (SD) associated with each parameter

2.6 *Statistical analysis*

The objective quantitative framework for classifying groundwater is based on statistical analysis. This approach facilitates the grouping of various groundwater samples and helps establish correlations amongst the different chemical parameters measured within those samples [63 – 65] (Nag and Das 2017, Nagarajan et al. 2010, Liu et al.2003). Different types of statistical analysis methods are being used applied historically to investigate quality of water and elucidate natural geochemical processes [66 – 70] (Nag 2014, Nag and Ghosh 2013, Routroy et al. 2013, Nag and Lahiri 2012, Nelson and Ward 1981). The standard approaches for interpreting groundwater chemical quality—such as plotting different individual ions or pairs of ions—are limited because they cannot simultaneously define the similarities or dissimilarities across all ions or samples in a single representation.

3. GROUNDWATER CHARACTERISTICS

pH of all natural waters is primarily regulated by the equilibrium between dissolved carbon dioxide ((CO_2^{2-}), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) ions. This delicate buffering system is highly sensitive to changes in both temperature and pressure, which can significantly alter the balance and, consequently, the water's pH level [71] (Karanth 1987). The groundwater pH levels in the Simlapal block are within a healthy, balanced range. They measure in between 6.45 and 7.32, which suggests the nature of water to be neutral to weakly alkaline. The neutral pH observed for most of the wells throughout the study area indicates equilibrium between carbon-dioxide, carbonate and bicarbonate. The weakly alkaline pH observed for the wells are located near to the stream channels showing relatively greater concentration of CO_3 and HCO_3.

The measurement of EC gives us knowledge about the extent of groundwater mineralization [72] (Naudet et al. 2004). The electrical conductivity, directly proportional to the ion concentration and is indicative of TDS in water. EC of groundwater in the Simlapal block ranges between 400 - 2800µS/cm. The lower values of EC suggest lower content of mineral in groundwater. The different types of groundwater on the basis of EC have been given by Sarma and Swamy 1981[73] .The groundwater of Simlapal block has been classified as low conductive (< 500 µS/cm). In general, the lower electrical conductivity (EC) values are observed in wells situated at higher elevations, which form the watershed and sub-watershed divides. The relatively higher EC values observed in the lower reaches and areas with flat slope suggest inverse relation with altitude.

TDS is a measurement representing the collective concentration of all mineral salts, organic and other matters present in a certain volume of water, and is usually designated in milligrams per liter (mg/L) (Dahaan et al. 2016). TDS concentration in Simlapal block ranges between 200 ~ 1,410 mg/L, classifying them within the fresh water category. The primary cause of groundwater hardness is the presence of dissolved carbonates, chlorides, and sulphates, specifically those of calcium and magnesium [74,44] (Alfaifi et al. 2020, Singh et al. 2012). The admissible limit for Total Hardness (TH) as per BIS 2012 guidelines (IS 10500:2012), is a maximum of 200 ppm. TH of groundwater in Simlapal watershed ranges from 88 to 245 ppm and fall under permissible limit.

The ion exchange process helps Ca^{+2} to enter into groundwater through the dissolution of aquifer minerals, and exchange of sodium by calcium through [75] (Elango and Kannan 2007), leaching from soil and human induced fertilizers. The main sources of calcium in the groundwater in hard rock areas is weathering of silicate minerals such as plagioclase, pyroxene and amphibole [75] (Elango and Kannan 2007) . In Simlapal area, the occurrence of calcium in groundwater varies from 43.685 mg/L to 409.92 mg/L. The high amount of calcium in Simlapal block is caused by weathering of plagioclase.

The Mg^{+2} is significant constituent of igneous rocks such as dunite, pyroxenites, amphibolite and basalts. The chief minerals that release magnesium to the water are olivine, pyroxene, biotite, hornblende, serpentine and talc [71,75] (Elango and Kannan 2007, Karanth 1987). In the Simlapal block, the presence of magnesium ranges from 2.58 to 267.07mg/L, and is derived from altered amphibolite and biotite minerals.

The Na^+ in the groundwater is basically on account of dissolution of evaporite deposits through meteoric water, weathering of sodium bearing minerals like nepheline, sodalite, glaucophane, plagioclase feldspar. The use of surface water for irrigation can lead to the build-up of salts, including sodium, in the soil and, as a consequence, in the groundwater [76,77] (Saha et al 2019; Mostafa et al 2017). Sodium concentrations in the Simlapal block range between 22 and 89 mg/L, resulting from the weathering of plagioclase feldspars.

Potassium found in groundwater primarily originates from silicate minerals—such as microcline, orthoclase, leucite, nepheline and biotite—that occur naturally in country rocks, as well as from their presence in fertilizers used in agriculture. The congregation of potassium in groundwater of Simlapal block ranges between 9.0 ~ 90 mg/L. A high concentration of potassium in groundwater can indicate natural geological processes such as the weathering and decomposition of K-feldspar minerals, along with significant input from human (anthropogenic) activities.

The most abundant and significant anion in groundwater is HCO_3. It is due to the complex interactions occurring between atmosphere, lithosphere and hydrosphere (Karanth, 1987). It includes both the process of carbon dioxide dissolving in water and the subsequent chemical breakdown of rocks due to this saturated water [78,79] (Raymahashay 1986, Nikumbh 1997). The occurrence of HCO_3 in Simlapal block ranges between 195.2 ~ 646.6 mg/L

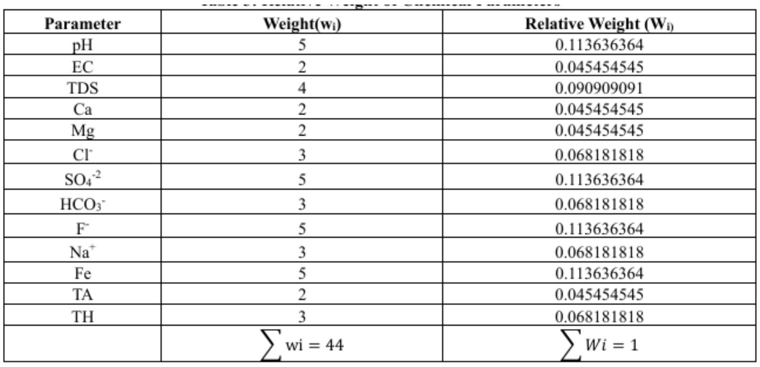
The chief sources of chloride are rainfall, chloride bearing minerals such as chlorapatite and sodalite, dry fallout in arid areas, artificial fertilizers and effluents from anthropogenic activities such as waste disposal or industries [71,79,80] (Nikumbh 1997, Hem 1992, Karanth 1987). The salinity ingression, halite solutions and presence of any evaporate minerals shows spike in the chloride content. The occurrence of unusually high amounts of chloride in groundwater is often considered a sign of contamination. The sources of this pollution can include the leaching of saline residues, sewage from the soil, and the salting of coconut trees [79,81] (Paulson et al. 1993, Nikumbh 1997). The content of chloride found in groundwater of the study area, which spans a broad range from 22.93 to 824.74 mg/L, is attributed *only* to either precipitation anthropogenic activities. This decision is drawn from the absence of any chloride minerals in the surrounding bedrock, which effectively rules out natural geological sources. Concentration of Sulfate in the Simlapal block groundwater ranges from 3.14 to 198.22mg/L, which is largely within the acceptable drinking water limits set by the Bureau of Indian Standards (200 mg/L). The abundance of sulfate (SO_4) within the groundwater is predominantly managed by equilibrium of several natural geochemical processes—including oxidation, reduction, precipitation, dissolution, and concentration—as water percolates through the aquifer. The main supply of sulphate in groundwater include naturally occurring sulphur minerals, the breakdown of sulphides of heavy metals found within igneous rocks and soil, and the use of artificial fertilizers [79, 80] (Nikumbh 1997, Hem 1992).

3.1 *Calculation of WQI of samples*

In order to synthesize complex water quality data into meaningful information, an effective role is played by Water Quality Index (WQI). It is a process of rating which represents the joint effect of various aspects on the overall water quality. The prime issue of WQI parameter is turning the data on quality of water into information that can be used by general people. Water quality is determined by several key parameters, (both physical and chemical) which includes pH, TDS, EC, TH, TA, Ca, Mg, HCO_3, sulfates (SO_4), Cl, Fe, Na, and F.

For calculating WQI, following three steps are considered. At the first step, a specific weight (w_i) has been designated for every 13 water quality criteria to reflect its contribution to the overall drinking quality of water (Table 3).

Table 3: Relative Weight of Chemical Parameters



Parameter	Weight(w_i)	Relative Weight (W_i)
pH	5	0.113636364
EC	2	0.045454545
TDS	4	0.090909091
Ca	2	0.045454545
Mg	2	0.045454545
Cl^-	3	0.068181818
SO_4^{-2}	5	0.113636364
HCO_3^-	3	0.068181818
F^-	5	0.113636364
Na^+	3	0.068181818
Fe	5	0.113636364
TA	2	0.045454545
TH	3	0.068181818
	$\sum wi = 44$	$\sum Wi = 1$

Parameters such as pH, fluoride, sulphate and iron are given a significant maximum value of five during water quality evaluation because they are crucial indicators of water safety and potability. Conversely, magnesium is only given a minimum weight of one, as it is considered less harmful to human health. In step two, the relative weight (Wi) is calculated following the below mentioned expression:

$W_i = \frac{wi}{\sum_{i=1}^{n} wi}$ ……. (2)

Where:

Wi = The calculated relative weight for a specific parameter.

wi = The initial, assigned weight of that specific parameter.

n = The total count of all parameters included in the calculation.

Essentially, the relative weight of a single parameter is found by dividing its assigned weight by the sum of all assigned weights across all parameters.

Table 3 illustrates the resulting Wi values that were calculated using this formula.

In the third stage, q_i a quality rating scale is evaluated for each constituents following the Bureau of Indian Standards (BIS) guidelines. This is achieved by taking the measurement of all parameters' concentration for the water sample, dividing it by its corresponding standard limit as defined by the Bureau of Indian Standards, and then multiplying the resulting value by 100.

This is written as follows:

$q_i = (C_i / S_i) \times 100$ ……. (3)

Where: qi = the quality rating scale for the i-th parameter

Ci = the concentration of the i-th parameter measured in the water sample

The Water Quality Index (WQI) calculation involves first determining the Sub-Index **Si** for each chemical parameter It is then used to derive the overall WQI using expressions 4 and 5

$SI_i = W_i \times q_i$ …… (4)

$WQI = \sum SI_i$ ……. (5)

The Water Quality Index (WQI) simplifies water assessment by combining scores for various parameters (where Si is the sub-index, qi is the quality rating, and n is total parameters) into a single value, allowing for easy classification into categories like "excellent," "good," "poor," etc., as detailed in Table 4, to quickly determine if water is potable.

Table 4. Water suitability classes according to different parameters showing sample numbers in different classes and their percentages

Parameters	Range	No. of Samples	Sample Nos.	Class	% of Samples
EC	<250	0	---------	Excellent	0
	250-750	5	3,5,9,10,12	Good	29.41
	750 - 2250	10	2,4,6,7,8,11,13,15,16,17	Permissible	58.82
	>2250	2	1,14	Unsuitable	11.76
TDS	<500	7	S3,S5,S6,S8,S11,S12,S13	Fresh water/desirable for drinking	41
	500-1000	6	S2,S4,S7,S15,S16,S17	Brackish water permissible for drinking	35
	1000-3000	4	S1,S9,S10,S14	Saline water/useful for irrigation	24
	>3000	0	--------	Brine water/unfit for irrigation and drinking	0
TH	0-60	0	--------	Soft	0
	61-120	0	--------	Moderately Hard	0
	121-180	0	--------	Hard	0
	>180	17	1 – 17	Very Hard	100
SAR	0 - 10	17	1 – 17	Excellent	100
	10 - 18	0	-----------	Good	0
	18 - 26	0	-----------	Permissible	0
	>26	0	-----------	Doubtful	0
SSP	< 20	11	1,2,4,5,7,9,13-17	Excellent	64.70
	20 - 40	6	3,6,8,10-12	Good	35.29
	40 - 60	0	----------	Permissible	0
	60 - 80	0	----------	Doubtful	0
	>80	0	----------	Unsuitable	0
MAR	< 50	7	2,6,8,11,14,16,17	Suitable	41.17
	>50	10	1,3,4,5,7,9,10,12,13,15	Unsuitable	58.82
PI	< 80	17	1 – 17	Good	100
	80 - 100	0	----------	Moderate	0
	100 - 120	0	---------	Poor	0
KR	< 1	17	1 – 17	Suitable	100
	>1	0	---------	Unsuitable	0
WQI	< 50	2	3,5	Excellent	11.76
	50 – 100	2	16,17	Good	11.76
	100 - 200	5	2,4,10,11,13	Poor	29.41
	200- 300	4	6,8,14,15	Very Poor	23.53
	>300	4	1,7,9,12	Unfit for Drinking	23.53

3.2 Groundwater suitability for Drinking purposes

The analysed values for water samples compared with the prescribed permissible limits specified in BIS 10500: 2012 (Table-2) guidelines for drinking water to determine its suitability for consumption.

Analytical values of those samples whose values are crossing the prescribed highest permissible limit is of utmost concern for drinking purposes. The comparison revealed that all samples of the Simlapal block for different physicochemical parameters are within desirable limit (Table 4). This indicates that the groundwater is pollutant free either coming from agriculturally based livelihoods or geo-genic components. Recent analyses indicate that the water samples in the Simlapal block are fulfilling the standards for potable water and are safe for drinking purposes.

3.2.1 Piper's Tri-linear Diagram

In order to have a better idea of the geochemical evolution of groundwater, several specialized graphical methods are utilized to visualize the principal dissolved ions for each sample. Among the key tools for water chemistry analysis are the Piper (1944) [82] trilinear, Schoeller (1965) [83], and Chadha (1999)[84] diagrams, crucial for visualizing groundwater types and relationships. These plots are instrumental tools in hydrogeology, as they allow for the effective categorization and comparison of various water types, while also facilitating the identification of the primary hydrogeochemical processes that influence the overall composition of the groundwater.

GW chart and Microsoft excel were used in preparing the diagrams. In a Piper diagram, the cations and anions are depicted in separate ternary plots that are then projected onto a central diamond plot. The apexes of the plots are specifically defined combinations of ions (Figure 3).

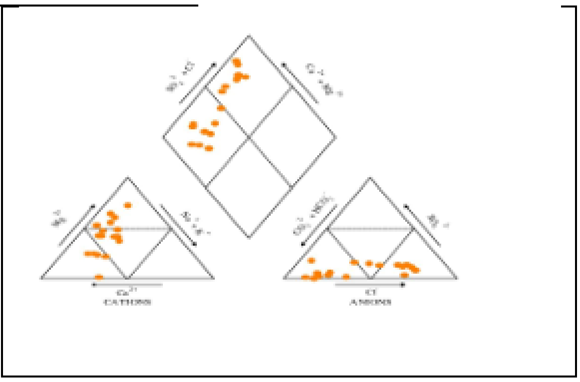


Figure 3. Groundwater samples plot in Piper Diagram at Simlapal block, Bankura District, West Bengal

To visually represent the geochemical facies of water samples using a Piper diagram, the relative concentrations of major cations and anions (typically in meq/L) are plotted to categorize samples based on their ionic composition. The resulting clustering of points within the diamond-shaped field determines the dominant water type (e.g., calcium-bicarbonate, sodium-chloride, or mixed types) prevailing in the investigated area. This in turn indicates the overall quality of water and hydrogeochemical evolution.

An assessment of the area's hydrogeochemical features indicates a clear division in water composition. Majority (55%) of samples, are classified as bicarbonate (HCO_3) or fresh water, while the remaining 45% are found within a silica (SiO_4) dominated zone. The chemistry of the groundwater is primarily controlled by the weathering of felsic granitic rocks. The interaction between the aquifer material and the groundwater is further enhanced by the region's semi-arid climate and low precipitation rates.

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3.2.2 Schoellar Diagram

A Schoeller diagram [82] (Schoeller 1965) is a semi-logarithmic chart used to visually represent the ionic composition of groundwater samples. This graphical method facilitates easier interpretation of which cations and/or anions have the highest or lowest average concentrations (Saka et al. 2013) [85]. Figure – 5 shows the plots of the abundance of key ions that determine the water's chemical character, including sulfate, bicarbonate, chloride, magnesium, calcium, sodium, and potassium.

The concentrations are typically written in milliequivalents per kilogram of solution (meq/kg). For each water sample, a distinctive profile line is created by connecting the data points for the seven ions across six uniformly spaced lines; this visualization allows for straightforward comparison of different samples and water types.

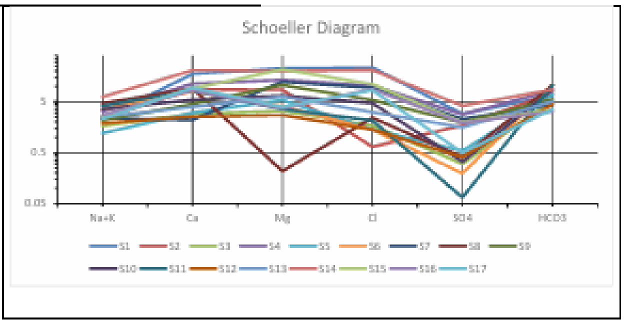


Figure 4. Schoeller diagram for Simlapal block, Bankura District, West Bengal

3.2.3 Chadha's Diagram

The Chadha’s (1999) [84] diagram helps visualize the hydrogeochemical evolution of the groundwater. This diagram serves as a useful tool for illustrating the progressive changes in the groundwater's chemical composition within the Simlapal block.

In this diagram (Figure 6), the abscissa (X-axis) plots the difference between alkaline earth metal cations (Ca + Mg) and alkali metal cations (Na + K). In the ordinate (Y-axis) the difference between weak acid anions (HCO_3 + CO_3) and strong acid anions (Cl^- + SO_4) is plotted where all values are expressed in meq/L%. The diagram has four distinct fields: recharge type, seawater type, reverse ion exchange type and base ion exchange type (Figure 5).

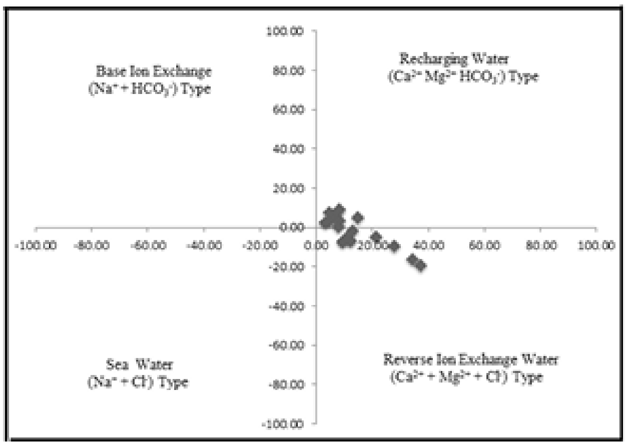


Figure – 5. Chaddha’s diagram for Simlapal block, Bankura District, West Bengal

The diagram being described is likely a modified Piper diagram of the standard Piper trilinear plot. The standard Piper diagram plots major ion concentrations in water samples to infer hydrogeochemical facies, which naturally helps visualize conditions like weathering, evaporation, and ion exchange processes

In this specific application, the resulting plot effectively groups groundwater samples into two primary classifications or "fields", i.e., recharging type and reverse ion exchange types. The samples occurring in recharging types are characterised by typically calcium and bicarbonate pre-dominating, which reflect recharge and weathering processes. Other samples which occupy reverse ion exchange field are characterized by calcium and magnesium with chloride, indicating reverse ion exchange. While water in the Recharge Type field suggests healthy soil with a stable composition, but the water in the Reverse Ion

Exchange field often contribute to the gradual deterioration of soil quality due to the change in cation balance. The findings of Chadha's plot are congruent with the findings of Piper plot.

3.2.3 Gibb's Diagram:

The diagram, developed by Gibbs in 1970 [58], effectively illustrates the interconnections in between the chemical constituents of groundwater and its surrounding geological environment. The Gibbs' diagram serves the purpose of delineating the primary origin and controlling mechanisms of water chemistry. Depending upon the analysis of the study area's groundwater samples, as presented in Fig. 6 of the referenced study, all samples fall within the field that indicates the chemistry of water to be primarily controlled by rock-water interactions.

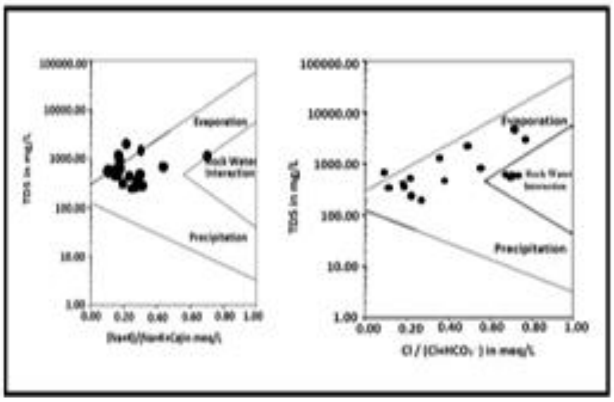


Figure 6. Gibb's diagram showing plots of (Na+K)/ (Na+K+Ca) vs. TDS & Cl / (Cl+HCO3-) vs. TDS

3.2 Groundwater suitability for Irrigational purposes

A country's economy is largely dependent on agriculture, which requires good quality water for irrigation. In agricultural sector, investments from international agencies have recently increased enormously. Besides this, the increase in population, along with rapid growth industrial development, result in groundwater pollution mainly from anthropogenic causes (Nemcic-Jurec et al. 2019) [86]. Water moving through an aquifer can cause minerals to disintegrate, potentially leading to secondary infections from the resulting contaminants (Eldaw et al. 2020) [87]

Various indicators have already been globally introduced by researchers to evaluate the quality of water intended for the purpose of irrigation. These key metrics help determine the water's suitability and potential impact on soil and crops, and include: EC, Sodium Adsorption Ratio (SAR), Sodium Percentage (Na%), Residual Sodium Carbonate (RSC), Soluble Sodium Percentage (SSP), Magnesium Adsorption Ratio (MAR), Kelly's Ratio (KR),) and Permeability Index (PI) [88 – 95] (Selvakumar et al. 2022, Sashikumar et al. 2017, Singaraja et al. 2015, Todd 1980, Szabolcs 1964, Wilcox 1955, Richards 1954, Kelley 1941).

Irrigational suitable water should have no negative impact on soils and plants, which is evaluated using the same parameters mentioned earlier. The permeability of soil is affected by high levels of dissolved minerals which lead to low productivity. Water suitability for agricultural purposes is commonly evaluated by analyzing specific criteria and plotting their values on established classification diagrams.

Key methods used to determine water suitability include: USSL Diagram (US Salinity Laboratory Diagram 1954) [96]; Wilcox Diagram: This chart uses the percentage of sodium and the total concentration of dissolved solids (EC) to evaluate the water's effect on soil permeability and crop growth

3.3.1 Permeability Index (PI)

Permeability Index (PI) stands for a standard soil criterion and is determined by the percentage of permeability induced by groundwater into the soil. Over time it is observed that nearly all alkaline ions are responsible for reducing soil permeability.

Doneen [97] introduced the Permeability Index (PI) in 1964 as a criterion for assessing the usability of water for irrigation, basing it on the concentrations of alkaline ions present in the groundwater

The PI depending on context of water sample is found using the equation labeled as 6.

$$PI = \frac{[\{Na + \sqrt{HCO3}\} * 100]}{(Ca+Mg+Na)} \quad \ldots\ldots\ldots\ (6)$$

Where, meq/L stands for the unit of ion concentrations.

Doneen's chart is a graphical tool used for assessing irrigational appropriateness of groundwater depending on its PI. In typical applications of this diagram, the PI values of a water sample are plotted on the Y-axis, while the Total Ion Concentration (or Total Dissolved Solids/TDS) of the sample is represented on the X-axis. The data points on the chart help to categorize the quality of groundwater for irrigation purposes (e.g., Class I, Class II, or Class III) (Figure – 7). For the study mentioned, every analyzed sample was identified as Class I, suggesting a desirable permeability of less than 80%.

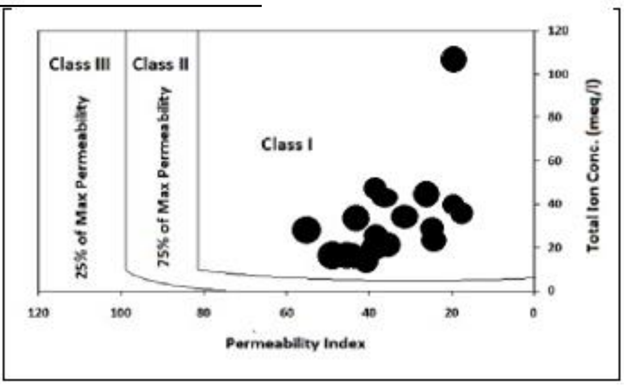


Figure 7. Doneen's Chart for Simlapal block, Bankura District, West Bengal

3.3.2 Sodium Soluble Percentage (SSP)

SSP value is used to evaluate the potential of groundwater to cause salinity or alkalinity issues in soil. High SSP values are indicative of water leads to (i) loss of soil structure, (ii) reduced soil permeability and (iii) decreased soil aeration (Singh *et al*. 2008) [98]

SSP is typically determined using the following formula (equation 7)

$$SSP = \frac{[(Na+K) * 100}{(Ca+Mg+Na+K)} \quad \ldots\ldots\ (7)$$

Where, meq/L stands for all cation concentrations.

Wilcox (1955) [93] diagram is used to categorize groundwater quality for agricultural use. This classification system evaluates the irrigation water quality hazards based on two key parameters: the water's electrical conductivity (EC), which is plotted on the X-axis, and its sodium soluble percentage (SSP), which is represented on the Y-axis The position of a data point on the diagram categorizes the groundwater, indicating the potential suitability or hazards for irrigation purposes (Figure – 8).

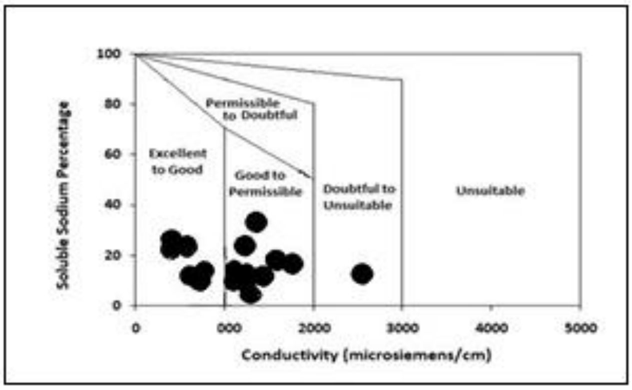


Figure 8. Wilcox Diagram for Simlapal block, Bankura District, West Bengal

3.3.3 Sodium Adsorption Ratio (SAR)

SAR, commonly known as the Sodium Adsorption Ratio, is an important parameter for assessing the salinity of groundwater. If irrigation water having a high SAR saturates the soil, it elevates the soil's sodium content compared to its calcium and magnesium levels. This exchange process results in soil becoming increasingly saline and alkaline. Elevated levels of salinity and alkalinity create an osmotic imbalance in plants and trees, which creates a hard situation for trees to absorb water and essential nutrients from the soil [99] (Subramani et al. 2005). This water stress inhibits growth and can ultimately be fatal to the plants.

The mathematical expression commonly applied for measuring SAR is given below: (Equation 8):

$$\text{SAR} = \frac{Na}{\sqrt{Ca+Mg/2}} \quad \ldots\ldots\ (8)$$

Where, meq/L stands for all cation concentrations. All samples are belonging to excellent category (Table – 4).

The groundwater is classified as ‘good’ for irrigation because its sodium hazard (SAR) and salinity (EC) levels, plotted on the U.S. Salinity Diagram, consistently fall within the low-risk C2 – S1 and C3 – S1 categories, indicating favourable conditions for agriculture (Figure – 9).

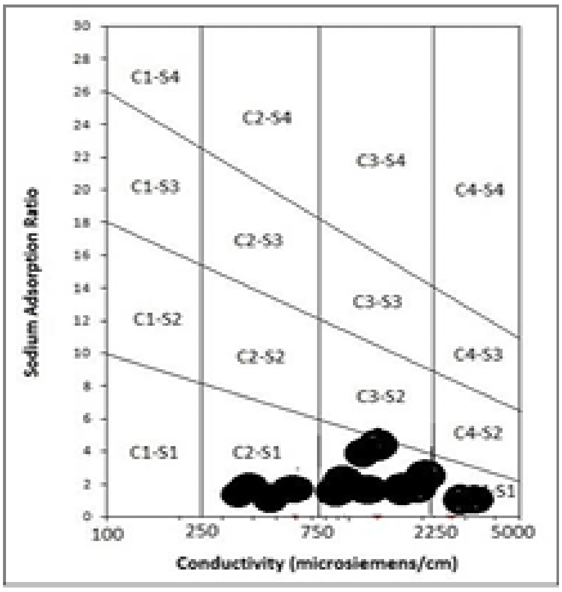


Figure 9. U. S. Salinity Diagram for Simlapal block, Bankura District, West Bengal

3.3.4 Kelly's Ratio

Kelly's (1941, 1976) Ratio (KR) is a calculation used to assess the sodium concentration relative to the levels of calcium and magnesium in a water sample.

The formula for Kelly's Ratio is expressed as:

$KR = Na^{+} / (Ca^{2+} + Mg^{2+})$ ……. (9)

Where, meq/L stands for all cation concentrations.

The groundwater in the studied area is categorized as suitable for agricultural purposes, after the determination made using the Kelly's Ratio (KR), where water with a value less than one ($KR<1$) is considered acceptable for irrigation, while a value greater than one ($KR>1$) indicates excessive sodium content and unsuitability.

3.3.5 Magnesium Adsorption Ratio

The equation for the Magnesium Adsorption Ratio (MAR), as defined by Paliwal (1972) [100], is typically expressed as:

$MAR = Mg \times 100 / (Ca + Mg)$ ……..(10)

Where, meq/L stands for all cation concentrations.

As noted by studies such as Kumar *et al*. (2007) [101], a high MAR value indicates an elevated concentration of magnesium relative to calcium in the groundwater. The prevalence of magnesium over calcium can adversely affect soil quality and potentially reduce crop yields by deteriorating soil structure and interfering with nutrient uptake by plants.

The MAR is a metric used for evaluating irrigation water suitability, with a threshold of 50 dividing suitable from unsuitable water. Based on this established criterion, the present study found that most of the samples exceeded the threshold and were therefore classified as unsuitable for irrigation

4. RESULTS AND DISCUSSION:

The total alkalinity (TA) of the collected groundwater samples showed a considerable range, from 160 to 530 mg/L. The average alkalinity across all samples was determined to be 340.63 mg/L. Importantly, all measured values were well within the generally accepted permissible limit of approximately 600 mg/L (Table – 1)

TDS of the collected water samples was found to be normal but, in some places, high values of 200 to 1410 ppm was also observed. The average value of TDS is found to be 674.4 ppm. Out of all the samples of investigation, 41% were identified as fresh; however, only 35% are considered safe for drinking, a designation made irrespective of their high total dissolved solids (TDS) levels mentioned in Table 4.

The pH levels, which fell within the range of 6.45 to 7.32, align with the ideal drinking water standards recommended by the World Health Organization (WHO 2004, 2011) [102,103]

Groundwater samples collected for the study showed a wide variation in electrical conductivity (EC), a measure of salinity, ranging from 400 to 2800 µS/cm, with an average value of 1134.4µS/cm. The elevated EC levels were likely caused by a high concentration of total dissolved solids (TDS). The findings indicate that the aquifer may have high salinity and a significant number of soluble electrolytes present in the groundwater (Kazi et al. 2009) [104].

The chloride (Cl) concentration ranged from 22.93 to 824.74 mg/L, averaging 245.20 mg/L. Sodium (Na), potassium (K), and sulfate (SO_4) ions exhibited concentration variations of 22–89 ppm, 9–90 ppm, and 3.14–70.04 ppm, respectively. Calcium (Ca) concentrations were found between 43.68 and 409.92 ppm, while magnesium (Mg) concentrations varied from 2.58 to 267.07 ppm.

Based on the study's findings (Table 4), all groundwater samples surpassed the permissible hardness limit of 180 ppm, categorizing the water across the entire study area as 'very hard'. Concurrently, the pH levels in all sampled villages were found to be alkaline and within the safe and desirable range recommended by the WHO (2004)[102] guidelines for drinking water quality

The experimental results suggest that the significant fluctuations observed in the levels of physical and chemical constituents, including the F- concentration, may stem from geochemical intervention within the impacted study area. Fluoride (F^-) concentrations in the groundwater samples ranged from 0.21 to 1.03 mg/L, averaging 0.46 mg/L. All measured levels were within the accepted safe threshold of 1.5 mg/L (Figure 10)

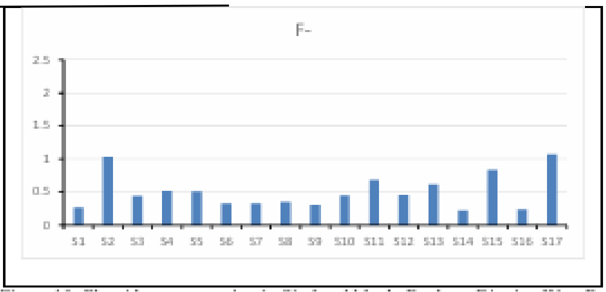
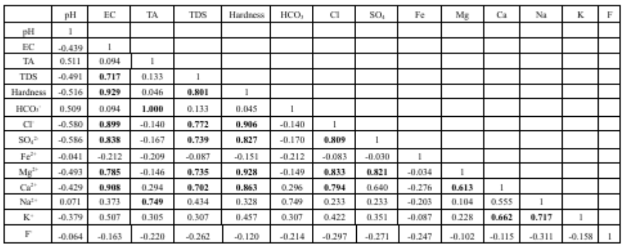


Figure 10: Fluoride concentration in Simlapal block, Bankura District, West Bengal

4.1 Correlation analysis of Simlapal block

The data presented in Table 5 consists of the specific correlation coefficient statistics for the rural parts of the Simlapal Block, Bankura District, West Bengal; these statistics are derived from a correlation matrix prepared for a session involving fourteen distinct variables.

Table 5: Correlation coefficient of water quality parameters. Significant values represent in bold



	pH	EC	TA	TDS	Hardness	HCO_3	Cl	SO_4	Fe	Mg	Ca	Na	K	F
pH	1													
EC	-0.439	1												
TA	0.511	0.094	1											
TDS	-0.491	**0.717**	0.133	1										
Hardness	-0.516	**0.929**	0.046	**0.801**	1									
HCO_3^-	0.509	0.094	**1.000**	0.133	0.045	1								
Cl^-	-0.580	**0.899**	-0.140	**0.772**	**0.906**	-0.140	1							
SO_4^{2-}	-0.586	**0.838**	-0.167	**0.739**	**0.827**	-0.170	**0.809**	1						
Fe^{2+}	-0.041	-0.212	-0.209	-0.087	-0.151	-0.212	-0.083	-0.030	1					
Mg^{2+}	-0.493	**0.785**	-0.146	**0.735**	**0.928**	-0.149	**0.833**	**0.821**	-0.034	1				
Ca^{2+}	-0.429	**0.908**	0.294	**0.702**	**0.863**	0.296	**0.794**	0.640	-0.276	**0.613**	1			
Na^{2+}	0.071	0.373	**0.749**	0.434	0.328	0.749	0.233	0.233	-0.203	0.104	0.555	1		
K^+	-0.379	0.507	0.305	0.307	0.457	0.307	0.422	0.351	-0.087	0.228	**0.662**	**0.717**	1	
F^-	-0.064	-0.163	-0.220	-0.262	-0.120	-0.214	-0.297	-0.271	-0.247	-0.102	-0.115	-0.311	-0.158	1

.

EC is having positive correlation with TDS, Hardness, Cl^-, SO_4, Mg and Ca; Total Alkalinity shows positive correlation with HCO_3 and Na; TDS is having a positive correlation with hardness, Cl^-, SO_4^{2-}, Mg and Ca; Cl^- exhibits positive correlation with SO_4, Mg^{2+}, Ca; SO_4^{2-} exhibits positive correlation with Mg; Mg also exhibit positive correlation with Ca; Ca and Na both exhibit a strong positive relationship with K. pH shows negative correlation with EC, TDS, Hardness, Cl^-, SO_4^{2-}, Mg^{2+}, Ca, K, Na and F^-; EC also negatively correlated with Fe, F-; Total Alkalinity and Bicarbonate show a negative correlation with Cl^-, SO_4^{2-}. Fe is having a negative correlation with Ca, Mg, Na, K and F^-. Fluoride is negatively correlated with Fe, TDS, Hardness, Cl^-, and SO_4^{2-}). All cations exhibited a negative correlation exclusively with F^-. Fifty-nine percent of the analyzed samples, specifically S2, S3, S5, S6, and S8 through S13, had a chloride concentration below the WHO guideline acceptable limit of 250 mg/L.

The concentration of chloride ions (Cl^-) is commonly acts as a contamination index of groundwater (Laluraj et al. 2005)[105]. The predominance of calcium (Ca) over sodium (Na) in water samples is primarily due to natural geological phenomena such as rock-water interactions and ion exchange. The fluoride content in the present study spanned a range of 0.21 to 1.23 mg/L, with an average concentration **of** 0.46 mg/L All tested groundwater samples were below the maximum permissible limit of 1.5 mg/L (WHO 2004)[102].

4.2 WQI and its spatial distribution

In the study area, water quality varied widely, with the Water Quality Index (WQI) spanning from 40 to 1363. This extensive range allowed for the classification of water samples into five distinct quality categories, encompassing everything from "excellent water" to "water unsuitable for drinking. Table 4 details the precise percentage distribution of water samples across specific quality categories. A high-Water Quality Index (WQI) in groundwater samples was associated with elevated levels of iron (Fe), total dissolved solids (TDS), total hardness (TH), bicarbonate (HCO_3), and fluoride (F). The categorization of these samples by their WQI class suggests that the majority fall into the 'poor category to unsuitable' for drinking, with only a few exceptions meeting the standards for safe consumption.

For the research region to be eligible for the "fit water" category, "special treatment" is therefore required. High TDS value was observed in groundwater samples may be related to geogenic activity; ions such as Cl^-, Na^+, and TA were found to exceed the allowable limit in those samples.

Based on the analysis of variety of parameters related to water quality, the groundwater in some villages of the research area is generally characterized as poor to unsuitable for use. The majority of calculated values exceeded the acceptable limits established by WHO and BIS. While a few local exceptions were noted, the overall data indicates significant water quality issues across the area.

5. CONCLUSIONS

This investigation assesses the groundwater quality of Simlapal Block, a vital local water source. The investigation specifically tries to delineate the main natural contaminants (geogenic solutes) that determine the water's chemical composition. The investigation uses the WQI and statistical methods to determine the water's suitability for consumption and other uses.

The investigation found that the majority of groundwater samples from the locations studied were primarily acidic, though a smaller number were alkaline. The high levels of electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), and chloride (Cl) observed in the samples were determined for establishing the interactions of the aquifer material and the groundwater, as well as significant evaporation.

Groundwater in the study area exhibits significant variations in its suitability for drinking, primarily due to iron (Fe) contamination.

- Three-fourths of the area is categorized as poor to unfit for consumption, with consistently high iron concentrations identified as the main reason for its unsuitability.

- The remaining one-fourth of the area is in a favorable ‘very good to good’ state for drinking, meeting quality standards

The majority of samples (55%) in the study area is classified as "fresh" water and deem suitable for drinking, according to results from a Piper Diagram analysis. This is noteworthy because the majority of groundwater samples concurrently exhibited higher salinity values, a condition attributed to elevated Electrical Conductivity (EC) readings.

Groundwater analysis indicates that all samples meet the Class I permeability standard, exhibiting greater than 75% permeability as determined by the Doneen's diagram (Figure 7).

According to the Schoeller diagram analysis, the specific concentration orders for various chemical elements are as follows:

- In milligrams per liter (mg/L) Ca>Mg>Na>K>; HCO_3>Cl>SO_4>Total Fe>F
- In milliequivalents per liter (meq/L) Mg>Ca>Na>K; Cl>HCO_3>SO_4>F

The data suggests a direct relationship between the pH levels and the concentration of fluoride in the groundwater, implying that the fluoride presence is probably for the natural dissolution of fluoride-bearing minerals in the surrounding geology.

The data indicates that higher pH levels are linked to elevated bicarbonate (HCO_3) concentrations, with a correlation coefficient (r^2) of 0.259. This relationship suggests an alkaline environment in the groundwater, caused by the presence of bicarbonate. This alkalinity, in turn, helps minerals dissolve into the water

Fluoride (F^-) concentration exhibits a moderate positive correlation with bicarbonate (HCO_3^-), as indicated by an r^2 value of 0.461. Conversely, fluoride has a negative correlation with calcium (Ca^{2+}) concentrations (Figure 11). Based on Gibb's diagram (Figure 6), the data suggest that rock weathering is the primary control on the composition of most samples.

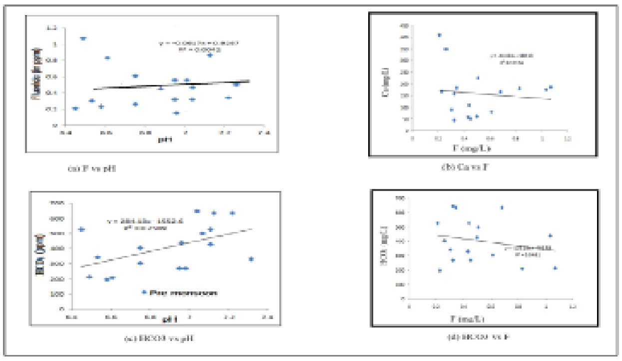


Figure 11: Scatter plot; measured difference between F and pH, Ca, HCO_3 and pH vs HCO_3

It can be concluded that groundwater chemistry is predominantly determined by the reactions that occur between the water moving through the reservoir domain and the geological formations found within that reservoir. From the comprehensive analytical results, the water in the study region is generally considered favourable for both domestic and agricultural use, with quality typically ranging from good to moderate**.** Isolated exceptions with localized quality issues were noted but are not representative of the broader area

A key objective of the study was to evaluate the local groundwater's suitability for both drinking and irrigation, which is critical in this rural locality since agriculture seems to be the fundamental source of income and there is no public water supply system for potable use.

The study aimed to determine if the local groundwater could support agricultural needs and provide safe drinking water for residents who lack a public water system. Residents within the Simlapal Block of the Bankura District are advised to ensure their water is adequately treated before consumption.

It can be inferred that both geogenic and anthropogenic actions (such as the application of fertilizer containing fluoride in the field leeches into groundwater) may be responsible for the pollution.

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Data availability statement: The authors confirm that the data supporting the findings of this study are available within the article.

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