Bulletin of Pure and Applied Sciences.
Geology (Geological Science), Vol.42F, No.1,
January-June 2023: P.106-131
Original Article

Print version ISSN 0970 4639
Online version ISSN 2320 3234
DOI: 10.48165/bpas.2023.42F.1.9
Available online at www.bpasjournals.com

Hydrochemical Characteristics of Groundwater Resources and Its Importance in the Assessment of Rural Water Supply in Southern India

[1]V. Ajaykumar and [1,2,3]N.C. Mondal*

Author's Affiliations:
[1]Earth Process Modeling Group, CSIR-National Geophysical Research Institute, Hyderabad, Telangana 500007, India
[2]Electrcial and Heliborne Geophysics Group, CSIR-National Geophysical Research Institute, Hyderabad, Telangana 500007, India
[3]Academy of Scientific & Innovative Research (AcSIR), Ghaziabad, Uttar Pradesh 201002, India

***Corresponding Author: Dr. N.C. Mondal,** Earth Process Modeling Group, CSIR-National Geophysical Research Institute, Hyderabad, Telangana 500007, India
E-mail: mondal@ngri.res.in; ncmngri@gmail.com

(Received on 28.01.2023, Revised on 29.03.2023, Approved on 10.05.2023, Accepted on 19.05.2023, Published on 15.06.2023)

How to cite this article: Ajaykumar V. and Mondal N.C. (2023). Hydrochemical Characteristics of Groundwater Resources and Its Importance in the Assessment of Rural Water Supply in Southern India. *Bulletin of Pure and Applied Sciences- Geology,* 42F(1), 106-131.

Abstract:
This article deals with the hydrochemical characteristics of groundwater resources that favor water supply in both irrigation and drinking uses at a rural area of Southern India. Groundwater samples were gathered from a village water-supplied wells, and analyzed for physiochemical parameters, and major ions including nitrate (NO_3^-) and fluoride (F^-) using standard methods, and also drawn their spatial distribution in the GIS platform. Results show that the dominancy of major ions is in order of $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > F^-$, and $Ca^{2+} > Mg^{2+} > Na^+ > K^+$. Among various parameters measured, TH (47%), Cl^- (40%), NO_3^- (7%), and Ca^{2+} (53%) exceeded the WHO permissible limits. Spatial distribution maps of the major ions had been prepared and found the appropriateness to utilize for both irrigation and drinking purposes at this rural area. According to the Piper diagram, three dominant facies are observed such as Na-Cl, Ca-Cl, and mixed Ca-Mg-Cl- types, whereas Gibbs plot has shown the dominance of groundwater evaporation. SAR, Na (%), KR, MAR, and USSL-diagram are used to evaluate irrigation suitability and improve water supply. The range of NO_3^- concentration was from 8.0 to 122.7 mg/L which may be the main cause of health risk whereas the F^- concentration is within the permissible limit. Assessment of health risks shows children more vulnerable to threat than adults. The corrosivity ratio (CR) of groundwater is also calculated to identify the supply well for groundwater use safely. In addition, the present groundwater conditions of rural water supply at this village have been discussed with local people the leave no one behind (LNOB).

Keywords: *Quality of groundwater; Suitability; Water Supply; Health Risks, Rural Area; Southern India.*

1. INTRODUCTION

Drinking water is vital for human beings. It meets from groundwater resources, and its consumption has increased in several sectors, including drinking, irrigation, and industrial needs, due to uncertainty in the rainy seasons. Groundwater is a renewable resource that is also safer than surface water. Human activity, on the other hand, can pollute aquifers, and ecosystems (Todd, 1980; Karanth et al., 1987; Saxena et al., 2005; Mondal and Singh, 2011; Li et al., 2016; Adimalla et al., 2018; Tiwari et al., 2020; Patel et al., 2020; Bhat et al., 2022, Ahmed et al., 2022).

Hence, information on groundwater quality and its characteristics is essential to understanding the water's suitability for various uses (Li et al., 2012; Mondal et al., 2016, 2020; Rahman et al., 2020a). If the parameters exceed the limits of the prescribed quality standards (WHO, 2011; BIS, 2012), it causes health problems when consumed. Furthermore, excessive groundwater extraction lowers groundwater water levels, resulting in poor water quality due to an increase in water-dwelling time within the aquifer systems (Wu et al., 2015; Subba Rao, 2018). In addition, groundwater contamination is also caused by the presence of polluted contaminants in soils and rocks (Suresh et al., 2007; Mondal et al., 2009; Nagaraju et al., 2016; Pandey et al., 2022). It is familiar that many aspects and their relations impact groundwater quality, including land use and land cover (LULC) changes (Singh et al., 2011), geological setup (Nagaiah et al., 2017), mineral composition (Mondal et al., 2009), hydrogeological environs (Soumya et al., 2013; Mondal et al., 2017), precipitation and evaporation (Mondal and Singh, 2011; Sharma et al., 2017). Due to the fast increase of urbanization, population explosion, and industrialization in present decades, the freshwater demand has increased enormously (Li et al., 2012; Adimalla et al., 2018; Aslam et al., 2021), which causes groundwater pollution.

Numerous studies of hydrochemistry have been investigated for different purposes (Wu et al., 2015; Li et al., 2016; Rahman et al., 2020b). The safety of drinking water is vital to the protection of human health. Using water quality data, research on the major contaminants in groundwater, such as F^-, NO_3^-, and trace elements, were analyzed for human health risk assessment (Chen et al., 2017; Ali et al., 2019; Yadav et al., 2019; Rahman et al., 2021; Toolabi et al., 2021). Ghalib (2017) analyzed the parameters that influence hydrochemistry and evaluated in Iraq. The anthropogenic and geogenic sources have a vital influence on the quality of groundwater fluctuation in Cuddalore, Tamil Nadu (Srinivasamoorthy et al., 2011). Mondal et al. (2009) evaluated the fluoride-rich zones in crystalline aquifers of the Kurmapalli watershed, Nalgonda district, Telangana. Sreedevi et al. (2019) appraised the quality of water for its suitability. In the coastal areas also, studies carried out on the hydrochemical characteristic of the coastal aquifers (Saxena et al., 2003,2004, 2005; Sarwade et al., 2007; Mondal et al., 2010, 2011; Selvam et al., 2013; Khan et al., 2021). Rahman et al. (2020b) investigated the hydrochemical characteristics for groundwater suitability in a part of Jaipur, Rajasthan. Reddy et al. (2015) assessed the mechanisms of F^- enrichment in groundwater of the Chimakurthy granitic pluton complex on a regional scale, particularly in Andhra Pradesh in Southern India. Subbarao (2018) also identified the groundwater suitability for both the purposes in Prakasan district, Andhra Pradesh. Especially in this rural area, it looks like there is no study carried out on the details of water supply with the help of hydrochemical characteristic behaviors. Thus, the present study focuses on 1) characterizing of groundwater quality in a remote rural area, namely Thurakapalem village, Prakasam district, Andhra Pradesh, Southern India, 2) investigating the suitability for groundwater use, and 3) assessing the non-carcinogenic health risks of human, and enlightening the local farmers and population on the groundwater suitability for various uses.

1.1 Brief Rural Area of Thurakapalem Village

The rural area (Thurakapalem village) covers around 8.82 km^2, and lies between Longitudes: 79°49'0'' to79°50'30''E and Latitudes: 15°44'30'' to 15°46'30''N at Tallur Mandal, Prakasam district, Andhra Pradesh State, India (Figure 1). It is located around 45 km the north of the district headquarters of Ongole.This village is surrounded by Mundlamuru Mandal towards the north, Addanki Mandal towards the east, Darsi Mandal towards the west, and Chimakurthi Mandal towards the south. It has a population as of 2020/21, of which males 2,844, females 2,732, and a total population of 5,792. The total number of households is around 1227. Agriculture is the primary source of income at this village, and irrigation is a time-consuming and long-term process. Most of the farmers depend on bore and tube wells, and about 80% of the area is being irrigated under the non-command area. Most farmers irrigate using submersible pumps. Major soil groups observed that this area is under red and black cotton soils.

Agricultural activity, especially paddy, is prominent, followed by paddy, vegetables, pearl millet, and cotton, which are irrigated crops.

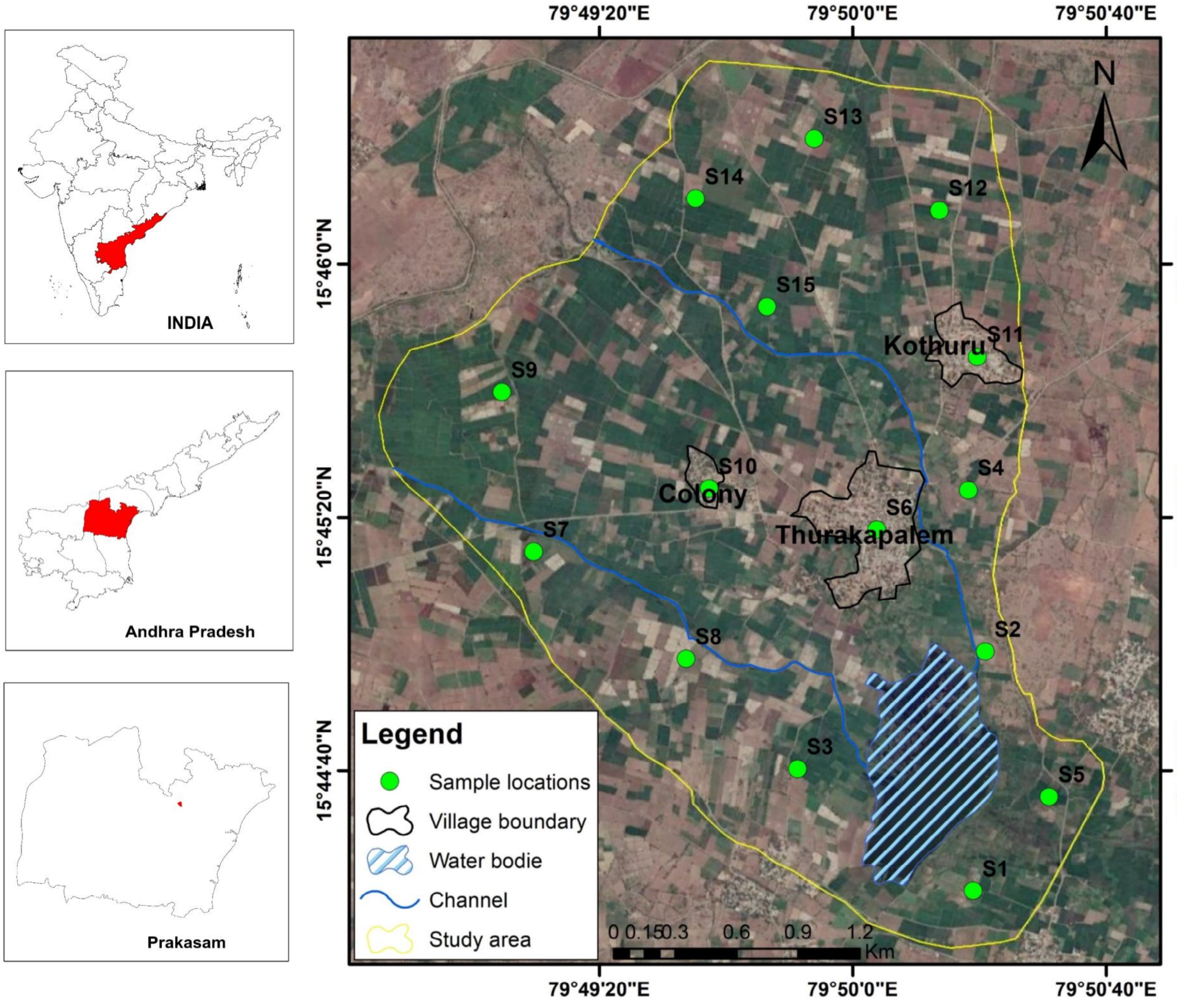

Figure 1: Location map of a rural area, Thurakapalem village in Andhra Pradesh, Southern India along with the sampling points and tank (source: Google Earth Pro)

1.2 Precipitation and Climate

Thurakapalem village (in Andhra Pradesh) experiences a semi-arid environment, and a subtropical continental climate categorized by severe summer and moderate winter. The lowest and highest temperatures are 28 and 39^{0}C, respectively. Throughout the year, the relative humidity is high, ranging between 75-80%. The relative humidity is about 71% in the morning and about 64% in the evening during the summer season, especially in May (CGWB, 2013). The rainfall data were gathered from the year 2010 to 2020 (source: IMD), and varied from 504 to 1231 mm/year. The maximum precipitation of approximately 1231 mm was noted in the year 2010 (Figure 2a). Mean yearly precipitation at this village is approximate 784 mm, and the monthly rainfall varies from negligible in March to 168.4 mm in August. The wettest month of the year is August. Mainly the rainfall contributes from both NE and SW seasonal rainfall. The percentage distribution of rainfall, season-wise, is about 57.56% in the SW-monsoon (June-September), about 33.60 % in the NE-monsoon (October–December), about 2.24% in the winter, and the summer is around 6.58% of the total rainfall. The monthly average rainfall distribution is presented in Figure 2b.

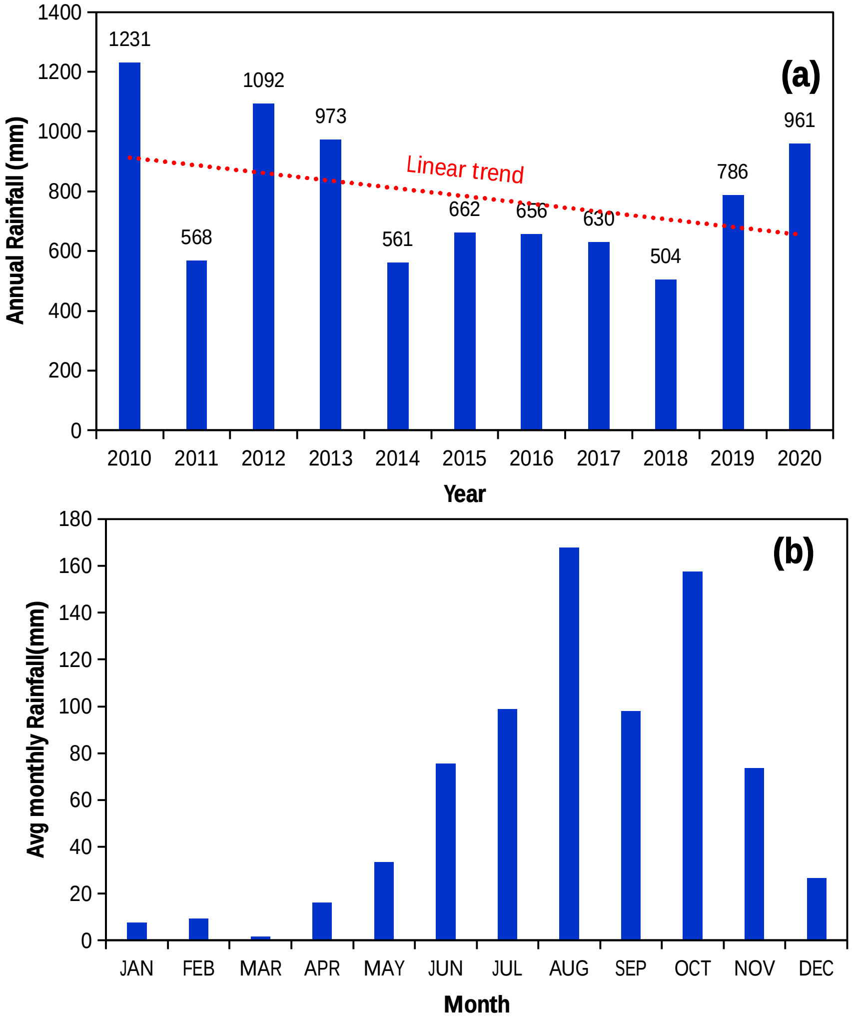

Figure 2: Precipitation (a) yearly (in mm) yearly, and (b) average monthly (in mm) at Thurakapalem village during the year 2010-2020

1.3 Geology

The study is geologically occupied by the rocks of the Chimakurthy plutonic complex group, unclassified metamorphic and Dharwar-Super Group rock assemblages belonging to Archaean-Proterozoic age along with mafic intrusive like gabbros, norite, and anorthosites (GSI, 2002; Reddy et al., 2016), as shown in Figure 3a. Most of the village is occupied by Gabbro-norite rock formation (~8.32 km^2), and the remaining minor portion covers anorthosite (~0.5 km^2) exposed in the northern part. Lineaments are also demarcated (NRSC Bhuvan website, https://bhuvan-app3.nrsc.gov.in). Lineaments are linear structural elements on a large scale. Lineaments, which control groundwater occurrence and its' movement, are extremely important for possible groundwater mapping because they act as essential (Mondal et al., 2008; Prasad et al., 2008; Ajaykumar et al., 2020). Two clusters of lineaments are demarcated trending to the NW-SE direction at this village, as shown in **Figure 3a**.

1.4 Digital Elevation Model (DEM)

The open-source SRTM DEM model with the resolution of 30×30 m is commonly used for the topographic elevation, slope, and drainage network maps of the study area, which were acquired from the CGIAR (http://srtm.sci.cgiar.org), and the spatial analyst tool in ArcGIS 10.4 was used to extract the data. The surface elevation varies from 42 to 79 m, amsl, as shown in Figure 3b. The slope ranges from 0 to 16.2^0, as shown in Figure 3c which control both the runoff and water infiltration from groundwater surface (Satapathy and Syed, 2015). It indicates under moderate slope in the north-western part, and the rest is nearly flat.

1.5 Drainage Pattern

Using the Hydrology Toolset in ArcGIS 10.4, the drainage network was made available using a digital elevation model (DEM). It is mainly being dendritic positioning from north-western to south, this drainage joins at the south part of the water body (area: ~0.48 km^2), shown in Figure 3b. The order of the streams network is in this area majorly first, second, and third order stream network. Finally, this drainage system meets the Dwarnapuvagu River outside to the south of this village, which is the ephemeral river that flows from the west to the east direction.

2. MATERIALS AND METHODS

2.1 Measurement of Groundwater Level

Groundwater measurement was carried out in August 2021. Water level data monitoring by using the water level indicator measured at 18 bore wells (Figure 3d). The depths of groundwater range from 10.3 to 19.2 m, bgl, with a mean depth of 15.67 m, bgl under the unconfined to semi-confined conditions. The total depth of the wells varied from 31.2 to 55.6 m, with a mean of 48.84 m. Most of the wells pumping by using 5 HP submersible pumps for irrigation purposes (in Table 1). The distribution of depth to groundwater level contour map was prepared by using the inverse distance weighting (IDW) method with the help of ArcGIS. The maximum depth to water level was observed at the N-W part (well no:17) of the area, while the minimum water level in the south-eastern part (well no:1), as shown in Figure 3d.

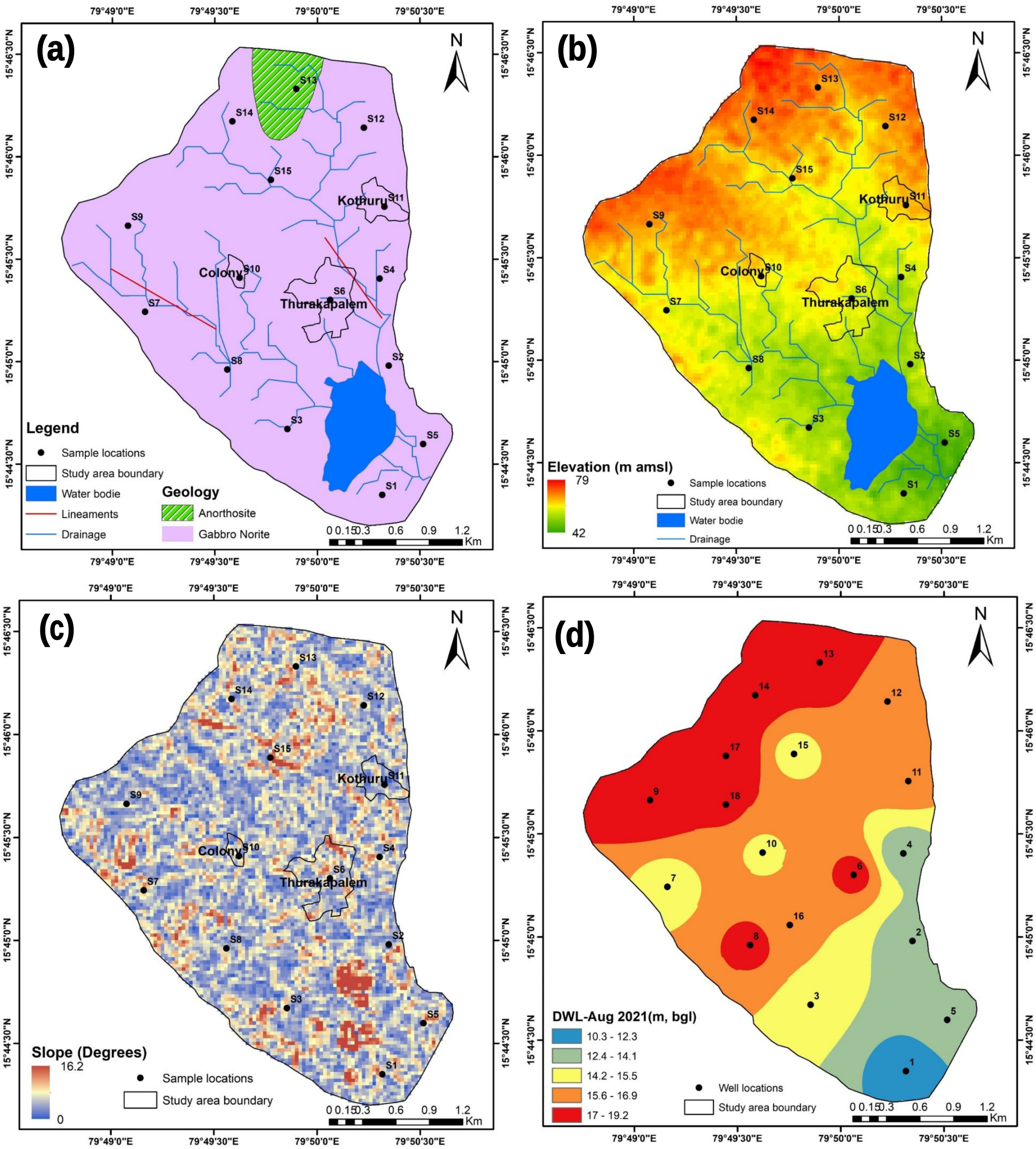

Figure 3: (a) Geological map in and around Thurakapalem village along with the sampling points, (b) Digital Elevation Model (range: 42-79 m, amsl) with the drainage network system, (c) Slope map (range:0-16.2 degrees), and (d) Spatial distribution of depth to water level (range: 10.3-19.2 m, bgl) in the month of August 2021

2.2 Sampling and Procedure

Fifteen water samples were gathered from the representative bore wells in August 2021, which are used for drinking water supply and irrigation. These samples were filled up in one-liter plastic bottles. The location of each well was noted using GPS (GARMIN-etrex20) for the geo-referencing. There was no air space between the bottles because they were firmly closed (APHA, 2012). Immediately the samples were transported to Telangana State Groundwater Department (TSGWD), Hyderabad Laboratory, for chemical analysis. The TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-,SO_4^{2-}, NO_3^-, and F^-concentrations were estimated using conventional water quality protocols (APHA, 2012). The pH, EC, and TDS were also estimated in-situ conditions with the help of Hanna portable meter (Model: HI 98107). Titrimetrically, total hardness, Ca^{2+}, and Mg^{2+} were evaluated using the EDTA standard. The HCO_3^- was assessed by titrating with standard HCl. $AgNO_3$ titration was used to calculate Cl^-. A Model 130 Systronics Flame Photometer was used to measure the Na^+ and K^+ concentrations. The SO_4^{2-} was analyzed, using a digital nephelo-turbidimetric procedure and NO_3^- was analyzed by Colorimetry with a UV-visible spectrophotometer single beam. The ion selective electrode was used to determine the fluoride concentration. The concentrations of all ions excluding pH and EC are measured in mg/L, whereas the EC (µS/cm) is at 25^{0}C. Each groundwater sample was tested for ionic-balance-error (IBE) less than 5% of total measured concentrations (Domenico and Schwartz, 1998) as below.

$$\text{IBE} = \frac{\sum \text{Cations} - \sum \text{Anions}}{\sum \text{Cations} + \sum \text{Anions}} \times 100 \qquad (1)$$

2.3 Hydrogeochemical Characteristics

Groundwater chemistry was used to categorize the hydrogeochemical profiles. Grapher Software was utilized to display the major ions on Piper diagram (1944) to determine distinct water types depending on the proportionality of major ions (meq/L). Gibbs diagram (Gibbs, 1970) was prepared to understand the rock, precipitation, and evaporation interaction of groundwater.

2.4 Indicators for Irrigation Suitability

The chemical composition of irrigation water determines its quality and its impact on irrigational lands and soils. Normally, the quality of irrigation water was appraised through the standards based on SAR, Na (%), KR, and MHR. These parameters are mostly used to evaluate groundwater quality for irrigation. These considerate standards, on the other hand, were computed as follows:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+})/2}} \ (Richards, 1954) \qquad (2)$$

$$\text{Na\%} = \frac{(\text{Na}^+ + \text{K}^+)}{(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+)} (Todd, 1980) \qquad (3)$$

$$\text{KR} = \frac{\text{Na}^+}{\text{Ca}^{2+} + \text{Mg}^{2+}} (Kelly, 1963) \qquad (4)$$

$$\text{MAR} = \frac{\text{Mg}^{2+}}{\text{Ca}^{2+} + \text{Mg}^{2+}} \times 100 \ (\text{Szaboles and Darab}, 1964) \qquad (5)$$

Ryzner (1944) proposed the corrosivity ratio (CR), which had been utilized to assessing of PVC pipes for transportation as.

$$\text{Corrosivity Ratio (CR)} = \frac{0.028\text{Cl}^- + 0.021\text{SO}_4^{2-}}{0.02(\text{HCO}_3^- + \text{CO}_3^-)} \qquad (6)$$

These indicators were used for the analysis of analytical hydrochemical parameters to identify groundwater quality for irrigation purposes.

2.5 Health Risks

Human hazard, dosage response, exposure, and risk are the four phases that the USEPA (2014) has standard as appropriate methodologies for evaluating human health risk (Adimalla et al., 2018; Rahman et al., 2021). In addition, three main paths via which humans are exposed to pollutants are water intake, inhalation, and direct skin contact (USEPA, 2006). Nitrate and fluoride were considered for the human health risk assessment (HHRA) since drinking water contamination was thought to be the main pathway in this investigation. The USEPA regards these two factors as non-carcinogenic pollutants. Average daily dose (ADD) of NO_3^- and F^- consumed of groundwater intake in the area was calculated for exposure assessment (USEPA, 2006; Adimalla et al., 2018) by the following equation.

$$\mathrm{ADD} = \frac{\mathrm{CPW \times IR \times ED \times EF}}{\mathrm{ABW \times AET}} \quad (7)$$

where, ADD: NO_3^- and F^- ingested (mg/kg/day), CPW: pollutant concentration (in mg/L), IR: ingestion rate/unit time (L/day), ED: exposure duration (year), EF: exposure frequency (days/year), ABW: average body weight of a person (kg), and AET: average exposure time (day) (Adimalla et al., 2018), This corresponds to the average lifespan of a person living (around 365 day) in the investigated area. The detailed data used is presented in Table 2. The hazard quotient (HQ) w.r.t. the reference dose of the exposure dosage is likely to occur as.

$$\mathrm{HQ} = \frac{\mathrm{ADD}}{\mathrm{RfD}} \qquad (8)$$

where, RfD: reference dose for chronic oral exposure/non-carcinogenic risk, which is 1.6 and 0.06 mg/kg/day for NO_3^- and F^-, respectively (USEPA, 2014; Adimalla et al., 2018). The following equation (9) was used to estimate the total hazard index (THI) of non-carcinogenic risk.

$$\mathrm{THI} = \sum_{i=1}^{n} \mathrm{HQ_i} \quad (9)$$

The limit of THI is 1.00 for the non-carcinogenic (USEPA, 2014). The THI (> 1.00) indicates a contaminant's non-carcinogenic risk above the permitted limit, whereas THI less than ‘1.00’ indicates a non-carcinogenic risk within the acceptable range.

Table 1: Details of well inventory at Thurakapalem village, Prakasam District, Andhra Pradesh, Southern India

Well. No	Longitude	Latitude	Elevation (m, amsl)	TD(m)	MP(m)	Dia.(m)	DWL (m,bgl)	Purpose
1	79.839	15.739	52	31.2	0.5	0.2	10.3	Irrigation
2	79.839	15.750	56	39.65	0.4	0.2	12.5	do
3	79.831	15.745	57	42.7	0.5	0.2	14.8	do
4	79.838	15.757	58	45.28	0.4	0.2	12.4	do
5	79.842	15.743	50	32.56	0.4	0.2	13.6	do
6	79.834	15.755	62	56.66	0.5	0.2	17.8	Drinking
7	79.819	15.754	63	54	0.4	0.2	14.2	Irrigation
8	79.826	15.749	58	50	0.4	0.2	17.8	do
9	79.818	15.761	70	53.2	0.4	0.2	18.6	do
10	79.827	15.757	66	54	0.4	0.2	14.9	Drinking
11	79.839	15.763	67	50	0.3	0.2	16.4	do
12	79.837	15.769	69	52	0.4	0.2	15.9	Irrigation
13	79.832	15.772	72	56	0.4	0.2	18.6	do
14	79.826	15.770	70	54	0.4	0.2	17.8	do
15	79.830	15.765	67	52	0.5	0.2	14.4	do
16	79.829	15.751	57	52	0.3	0.2	15.8	do
17	79.824	15.765	73	52	0.4	0.2	19.2	do
18	79.824	15.761	68	52	0.4	0.2	17.2	do

#TD: Total depth of the well, MP: Measuring point, Dia.: Diameter of the well, and DWL: Depth to water level

Table 2: Parameters used for estimating the non-carcinogenic health risk at rural area, Thurakapalem village, Southern India

Parameters/frequency	Men		Women	Children	Reference
IR (in L/day)	2.5		2.5	0.78	USEPA, 2014
ED (in year)	64		67	12	Adimalla et al., 2018; WHO, 2013
EF (in days/year)	365		365	365	USEPA, 2014
AWB (in kg)	65		55	15	ICMR, 2009
AET (in days)	23360		24455	4380	USEPA, 2014, WHO, 2013

3. RESULTS AND DISCUSSION

3.1 Drinking Water Suitability

Table 3 compares descriptive data considering the statistics, and major ions of the samples to the Bureau of India Standard (BIS, 2012), and World Health Organization (WHO, 2011) for drinking purposes. It has shown that the order of dominance ions as Ca^{2+}> Mg^{2+}> Na^{+} >K^{+}, and HCO_3^{-}> Cl^{-}> NO_3^{-}> SO_4^{2-} > F^{-}.

3.2 Physicochemical Parameters

The pH values determine the acidic or basic character of groundwater, which is orderly by the CO_2^{-}, CO_3^{-} – HCO_3^{-} balance (Hem, 1991). In the area, it ranged from 6.50 to 6.90, with a mean of 6.73**.** (Table 3). The attribute of an aqueous medium's electrical conductivity (EC) influences how much current, it can transport. The maximum acceptable limit of EC values according to (BIS, 2012) is 1500 µS/cm. The average EC value was 1455.6 µS/cm, with values ranging from 525 to 2452 µS/cm. About 53.4% samples met within the WHO guidelines, and the rest 46.6% of samples exceeded the WHO limits. The total quantity of inorganic and organic dissolved components in an aqueous solution is measured by TDS. The major elements of cations in groundwater include Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} concentrations, whereas anions include HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO_3^{-}, and F^{-} concentrations. The range of TDS values ranges from 528 to 1569 mg/L, with an average of 931.6 mg/L. The 100% samples exceeded the WHO highest desirable limit (HDL), and only two samples exceeded the WHO maximum permissible limit (MPL). Total hardness (TH) varies from 339.0 to 999.8 mg/L, with an average of 569.2 mg/L. The highest allowable concentration of TH for drinking purposes is 500 mg/L (WHO, 2011), and the outcomes show that about 46.6% of the samples were above this limit. Total hardness in groundwater can be determined with the help of Ca^{2+} and Mg^{2+} concentrations (Sawyer et al., 1967).

3.3 Major Ions Chemistry

Cation concentrations were in descending order of Ca^{2+}> Mg^{2+}>Na^{+}> K^{+} contributing to 39% > 31% > 27.8% > 2.2%, respectively. Calcium was the most abundant element at this village. The Ca^{2+} concentration varied from 56 to 200 mg/L (Table 3). Groundwater quality of Ca^{2+} in the study area, about 53.3% of samples exceeded the WHO highest desirable limit (>75 mg/L). The magnesium concentration ranged from 48.6 to 126.4 mg/L, with an average of 78.8 mg/L. All samples exceeded the highest desirable limit (>30 mg/L). The Na^{+} concentration ranged from 40 to 145 mg/L, with an average of 70.5 mg/L. As per the WHO standards, all the samples are under the permissible limits for drinking purposes (Table 3). The K^{+} concentration has the lowest content, with a mean of 6 mg/L and a range of 2.0 to 15.4 mg/L. Anions concentrations were observed in the descending order of concentration in this investigation is HCO_3^{-}> Cl^{-}> NO_3^{-}> SO_4^{2-}> F^{-} with a percentage of about 55% > 35.93% > 5.4% > 3.4% > 0.27%, respectively. Bicarbonate is the utmost prevalent and stable ion in water (Vaiphei et al., 2020). At the village, it varied from 250 to 490 mg/L. The concentration of Cl^{-}varied from 50 to 600 mg/L and with a high chloride content (>200 mg/L), it is of saline nature (WHO 2011). In the area, about 40% of the samples had >200 mg/L. The sulphate ion varied from 12.3 to 30.0 mg/L, which is within the WHO permissible range but it enters groundwater through the oxidation of sulphite minerals like pyrite (FeS_2) (Yadav et al., 2012; Vaiphei et al., 2020).

The concentration of NO_3^- ranged from 8.0 to 122.7 mg/L and is presented in Table 3. One sample (at S6) had more than 45 mg/L, which is a desirable limit for drinking water. Because during the rainy season, it infiltrates through the vadose zone and also enhancing in the groundwater (Kumar et al., 2016). Methemoglobinemia, stomach cancer, goiter, birth abnormalities, and hypertension can all be caused by high nitrate concentrations (>45 mg/L) (Bao et al., 2017). The average fluoride concentration is observed around 0.5 mg/L, with the lowest and highest concentrations of 0.3 and 1.0 mg/L, respectively. Groundwater at this village is safe in-term of fluoride (permissible limit:<1.5 mg/L).

3.4 Spatial Distribution of Hydrochemical Parameters

In the ArcGIS 10.4 platform, the spatial distribution of groundwater quality maps had been deduced by using the spatial interpolation technique with the help of Inverse Distance Weighted (IDW). The spatial distribution of pH had been prepared and depicted in Figure 4a. It specifies that groundwater is acidic. In the northern part, pH varied from 6.8-6.9, and at the lower part, it indicates the low ranges of 6.5-6.7 and is more acidic in nature. The EC distribution (Figure 4b) showed that higher EC values were observed in the central part (at the well-S3, S4 & S6) than in the northern part. The TDS (Figure 4c) had shown that the maximum TDS was observed at the southwestern part than in the central part (at the well-S3, S5 & S6). The minimum TDS values were observed in the northern part. Figure 4d represents the spatial distribution of Total Harness, which had been observed a very low in concertation compared to central and southern parts of the village.

Spatial distribution of Ca^{2+} had been observed that the maximum calcium concentration was found in the southern and central parts (at the sample-S1, S3, and S5) than in the northern region (Figure 5a). The maximum concentration of magnesium in the central and S-W parts of the area (Figure 5b). Water with high calcium and magnesium concentrations forms layers in electrical equipment and pipelines, making it unsafe to however water can be used after boiling and cooling thought leaves white precipitation at the bottom of the vessels. Moreover, the spatial distribution maps of Na^+ and K^+ concentrations are presented in Figures 5 c, d. As per these concentrations, groundwater is good for drinking purposes at this village. In the eastern part of the village, the HCO_3^- concentration was rather high (at the well- S6 and S4), as shown in Figure 6a. In therest of the village, HCO_3^- concentration is in the medium range. The Cl^- concentrations were found to be more in the central and southern portions (at the S3, S5, & S6), as shown in Figure 6b, but the lower Cl^- concentration was found at the northern part. The F^- and NO_3^- distributions were depicted in Figures 6c-d, which indicates that groundwater samples are within the WHO permissible limits. Only the highest NO_3^- value (122.7 mg/L) was observed in the central-eastern part (at S-6) of this village, which is more than 45 mg/L (WHO, 2011). The sample (S-6) was collected from the bore well (no.:6) located at the center of Thurakapalemvillage and was intended for consumption as drinking water (in Table 1). The possible sources of NO_3^- pollution are the leachates that had accumulated in groundwater from nearby animal wastes and septic tanks.

3.5 Groundwater Types

The relationship among major ions, as well as their behavior, is explained by the groundwater facies. It supports the various water types (Piper, 1944) as well as the knowledge of groundwater's genesis and geochemical development. Hence, the facies were calculated using Cl^-, SO_4^{2-} and HCO_3^-; and Ca^{2+}, $Mg^{2+,}$ Na^+, and K^+ plotted in Piper diagram **(Figure 7).** On this diagram, the geochemical evolution mechanism is depicted in 6-different water types such as Type-1 (Ca–Cl type), Type-2 (Mixed Ca-Mg-Cl type), Type-3 ($Ca-HCO_3$ type), Type-4 (Na–Cl), Type-5 (Mixed Ca–Na- HCO_3) and Type-VI ($Na-HCO_3$). The majority of the samples belonged to the CaCl type. But the samples at S3,5,8, and 11 were found in the Na-Cl dominant type clusters. Three dominant hydrogeochemical facies such as Ca-Cl, mixed Ca-Mg-Cl, and Na-Cl types were found at this village.

Table 3: Brief **s**tatistics of the empirical hydrochemical data of groundwater samples at Thurakapalem village, Prakasam district, Andhra Pradesh, India

Water quality parameters	BIS (2012)		WHO (2011)		Range		Avg.	SD	% of the samples crossed the HDL limit (WHO)
	HDL	MPL	HDL	MPL	Min.	Max.			
pH	6.5	8.5	7.0	8.5	6.50	6.90	6.73	0.1	0.0
EC	-	-	-	1500	825	2452	1455.6	533.6	46.6
TDS	500	2000	500	1500	528	1569	931.6	341.5	100.0
TH	100	500	100	500	339.9	999.8	569.2	205.9	46.6
Ca^{2+}	75	200	75	200	56	200	98.1	45.3	53.3
Mg^{+}	30	100	30	150	48.6	126.4	78.8	27.2	100.0
Na^{+}	100	-	-	200	36	145	70.5	32.5	ND
K^{+}	10	-	-	-	2.0	15.4	4.2	3.3	ND
HCO_3^{-}	300	-	200	-	250	490	352.0	59.2	100.0
Cl^{-}	250	1000	200	600	50	600	230.7	175.7	40.0
SO_4^{2-}	200	400	200	400	12.3	30.0	21.9	5.5	ND
NO_3^{-}	45	-	45	-	8.0	122.7	35.0	27.1	6.6
F^{-}	0.6	1.2	1.0	1.5	0.3	1.0	0.5	0.2	6.6

All ions: in mg/L except pH and EC (in µS/cm), Min: Minimum, Max: maximum, Avg.: Average, SD: Standard deviation, HDL: Highest Desirable Limit, MPL: Maximum Permissible Limit, and ND: Not detected

3.6 Sources of Dissolved Elements

The water quality data by the Gibb's method of interpretation is helpful to identify the origin of dissolved solids in the water samples and their corresponding aquifer features. Evaporation, precipitation, and rock-water interaction dominances are examples of them. The ionic ratios between $Na^{+}+ K^{+}/(Na^{+}+ K+Ca^{2+})$ and $Cl^{-}/(Cl^{-} + HCO_3^{-})$ versus TDS values in groundwater were drawn, as presented in **Figure 8**. The most samples were found to be in the evaporation dominance group. This evaporation dominance supported an engagement in the salinity by enhancing both Na^{+} and Cl^{-} ions in terms of TDS. The augmentation of Na^{+} and Cl^{-} concentrations by anthropogenic activities and return flow from irrigation has a comparable effect on evaporation at Thurakapalem village.

3.7 Irrigation Suitability

Water quality used for irrigation in every village is critical to ensuring optimum agricultural yields, soil efficiency, and environmental safety. Instantaneously, the source elements of the water have a significant impact on the irrigation water quality (Oster, 1994). Characterizing the feasibility of groundwater for irrigation, water mineralization and its effects on soil and plants are dynamic processes. Consequently, various agricultural and soil scientists produced indices such as USSL (1954), Na (%), MAR, and KR, among others, to analyze groundwater suitability for irrigation, which are discussed herewith.

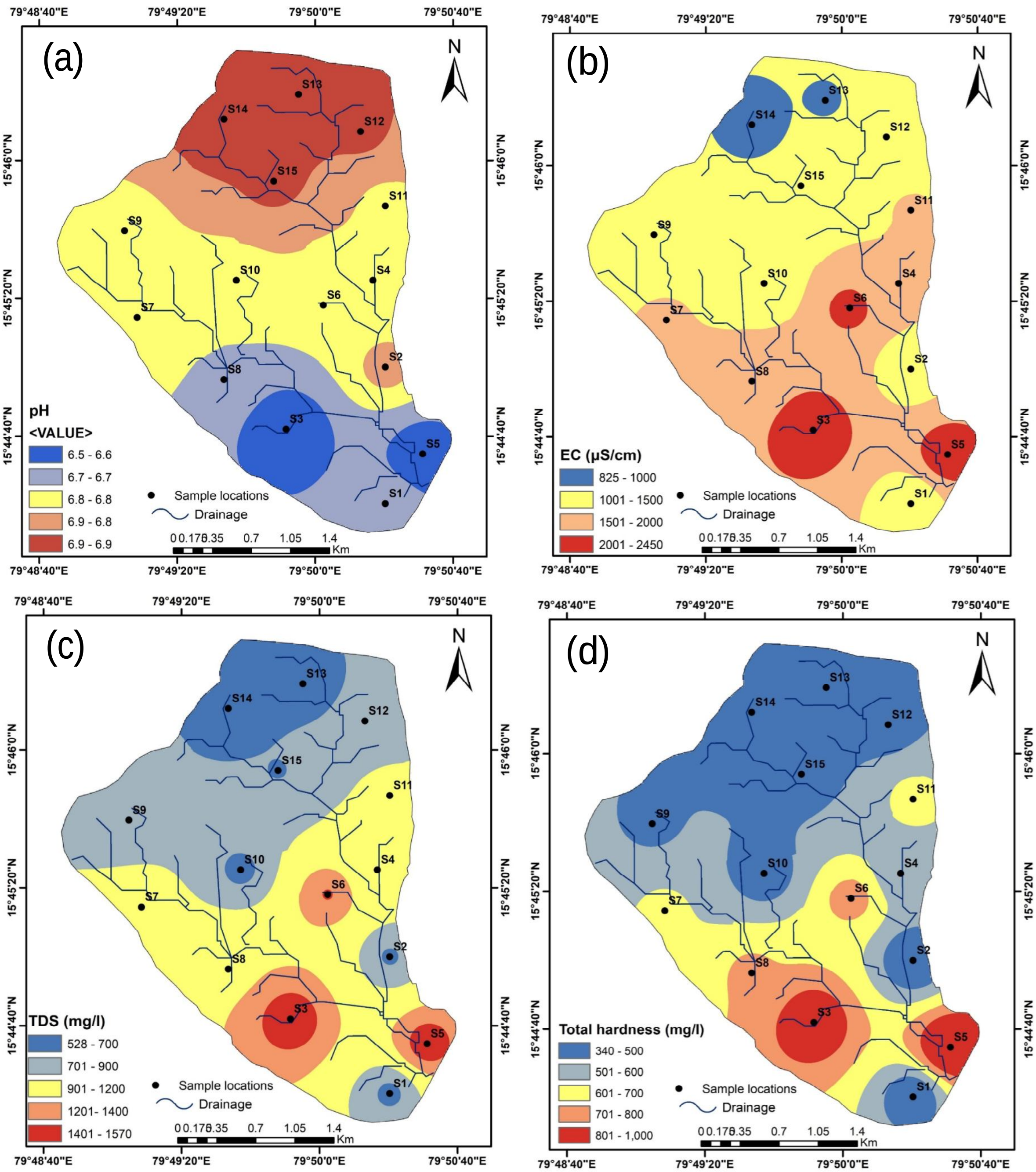

Figure 4: Spatial distributions of **a** pH, **b** electrical conductivity (in µS/cm at 20^{0}C), **c** TDS (in mg/L), **d** total hardness (in mg/L) in groundwater at Thurakapalem village, Prakasam district, Andhra Pradesh

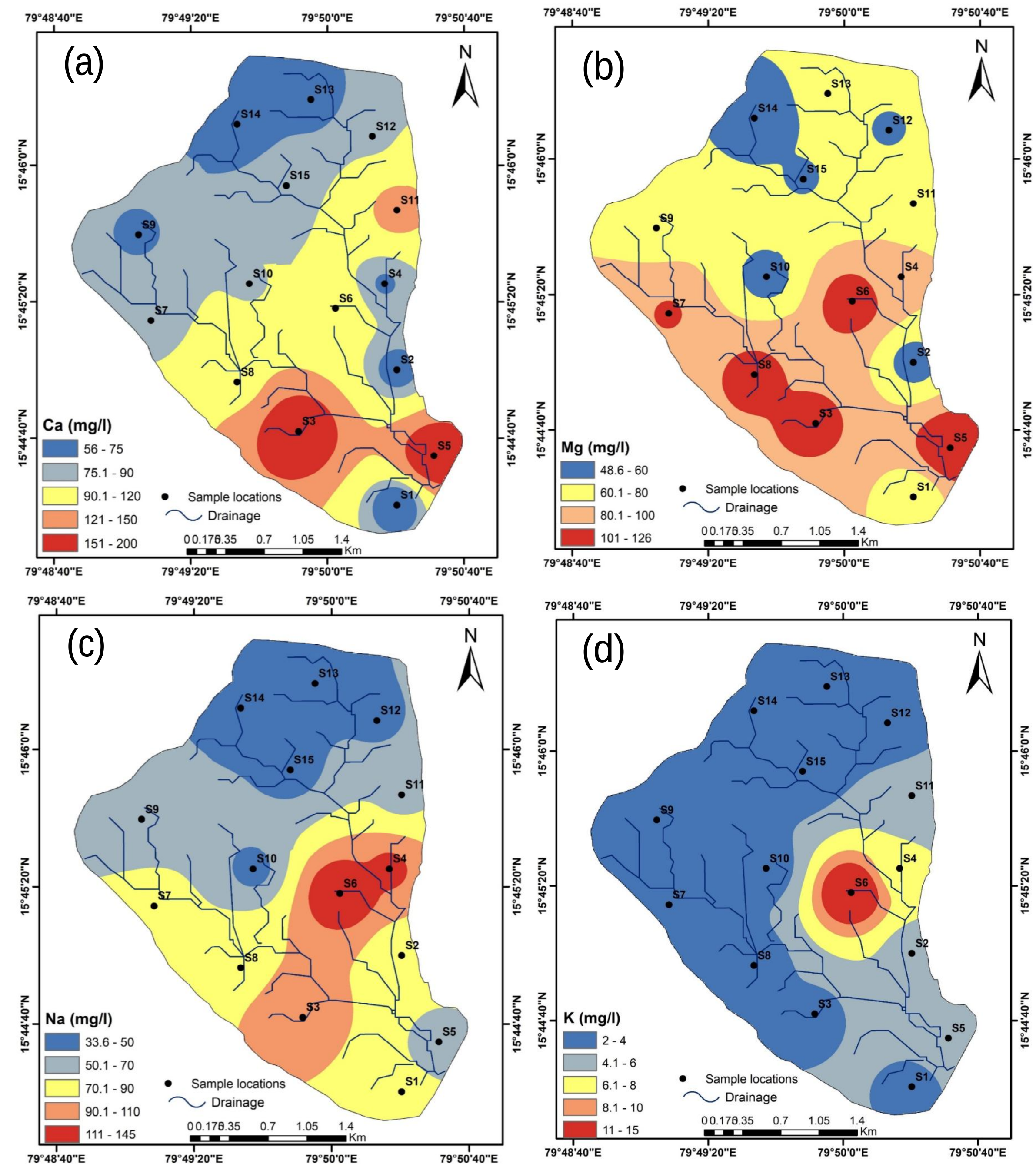

Figure 5: Spatial distributions of **a** calcium, **b** magnesium, **c** sodium, **d** potassium concentrations (in mg/L) at Thurakapalem village, Prakasam district, Andhra Pradesh

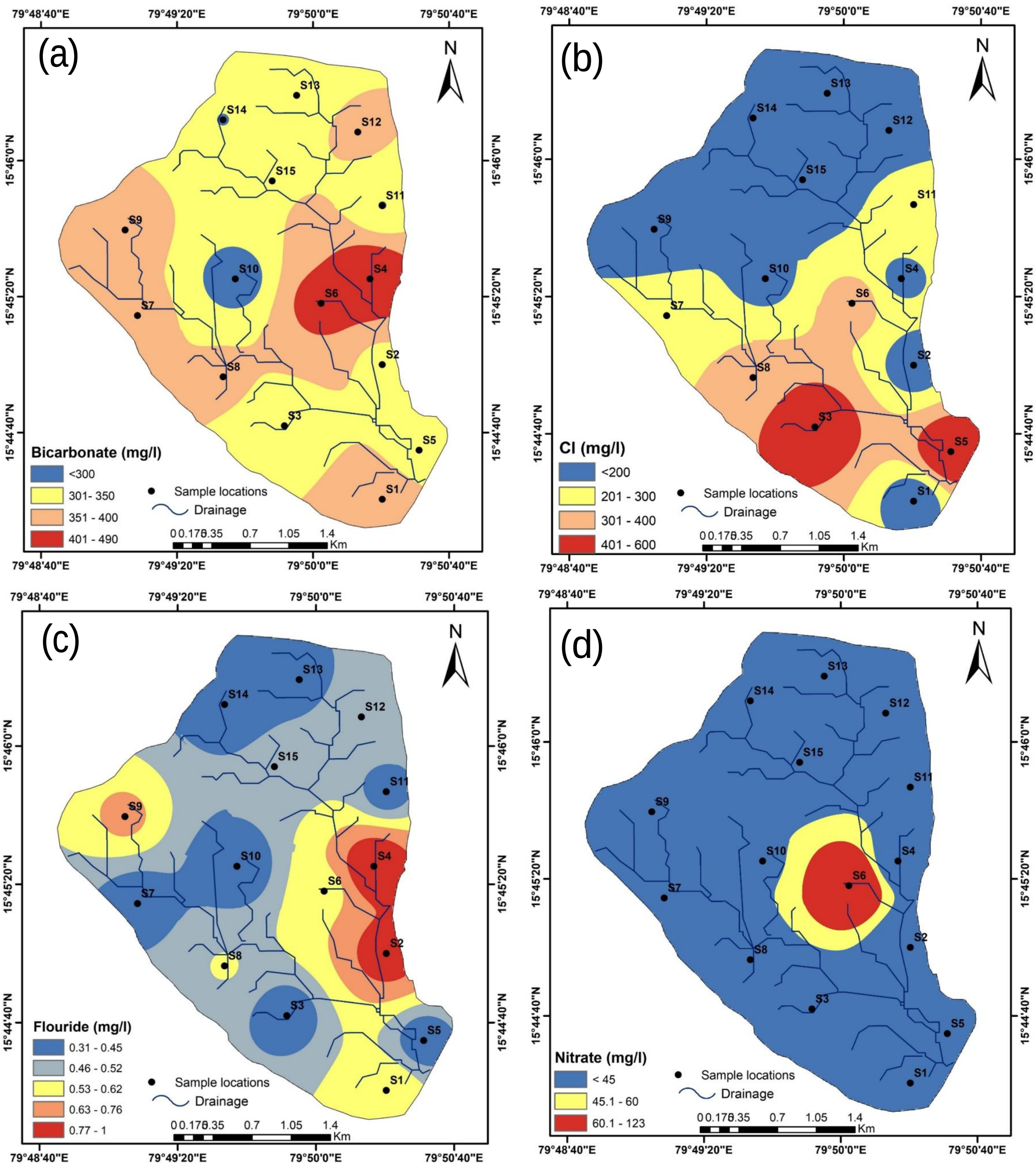

Figure 6: Spatial distributions of anions **a** bicarbonate, **b** chloride, **c** fluoride, **d** nitrate concentrations (in mg/L) at Thurakapalem village, Prakasam district, Andhra Pradesh

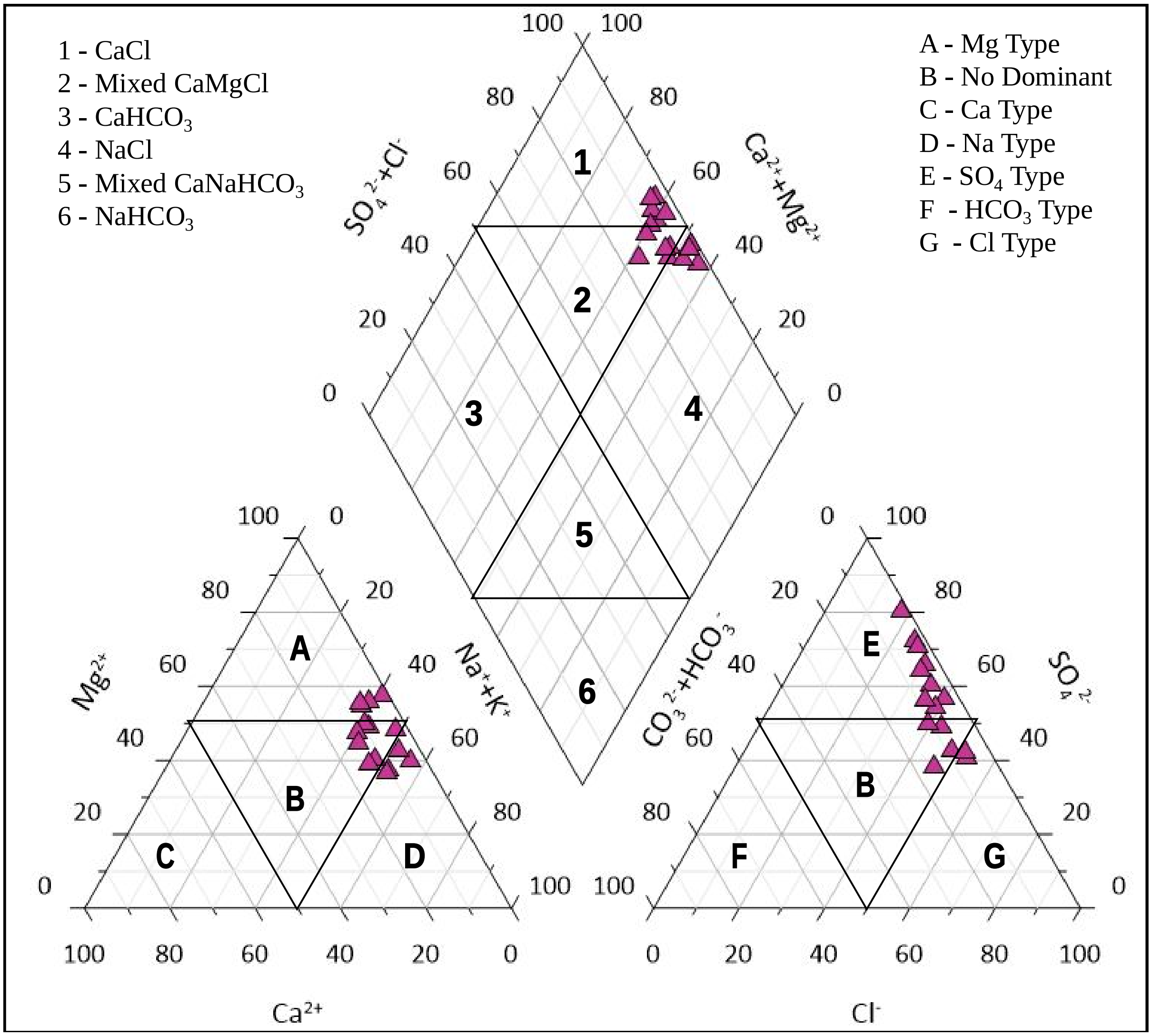

Figure 7: Showing the Piper's diagram for the groundwater types at Thurakapalem village, Prakasam district, Andhra Pradesh

3.8 US *Salinity Diagram*

In the USSL diagram, the EC and SAR of groundwater were presented. According to the results obtained, the most groundwater samples were classified as having high salinity and low sodium hazard (C3-S1), as presented in Table 4. It had proven that the quality of groundwater was appropriate for irrigation in this village. Only two samples at S3 and S5 were fallen on the very high salinity and low sodium hazard (C4-S1) type. Salinity high, may impact crop development, as well as produce osmotic and nutritional problems (Lauchli and Epstein, 1990). Therefore, the SAR was estimated as an indicator of sodium hazard, which varied from 0.74 to 2.28, with a mean of 1.28. The salinity hazard (EC in µS/cm) ranged from 825 and 2452 µS/cm, with an average of 1455.6 µS/cm (in Tables 2 & 3).

3.9 Sodium Percentage (Na%)

The porousness and texture of the soil are affected by the Na% in irrigation water. It also hardens the soil (Trivedy and Goel 1984). Thus, it is a vital role in categorizing water based on Na% (Wilcox 1955). The Na% of the samples varied from 12.37 to 33.45%, with an average of 21.72% at this village. The Na% values of groundwater samples at the village showed that about 46% of the samples fallen in the excellent category, and the remaining 54% of samples fallen in the good category (in Table 4).

3.10. Kelly's Ratio *(KR)*

The KR values calculated varied from 0.13 to 0.48, with an average of 0.27. (Table 4). The value of KR ≤1.00 specifies that the water is good for irrigation (Ayers and Westcot, 1985), In contrast, KR values > 1.00 are measured as suggestive of causing alkali hazards to the soils. It was found all the sampled waters were of "good" quality for irrigation purposes at this village.

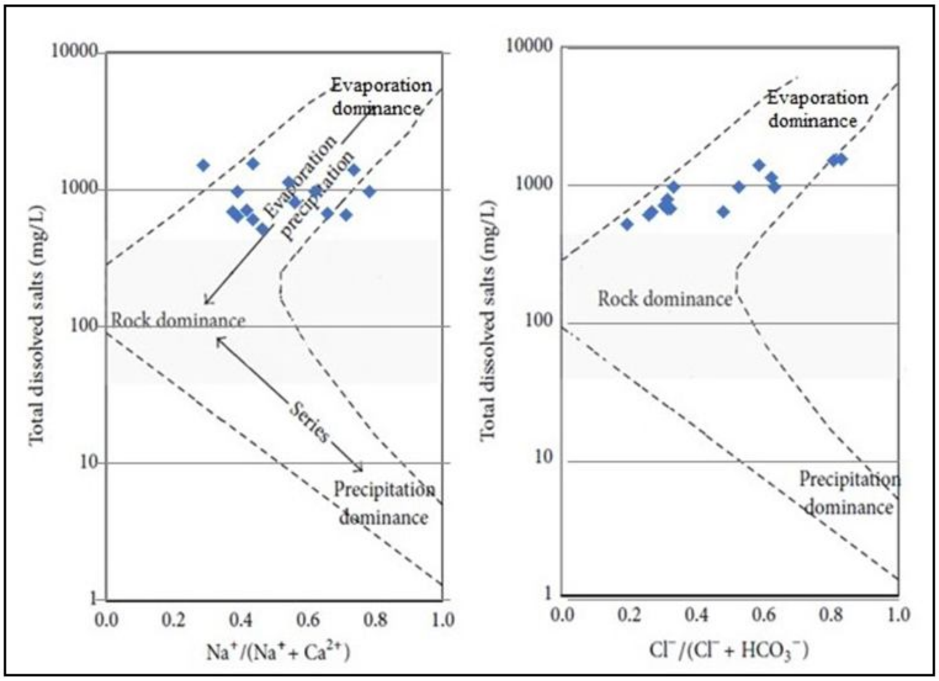

Figure 8: Showing the Gibb's plot of the collected groundwater samples at Thurakapalem village, Prakasam district, Andhra Pradesh

Table 4: Groundwater suitability for the irrigation purpose based on several indices at Thurakapalem village, Prakasam district, Andhra Pradesh

Groundwater classes	Range	(%) of the samples	Sample nos.
Based on EC in µS/cm			
Excellent	<250	-	-
Good	250-750	-	-
Fair	750-2250	86.60	S1,2,4,7-15
Poor	>2250	13.30	S3,5,6
Based on Na%			
Excellent	<20	46	S3,5,8,10-15
Good	20-40	54	S1,2,4,6,9
Permissible	40-60	-	-
Doubtful	60-80	-	-
Unsafe	>80	-	-
Based on SAR			
Excellent	<10	100	All
Good	10 to 18	-	-
Fair	18-26	-	-
Poor	>26	-	-
Kelley's Ratio			
Good	$\leq$1.00	100	All
Not good	>1.00	-	-
MAR			
Suitable	<50	20	S3,10,11
Not suitable	>50	80	S1,2,4-9,12-15
CR			
For any pipes	<1.0	53.3	S-1,2,4,9,12-15
Only for PVC pipes	>1.0	46.6	S-3,5-8,10,11

3.11 Magnesium Absorption Ration *(MAR)*

Szaboles and Darab (1964) proposed the MAR as one of the hydrochemical indicators for determining water quality for irrigation. Generally, the water has Mg^{2+} and Ca^{2+} concentrations to maintain a condition of equilibrium. Nevertheless, declining water levels increase water salinity, which reduces agricultural productivity (Joshi et al. 2009). A high MAR value (>50%) has a harmful impact on both soil fertility and crop yield (Subba Rao et al., 2012). The range of MAR values were from 46.86 to 67.78%, with a mean of 57.48%, which indicates that only 20% of samples were suitable for the irrigation.

3.12 Corrosivity Ratio *(CR)*

The groundwater Corrosivity Ratio (CR) of groundwater is critical when selecting water-supply pipes. This CR employs an electrolytic reaction between water and pipes. It occurs and rusts away the metal surface once it occurs. The majority of the cases are caused by salinity. Calculating the CR of groundwater samples is an essential aspect of both industrial and household activities. This detail of groundwater at Thurakapalem village is emphasized with the CR suggested by Ryzner (1944). The groundwater of CR<1.0 is considered safe for transmission via any pipe, however, groundwater with a CR>1.0, is harmful and should not be supplied through metallic pipes (Mondal et al., 2016). The CR was determined using equation (6). In this village, the CR values varied from 0.52 to 4.77, with an average of 1.71. About 53.3 % of monitoring wells with a corrosivity ratio less than 1.0 could be transported using any kind of pipe (Rahman et al., 2020a), whereas the remaining 46.6 % of the wells with a CR> 1.0 required only PVC pipes for both drinking and irrigation needs. Figure 9 shows the spatial distribution of CR values, and it indicates the lower CR values in the northern part of the area. The remaining part in the southern site had shown that the CR values were higher. The well waters at S-3, 5-8, 10, and 11 (in Table 4) were only suitable for PVC pipes for the transportation of groundwater.

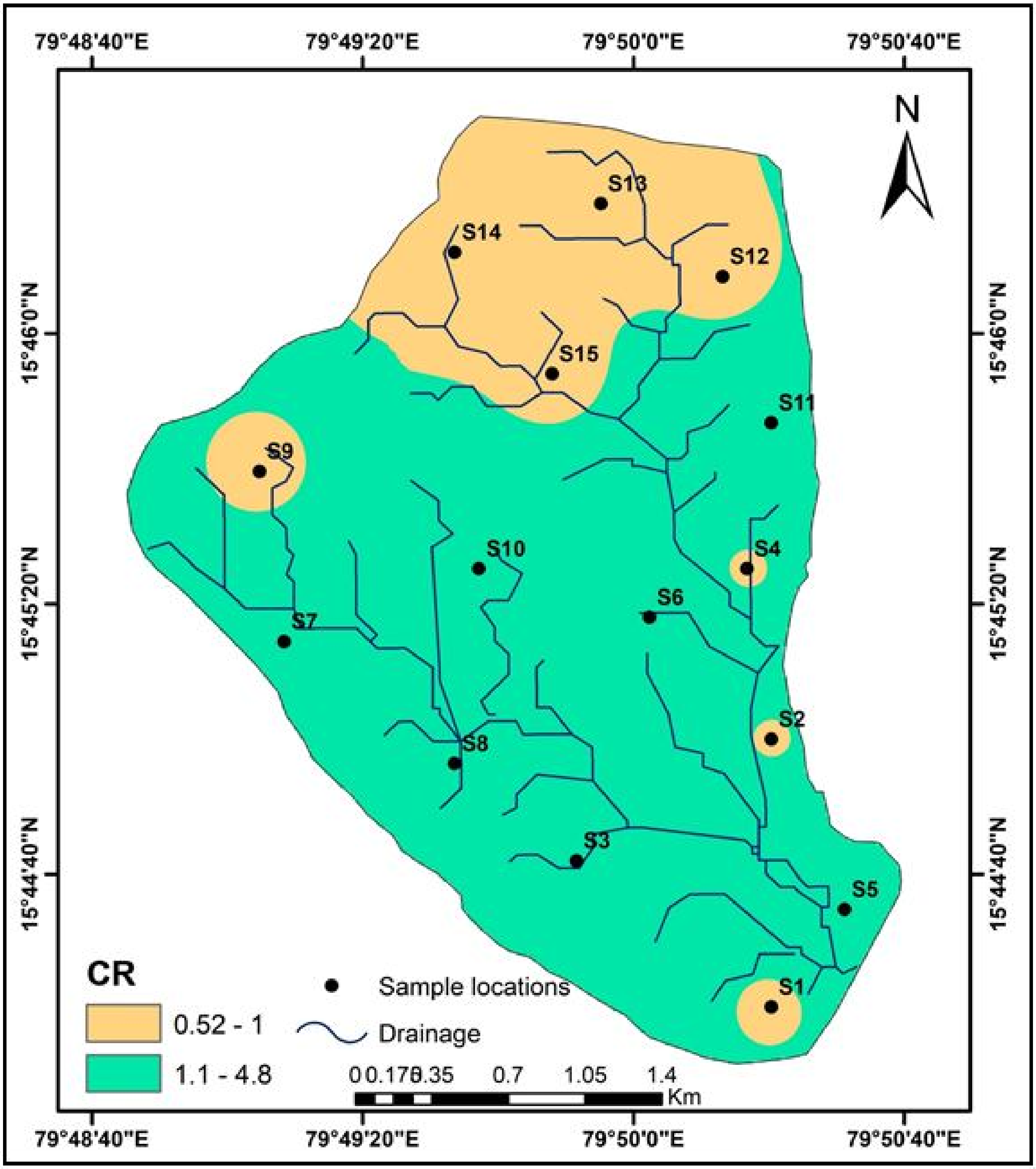

Figure 9: Spatial distribution of Corrosivity Ratio (CR) at Thurakapalem village, Prakasam district, Andhra Pradesh

3.13 Non-Carcinogenic Health Risks

Human health risks of men, women, and children had been calculated separately as per the USEPA standards (2014), as presented in Table 5 showing the THI and HQ due to the ingestion of NO_3^- and F^- for children, women, and men at each well site. The HQ-F^- ranged from 0.20 to 0.64 for males, with an average of 0.33, while for females and children, the varied from 0.23 to 0.76, and 0.27 to 0.87, respectively. The value of HQ-NO_3^- varied from 0.19 to 2.95 for males, with a mean of 0.84, whereas for females and children, they varied from 0.23 to 3.49, and 0.26 to 3.99, respectively. The maximum value of HQ-NO_3^- was encountered at the well-S6 located at the center of village, indicating that the NO_3^- concentration is a possible non-carcinogenic issue and may have adverse health consequences in the following order: children (3.99) > women (3.49) > men (2.95). THI values ranged from 0.58 to 3.30 (mean: 1.17) for men, 0.69 to 3.90 (mean: 1.39) for women, and 0.79 to 4.46 (mean: 1.59) for children (Table 5). In the present investigation, the percentages of THI obtained for males and females were 60% and 73%, respectively, of the samples, groundwater over the reference value (THI = 1.00), while about 80% of the samples (at the well-S-6,9,12,5,11,10,13,4,8,15,3, and 2) surpassed the maximum permissible limit of THI for the children, as shown in Figure 10.

This study was only based on the major ions of the collected groundwater samples including NO_3^- and F^- concentrations. But the groundwater quality could be changed over-time, making it difficult to assess the long-term impacts of contamination with the help of one-time sampling. This can make it challenging to identify the specific sources of pollution/contamination, or to determine the effectiveness of remediation efforts at this rural area without the additional studies of trace elements and organic substances in soil, surface water bodies, and groundwater. There were also limitations in the analytical methods used to measure groundwater quality, which can affect the accuracy and precision of the empirical data obtained for this analysis. Also, the cost of the monitoring and sampling program can be prohibitively expensive, which was the limited scope of this study.

Table 5: Estimated the HQ and THI of non-carcinogenic risk due to F- and NO_3^- in groundwater at the rural area (Thurakapalem village), Southern India

Sample Id	**HQ-Fluoride**			**HQ-Nitrate**			**Total Hazard Index (THI)**		
	Men	**Women**	**Children**	**Men**	**Women**	**Children**	**Men**	**Women**	**Children**
S1	0.39	0.46	0.53	0.19	0.23	0.26	0.58	0.69	0.79
S2	0.58	0.68	0.78	0.23	0.27	0.31	0.81	0.95	1.09
S3	0.23	0.27	0.31	0.68	0.80	0.92	0.91	1.07	1.23
S4	0.64	0.76	0.87	0.51	0.60	0.69	1.15	1.36	1.56
S5	0.24	0.28	0.32	0.98	1.16	1.33	1.22	1.44	1.65
S6	0.35	0.42	0.48	2.95	3.49	3.99	3.30	3.90	4.46
S7	0.24	0.28	0.32	0.45	0.53	0.61	0.69	0.81	0.93
S8	0.34	0.40	0.46	0.79	0.94	1.07	1.13	1.34	1.53
S9	0.42	0.50	0.57	1.05	1.24	1.42	1.47	1.74	1.99
S10	0.20	0.23	0.27	1.00	1.18	1.35	1.20	1.42	1.62
S11	0.24	0.29	0.33	0.97	1.15	1.32	1.22	1.44	1.64
S12	0.33	0.39	0.44	0.90	1.07	1.22	1.23	1.45	1.66
S13	0.26	0.30	0.35	0.93	1.10	1.26	1.19	1.40	1.60
S14	0.23	0.27	0.31	0.37	0.43	0.50	0.60	0.71	0.81
S15	0.29	0.35	0.40	0.62	0.73	0.83	0.91	1.08	1.23

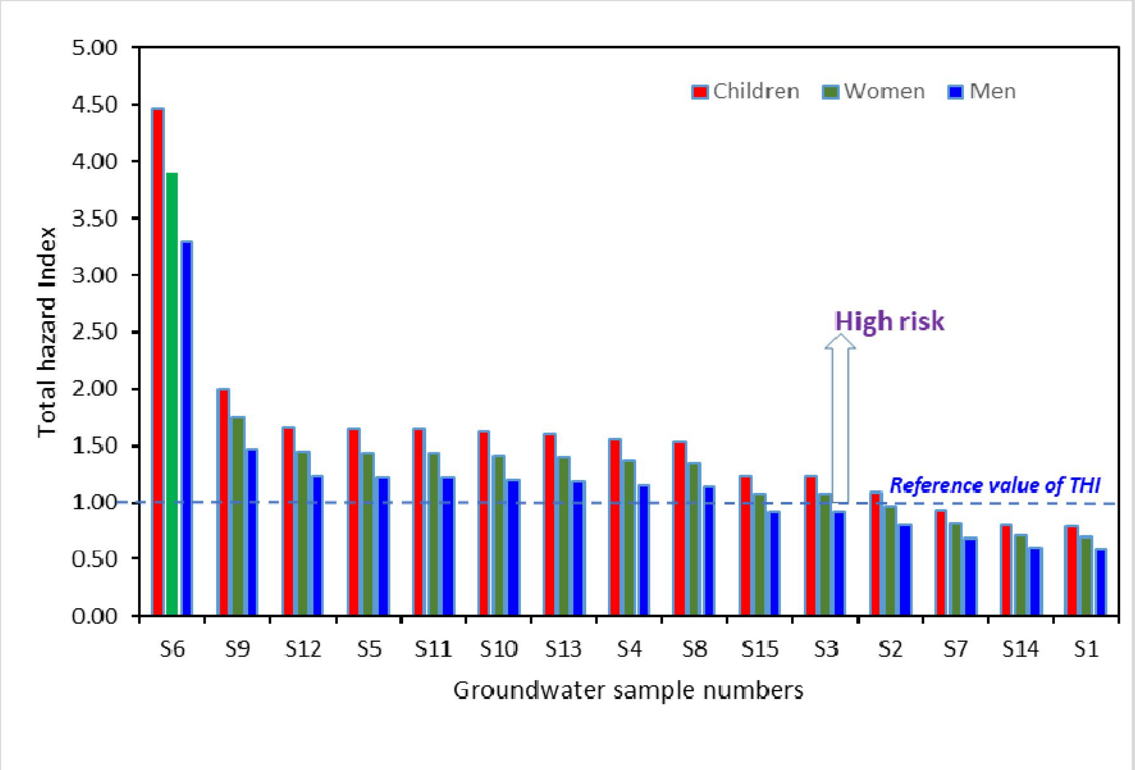

Figure 10: Variation of total hazard index (THI) at each well site for children, women, and men at Thurakapalem village, Prakasam district, Andhra Pradesh

3.14 Awareness and Leave No One Behind of Groundwater Management

The CSIR-800 Societal Program is mainly focused on the enhanced income and improving the quality of life of the 800 million people of India. In this program, this Thurakapalem village, Prakasam district, Andhra Pradesh was selected after evaluating the suitability of groundwater for both irrigation and drinking purposes on its quality. This initiative would go a long way toward ensuring effective groundwater resource management. It also raises public awareness and leave no one behind (LNOB) about the possible health risks associated with drinking groundwater, which contains a high concentration of F^- and NO_3^-, and other elements. Figure 11a shows that the discussion was taken place among local farmers considering the results obtained from the analytical hydrochemical analysis. One of the farmers, Mr. V. Purna Rao at this village said that in the summer season, they did not have sufficient water for the irrigation. Due to the poor groundwater quality at this village, many people of that village used the RO filter plant arranged by Gram Panchayat for drinking purposes. After the analysis of groundwater quality, it was informed the farmers that the nitrate concentration (>122 mg/L) of groundwater at S-6, as shown in Figure 6d was very high only in the central part of this village, and was above the permissible limit for drinking purpose. It had been advised that they should not use it. Groundwater quality in-term of TDS and TH values, as shown in Figures 4c, d, was not good in the southern part of this village, and advised to use only bore wells located in the northern part.

Transportation of groundwater for various purposes that the northern part of Thurakapalem village used only metallic pipes to the consumer end (in Figure 9). The PVC pipes could be utilized in the remaining part of this village. Based on the water quality study, people were warned against the utilization of contaminated groundwater for drinking. Also, it was suggested that the farmers should implement micro-irrigation techniques such as micro-sprinklers and drip irrigation, which will increase the area of cultivation with less water consumption. Controlling human activities, implementing rainwater harvesting systems, soil, and implementing water treatment methods, increasing public awareness, and creating a network for quality monitoring of groundwater were all mentioned as ways to improve groundwater quality and limit the number of bore wells in the area.

An increasing number of wells will make a sieve of our land! Bore wells should not be drilled beyond 60 m, and micro-irrigation would have to increase. A discussion with school children of MPUP Govt. School at Thurakapalem village was about the adverse impacts of poor water quality on human health, and agricultural lands (**Figure 11b**). They had learnt about the hydrological cycle, the origin of groundwater, and health hazard effects due to the consumption of poor-quality groundwater. The school students mainly benefited from this discussion by gaining knowledge about the importance of groundwater and its occurrence at this village, and how to manage the precious groundwater resources efficiently.

Figure 11: Created awareness of the favor supply based on the groundwater quality among a) farmers, and b) school children of MPUP Govt. School of Thurakapalem village, Prakasam district, Andhra Pradesh

4. CONCLUSIONS

Hydrogeochemical characterization and awareness programs are conducted for assessing groundwater quality to be used for irrigation and drinking at a rural area (Thurakapalem village), Prakasam district, Andhra Pradesh, Southern India. The results of empirical hydrochemical data are compared with the BIS and WHO standards. The major ions are in the descending order of HCO_3^-> $Cl^–$> NO_3^-> SO_4^{2-} > $F^–$, with a percentage of about 55% > 35.93% > 5.4% > 3.4% > 0.27%, and Ca^{2+}> Mg^{2+}>Na^+> K^+ contributing about 39% > 31% > 27.8% > 2.2%, respectively. At this village, the $Cl^–$, NO_3^-, and Ca^{2+} concentrations exceeded the permissible limits of 40%, 6.6%, and 53.3% of the analyzed samples. From the Piper diagram, three dominant hydrochemical facies such as Ca-Cl, mixed Ca-Mg-Cl, and Na-Cl types are found. The US Salinity diagram specifies that the maximum samples fallen in the high salinity and low sodium hazard (C3-S1 type) category, and groundwater quality is acceptable for irrigation. Only two samples (at the well-S3 and S5) are fallen in the very high salinity and low sodium hazard (C4-S1) type. The calculated parameters like EC, Na%, SAR, and KR show that almost all groundwater samples have of good quality for irrigation use. The corrosivity ratios show that about 53% of the monitoring wells (CR: <1.0) could be transported using any pipes, whereas the rest 47% well waters (CR> 1.0) require only PVC pipes while transporting groundwater for both irrigation and drinking uses. The range of NO_3^- concentration is from 8.0 10 122.7 mg/L which may be the main cause of health risk whereas the F^- concentration is within the permissible limit. The possible sources of NO_3^- pollution include agricultural fertilizers, animal waste, and septic tanks at this village. Overall the non-carcinogenic health hazards range from 0.58 to 3.30 (males), 0.69 to 3.90 (women), and 0.79 to 4.46 (children). About 60, 73, and 80% of the total samples are above the permissible limits for the THI=1.00 for men, women, and children, respectively. This risk study indicates that the children at this rural area are at a higher risk than adults due to NO_3^- toxicity-related health issues. Public awareness programs are arranged among small and marginal farmers, and school children at Thurakapalem village on the implications of groundwater quality on human health and irrigation practices, and rainwater harvesting techniques, which influences the sustainable development of groundwater resources at this village level.

5. ACKNOWLEDGMENTS

Director of CSIR-NGRI, Hyderabad has allowed and permitted to publication of this article (Ref. No: NGRI/Lib/2022/Pub-55). The first author has done this research work for the societal program of his Ph.D. Thesis under the DST-INSPIRE Fellowship (Ref. No: IF160571, dated: June 7, 2017). Director of Ground Water Department, Telangana has provided the analytical facility to analyze the groundwater samples. The authors are thankful to them.

6. CONFLICTS OF INTEREST

The authors declare no competing interest.

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