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Source Sustainability of Fractured Anorthositic Aquifer System in the Rarh Bengal and Socio-Cultural Implications

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Abstract

Hydraulic properties of fractured rock aquifers in the Bankura anorthosite were determined by test pumping at the Narrah test site in Rarh Bengal. The study area with a moderately high composite development index is socio-economically backward. Geological log showed occurrence of banded gneiss and Bankura anorthosite. The fractured aquifer occurs in depth range from 135.5 to 138.6 mbgl. The discharge is about 4.0 L/s with an air compressor, which was sustainable after 300 minutes of test pumping. A high well recovery of 93.11% shows the sustainability of the anorthositic aquifer. The field-based hydraulic conductivity matches with published mean hydraulic conductivity of anorthosite. Although transmissivity of the aquifer is low (<10 m^2/day), calculations show that the bore well would meet water requirement of 11.61% of the population of Narrah, thus aiding in solving the water scarcity problem of the area. Iron contamination in the area is attributed to colonial growth of iron-oxidizing bacteria and absence of ferruginous minerals in the geological log. Solutions to iron contamination are aeration and oxidation, followed by rapid sand filtration by installing iron removal plants through government funded schemes. Due to hydrogeochemical affinity of iron with platinum group elements, especially palladium as a pathfinder element, the area is strategically important for mineral exploration. A judicious management of the fractured anorthositic aquifer is recommended to address the water scarcity problem, which would improve the existing socio-cultural condition. The success can be replicated in other similar areas of the Rarh region with analogous hydrogeological conditions.

Keywords: Rarh; Bankura anorthosite; Fractured rock aquifer; Socio-cultural condition; Source sustainability

Introduction

Geological characteristics indicate that the anorthosite ($CaO.Al_2O_3.2SiO_2$) is categorized as a plutonic rock. Mineralogically the rock is almost entirely composed of plagioclase feldspar (90% or more) like oligoclase, andesine, labradorite or bytownite. In Precambrian shield area, anorthosites occur as layered complexes or as non-stratiform intrusions [1]. The massif type anorthosite of Proterozoic age consists of intermediate plagioclase (An-40 or An-60) of the plagioclase Solid Solution Series along with associated primary minerals like olivine, pyroxene, iron-titanium oxides, and apatite. In the present study, an attempt was made to characterize the fractured rock aquifers in the Proterozoic massif type Bankura anorthosite, by constructing a piezometer at Narrah village of the Rarh region in the State of West Bengal. Owing to its consolidated formation characteristics, the Down the Hole Hammer (DTH) drilling method was used to construct the piezometer. The key aims of the construction of the piezometer are to demarcate the fractured rock aquifers, estimate the aquifer parameters by test pumping, assess the source sustainability through characterization of the aquifer, and assess groundwater quality especially with reference to fluoride and iron contamination in groundwater. The site is situated about 10 km northeast of Bankura city and about 204 km northwest of Kolkata. The site is approachable from Kolkata *via* national highway-2 and Barjora-Beliator-Makurgram-Joykrishnapur road. Narrah village is a part of the Narrah gram panchayat with a geographical area of 79.76 ha. The village is located in Bankura-II community development block. As per Census 2011 data, the total population of the village was 3266, and the literacy rate was 71.49%. Considering a decadal population growth of 13.49%, the village population is estimated at 16923 in the current year 2024.

Socio-cultural and socio-economic conditions

The Scheduled Caste (SC) population in Narrah village was 1207, which is 37% of the total population. At regional scale, the population of the SC category was 41998, which is 29.81% of the population of Bankura-II block. Similarly, population of the Scheduled Tribe (ST) category was 3508, which is 2.49% of the block population [2]. Although the population of ST category in Narrah was insignificant (0.03% of the village population), entire Bankura district has been categorized as economically backward [3]. Histograms showing the demographic variations with reference to the socio-cultural condition are shown for Narrah village (Figure 1A) and for Bankura-II block (Figure 1B).

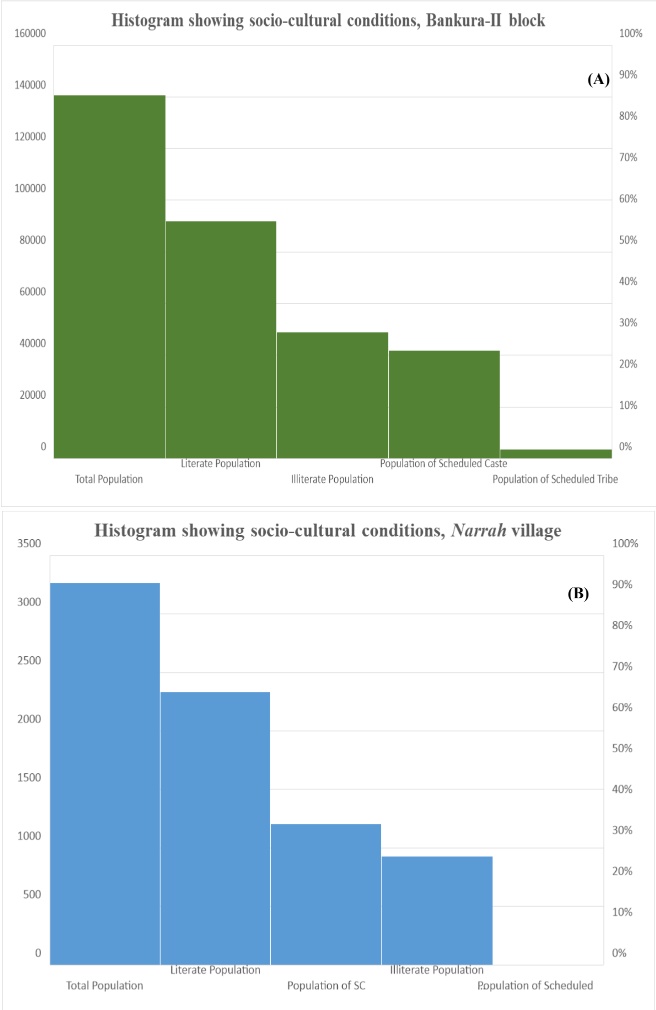

Figure 1: A) Histograms showing socio-cultural conditions Narrah village, B) In Bankura-II block.

The Bankura district receives financial aid through the backward region grants fund of the government of India. Published data shows that in Bankura-II block, 8400 families live Below the Poverty Line (BPL). The percentage of BPL families in Bankura-II block was a staggering 38.48%. Calculation of the Multidimensional Poverty Index (MPI), which measures poverty in terms of education, health and living conditions [4], Bankura district was assigned an MPI of 0.27. Using a logistic regression analysis, a positive correlation was found between the MPI and household income poverty. The MPI varies widely between castes and major occupational groups.

A Google Earth map of the area (Figure 2), showing the Rarh region of West Bengal, was used to visualize the different landforms and infrastructure in and around the test area. Visual analysis of the Google Earth map is a relatively simple and quick method to analyze the topography, drainage and man-made infrastructure. The location map shows that the Narrah test site is connected by a network of major and minor roads (steel grey colour) and by the railway track shown in black. The sandy areas along the river Dwarkeshwar in the southern part of the area appears as yellowish-brown bands. Vegetation is generally sparse, except for the dense forest in the south-central part, which appears dark green. A dense road network in the south-western part constitutes a part of the urban area of Bankura city.

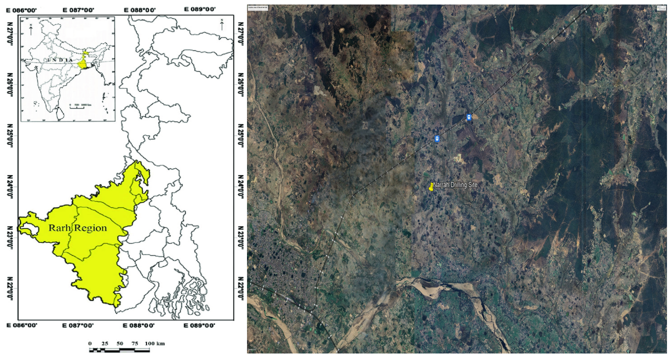

Figure 2: Google Earth map of the area showing Rarh region (inset).

Researchers often use the Composite Development Index (CDI) to assess the level of socio-economic development of rural populations. The CDI is calculated based on a statistical analysis of various socio-economic indicators related to demography, agriculture, livestock, education, health care, electricity supply, banking, transportation and water supply [5-7]. The sustainable supply of water to the villagers for drinking, domestic use and agricultural irrigation will increase the CDI and thus lead to a better livelihood for the small and marginal farmers.

Justification of the study

The study focuses on a part of Rarh Bengal where the socio-economic development is average as shown by a CDI of 0.123 in the Bankura-II community development block [6] where the Narrah test site is located. Overall, the CDI in the entire Bankura district is very low compared to other parts of the State of West Bengal. The rural population of Bankura district is heavily dependent on agriculture for their livelihood. Based on six categories of socio-economic development, the estimated CDI of Bankura-II block is 0.44, and the block is categorized as 'moderately developed' [7]. Murmu also pointed out the urgent need to improve various socio-economic indicators to transform the area into a 'well-developed block' with a CDI of >0.47. According to the District Human Development Report, the study area is prone to drought and 28 habitations were categorized as 'partially covered' as per the drinking water supply guidelines [3]. Even in Bankura City, the district headquarters, the poor socio-economic condition of the slum dwellers, which have little access to drinking water, was highlighted in a recent study [8]. Maji and Sarkar used the level of irrigation facilities as an economic indicator for calculating the index value (z-score) through a geospatial analysis at the block level in district Bankura [5]. The study area was characterized by very low development in irrigation facilities with a negative index value ranging from -1.42 to -1.02.

According to the latest estimate of dynamic groundwater resources, the stage of groundwater extraction in Bankura-II block was estimated at 24.39%, indicating that the area falls into a “safe” category [9]. However, no attempt was made to quantify groundwater resources of the deeper, fractured rock aquifers (>100 m depth), thereby limiting the scope of a holistic assessment of both the weathered and the fractured rock aquifers at a regional scale. The source sustainability of the deeper, fractured rock aquifers (Aquifer-II) was also not comprehensively assessed during any previous study. Hydrogeological investigations and aquifer tests in the Bankura-II block have shown that discharge of bore wells in the fractured aquifer systems is generally low, often <1 L/s [10]. The present study aims to improve the socio-economic situation of the area by ensuring water supply to rural households through supply-side management of the fractured

Bankura anorthosite aquifer. The importance of sustainable water supply through bore wells tapping the fractured aquifer is of great importance for improving the livelihood of the large scheduled caste and scheduled tribe population (about 37% of the village population at Narrah) living below the poverty line.

Materials and Methods

For drilling the test well at Narrah, a DTH (Down the Hole Hammer) drilling rig (Model: DTH/KLR-15/135) was used, which was capable of drilling through the weathered zone at a shallow depth (<30 m) and laying a steel pipe of 178 mm (7 inch) diameter. During the drilling through the shallow weathered zone, a 254 mm (10 inch) diameter button bit was used to drill up to a depth of 27.0 mbgl. The massive and fractured hard rock (banded gneiss and Bankura anorthosite) was drilled up to a depth of 150.8 mbgl using a 6.5 inch (165 mm) diameter button bit. During the field test, a handheld Garmin Etrex 30x Global Positioning System (GPS) receiver was used for geo-location. A 20X magnification pocket lens was used to study the lithology and structure of the rock fragments in detail, including patterns of fractures, joints, and gneissic banding. A rust-resistant Galvanized Iron (GI) sample preservation box with 48 compartments was used to store the rock samples for lithological and structural analysis.

The aquifer test was carried out using an Encardio Rite electrical water level sounder having 100 m cable length. During the Preliminary Yield Test (PYT), the Kirloskar air compressor with a capacity of 250 PSI was used to pump the well. The controlled discharge of the well was measured using a rust-resistant GI V-notch weir plate, placed in an open channel approximately 15 m long and 0.6 m wide to measure the height of the water column (H), which was converted to discharge (Q) using a standard empirical relationship:

$$Q=1380 \times H^{2.5} \quad \text{Equation (1)}$$

Where Q is in L/s and H is in m.

During the test pumping, the compressor was operated at a capacity of 350 PSI for 100 minutes, followed by a 200-minute recovery test. Recovery data was recorded at 1-minute intervals for the first 10 minutes, 2-minute intervals for the next 20 minutes, and 5-minute intervals for the next 30 minutes. During the end phase of the recovery test (from 60 to 200 minutes), a uniform time interval of 10 minutes was used to measure the recovery water level. The residual drawdown (s') and the ratio of time since pumping started versus time since pumping stopped (t/t') were used to estimate the transmissivity (T) of the Bankura anorthosite aquifer.

Results

Geology

In the state of West Bengal in India, the Bankura Anorthosite Complex (BAC), also well-known as the Bengal anorthosite massif and is described as a “tadpole-shaped” massif. The formation is present over an area of about 250 km^2 and is occurring in the high-grade metamorphic rocks of the granulite facies along the eastern margin of the Proterozoic Chotanagpur Granite-Gneiss Complex (CGGC). The geology of the CGGC comprises high-grade basement gneiss, including quartz-feldspar gneiss, biotite-hornblende gneiss, hornblende gneiss, migmatite, charnockite, and leptynite. The gneissic rocks contain inclusions of supracrustal metasedimentary rocks such as calc-silicate granulite, quartzite, mica schist, sillimanite schist, khondalite, and quartz magnetite. The rocks of the CGGC are intruded by mafic-ultramafic, massive anorthosites, and granitic rocks [11]. Published research shows that the plagioclase-feldspar cumulates in the core are aligned by magmatic flow, whereas the euhedral plagioclase crystals are aligned along the anorthosite dykes in the Bengal anorthosite massif [11,12]. The basement of the anorthosite massif has the shape of a plate [13] or an inverted cone or wedge as inferred from gravity data [14]. Radiometric age determination of uranium-lead zircon in a Thermal Ionization Mass Spectrometer generated an age of 1550 ± 2 Ma for the Bankura anorthosite complex [15]. The gneissic rocks of CGGC and different varieties of Bankura anorthosites are mapped in detail along the geographical stretch of Saltora-Ledapalash-Kusthalia-Nandanpur section [12,16]. The studies reveal that the thickness of BAC is less than 200 m with a high gravity of 20 milli Gals in the eastern part of the BAC and low gravity of 4-5 milli Gals in the western part of the complex [14].

The exploratory drilling at Narrah piezometer construction site at Bankura indicates that the weathered laterites and fragments of Chotanagpur Granite Gneiss (CGG) are present at shallow depth of around <30 metre below ground level (mbgl), whereas crushed rock fragments of the CGG were documented at intermediate depth (>30 to ~85 mbgl). Further, the Bankura anorthosites were observed at deeper levels (>85 to ~143 mbgl) and fragments of the CGG were recorded at the bottom-most part (within ~143 to ~151 mbgl). A study of the geological log (Table 1) indicated the presence of grey, white, and mottled varieties of the Bankura anorthosite. A pocket lens of 20X magnification was used to identify quartz and K-feldspar and fine gneissic bands, microfractures, and joints. A pie chart showing the depth-wise distribution of the major lithological types is presented in Figure 3.

Depth range (m)		Geological characteristics
From	To	
0	6.1	Laterites, weathered and friable, yellowish brown coloured.
6.1	24.4	Crushed rock fragments, grey to yellowish grey coloured, mixed with clay matrix and quartz (gneissic rocks of the CGGC).
24.4	85.4	Gneissic rock fragments (nominal size: 5 mm to 2 cm) of variegated colour (grey, flesh red, and black); K-feldspar and fine gneissic banding identified using a pocket lens.

85.4	128.1	Highly angular rock fragments of variegated colour but appear greyish white in bulk samples; white, mottled, and grey variety of the Bankura anorthosite.
128.1	134.2	Boulder, cobble and pebble-sized, angular rock fragments of gneiss of the CGGC; fine gneissic banding identified with a pocket lens.
134.2	143.4	Pebble to granule-sized, angular, and crushed fragments of the Bankura anorthosite, fracture zone identified from 135.5 to 138.6 mbgl.
143.4	150.8	Crushed rock fragments of micaceous gneiss with flakes of muscovite and biotite; gneissic rocks of the CGGC.

Table 1: Geological log at Narrah test site.

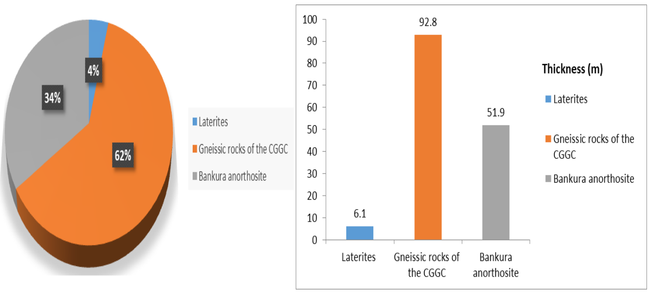

Figure 3: Depth-wise distribution of major lithological types, Narrah test site

Figure 3 shows that the thickness of the metamorphic rocks of the CGGC (92.8 m) constitutes 62% of the total thickness (150.8 m) in the geological log, while the thickness of the Bankura anorthosite (51.9 m) is represented as 34% of the total thickness of the geological log. The thickness of laterites (6.1 m) is only 4% of the thickness of the geological log, representing the shallowest depth in the drilling record in Narrah test site.

General hydrogeology and exploratory drilling

A study to map the groundwater potential in this area using thematic layers of hydrogeomorphology, lithology, and gradient and lineament density has shown zones of very good, good, medium, and poor groundwater potential using the weighted index overlay model [17]. A study of water logging and landscape in the North-Western part of Bankura district, which includes the drought-prone blocks of Gangajalghati, Mejhia and Saltora, has shown a minor, but gradual decline in groundwater table by 1.85 cm/year [18]. In the hard rock areas of peninsular India, fractured aquifers in the anorthosites are reported to yield <2 litre per second (L/s). However, the detailed geophysical surveys in the peninsular India have revealed the presence of potential fracture zones [19]. However, a detailed study on aquifer characterization in the area using pumping test at controlled discharge is lacking. Based on the field test in Narrah test site, the Bankura anorthosite aquifer has shown a sustainable air compressor discharge of about 4 L/s. A submersible pump with a capacity of 10 HP is expected to deliver ~6 L/s, which is sufficient to meet the water demand for drinking and domestic purposes as the area is water-scarce and drought-prone. As there are no major surface water sources in the area in the form of year-round flowing rivers, groundwater is the only resource for the community's water supply.

The Static Water Level (SWL) at the test site was 5.79 mbgl. An investigation of the lithological samples collected from the drilling revealed the presence of fractured rock aquifers in the Bankura anorthosite in the depth range of 135.5 to 138.6 m. During the systematic hydrogeological survey and correlation of borehole lithology under the national aquifer mapping and management project by CGWB, two aquifer systems were identified. The shallow aquifer (Aquifer-I) occurs at a depth of 6.0 to 18.0 mbgl and the deeper fractured rock aquifer (Aquifer-II) occurs at 35.0, 70.0 and from 135.0 to 139.0 mbgl [10].

Well design

In the geological log at Narrah test site, a fracture zone of 3.1 m thickness was identified in the depth range from 135.5 to 138.6 mbgl. During the pumping test, which included both pumping and recovery data to characterize the response of the fractured rock aquifer, the well discharge was sustained during the test period of five hours. The pumping test was conducted using an air compressor with a capacity of 350 Pounds per Square Inch (PSI). Based on the geological log, the recommended well design at the Narrah test site is prepared (Table 2).

Depth range	Pipe diameter	Pipe length (m)	Description
0.5 magl–27.0 mbgl	7-inch (177.8 mm)	27.5	Mild steel blank casing pipe
27.0–150.8 mbgl	--	--	Uncased well

Table 2: Well design, Narrah test site.

Well hydraulics and aquifer properties

A Preliminary Yield Test (PYT) was conducted in the piezometer at Narrah test site, during which depth to water table data was recorded during 100 minutes of pumping and 200 minutes of recovery. Field photographs of recording the compressor during the PYT is shown in Figure 4a and the discharge measurement using 90° V-notch weir plate is shown in Figure 4b. Data on well hydraulics obtained during the PYT is summarized in Table 3.

Figure 4: a) Discharge of the bore well during the preliminary yield test at Narrah 4, b) Measurement of discharge using 90° V-notch weir plate.

Static water level (SWL)	5.79 mbgl
Pumping water level (after 100 minutes)	39.90 mbgl
Maximum Drawdown	34.11 m
Recovery water level (after 200 minutes)	8.14 mbgl
Sustainable Discharge	3.91 L/s, 337.82 m^3/day

Table 3: Data on well hydraulics, Narrah test site.

The well Recovery (R_w) was 93.11% after 200 minutes of recovery, which is calculated as follows:

R_w=((34.11–2.35)/34.11) × 100%

=93.11 %

The high well recovery (>90%) indicates that the fractured rock aquifer is sustainable at a discharge of 3.91 L/s, which is significant as the area is drought prone. Transmissivity of the aquifer was estimated using the recovery method, in which the ratio t/t' is plotted against the residual drawdown (s'), shown in Figure 5.

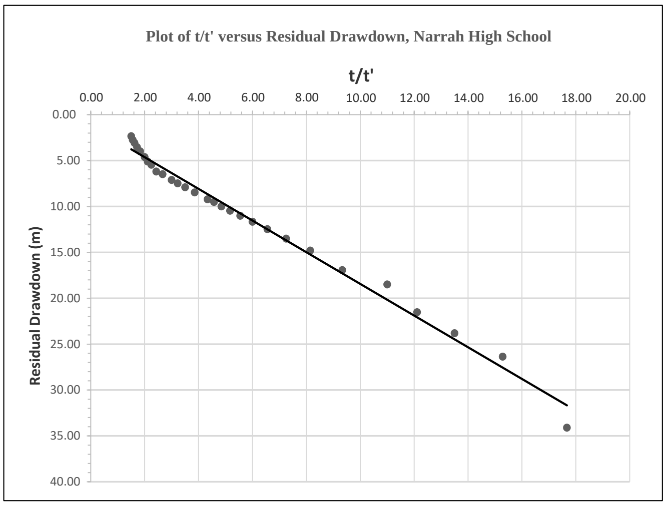

Figure 5: Theis recovery plot, Narrah test site.

The following parameters were measured during the PYT at Narrah:

Discharge (Q)=3.91 L/s=337.82 m^3/day

Residual drawdown change per log cycle of time ($\Delta s'$)=17.0 m

Transmissivity (T)=(2.303 Q/(4π$\Delta s'$)) m^2/day=3.64 m^2/day

The Transmissivity of fractured anorthosite aquifer is >1 but <10 m^2/day, which is categorized as low [20]. However, as the well discharge is sustainable even after 6 hours of pumping, the bore well at Narrah will be suitable for water supply at the community level. Using the saturated aquifer thickness (b), which is the thickness of the fracture zone (3.1 m) and the field-derived value of transmissivity (3.64 m^2/day) at Narrah, the hydraulic conductivity (K) of the Bankura anorthosite aquifer is estimated using the equation:

$T=K.b$ Equation (2)

$K=T/b$ Equation (3)

Hydraulic conductivity (K)=(3.64/3.10) m/day=1.17 m/day

The field-derived hydraulic conductivity at the Narrah test site is similar and comparable to the mean hydraulic conductivity of anorthosite aquifers (2.16 m/day) obtained by specific capacity tests in 516 sites and short duration pumping tests in 21 sites in the Saguenay watershed of Quebec Province, Canada [21]. Although the Bankura anorthosite aquifer is expected to solve the problem of water scarcity at the community level, several tests on source sustainability need to be taken up on a larger scale. It is expected that a series of bore wells tapping the Bankura anorthosite aquifer would cater to the drinking water requirement of the stakeholders at the block and district level through large-scale projects funded by the government. An assured water supply on a regional scale would improve the existing socio-economic conditions, which would be reflected by an increase in the CDI of the rural populace.

Groundwater quality

Hydrogeochemical modelling with PHREEQC in the Precambrian Egersund anorthosite in Norway [22] has shown a geochemical evolution trend with high pH, low-calcium, and high-sodium groundwater in the crystalline bedrock aquifers. The temporal geochemical evolution of groundwater during water-rock interaction with an anorthosite aquifer is satisfactorily explained by weathering of plagioclase feldspar with concomitant precipitation of calcite. In the Indian context, Nag and Das [23] reported that groundwater samples collected from bore wells in parts of the Bankura-II block (Bikna-

Makurgram-Dhumara-Khemua-Pratappur section) have an abundance of the major ions as follows: HCO_3>Cl>SO_4 and Ca>Na>Mg>K. The analysis of the suitability of groundwater for irrigation was carried out using the USSL classification, which showed that the groundwater is suitable for irrigation as the samples belong to classes C1S1, C2S1 and C3S1. Following a standard method [24,25], the authors while calculating the Water Quality Index (WQI) in Bankura block-I and Bankura block-II found that during the pre-monsoon season, 89% of the water samples are suitable for drinking, with WQI ranging from excellent (0-25) to good (26-50). However, in the post-monsoon season, about 30% of the samples are not potable (WQI>100). The fluoride and iron contamination in groundwater was not investigated during the study.

In Peninsular South India, a hydrogeochemical study [26] in the Sittampundi anorthosite complex in Tamil Nadu has highlighted the potential for exploration of Platinum Group Elements (PGE) during rock-water interaction in a suite of gabbro, pyroxenite, amphibolite and anorthosite with bands of chromitite. High Resolution Inductively Coupled Plasma Mass Spectrometer (HR-ICP-MS) was used to analyse groundwater samples collected from 26 bore wells and 11 dug wells along the Sittampundi-Chinnapalayam-Pamandapalyam-Tottiyanatham-Vadivelpalayam-Karungalpatti section. The study has shown that PGE, especially palladium (Pd), ruthenium (Ru), and Rhodium (Rh) are leached under favourable Eh-pH conditions. During water-rock interaction in the Sittampundi anorthosites, Pd was mobilized in the alkaline environment and widely dispersed in groundwater samples following the drainage pattern in the catchment area.

During hydrolysis of plagioclase feldspar in anorthosites, there is a possibility of leaching of aluminum (Al) from the aquifer material into groundwater during the water-rock interaction. Published research has shown aluminium toxicity in groundwater in the spring water of Obninsk and Kaluga region in Russia [27], where the maximum aluminium concentration (0.65 mg/L) has exceeded the maximum allowable concentration of 0.50 mg/L. It is suggested that alunimium concentration in the Bankura anorthosite and the groundwater in the study area should be measured periodically to assess the possible toxicological effect of aluminium on human health and to suggest possible remedial measures.

A hydrochemical study under the national project on aquifer mapping and management revealed a double aquifer system at a regional scale [10]. The shallow aquifer (Aquifer-I) occurs in the weathered zone from 6 to 18 mbgl. This aquifer is free of fluoride contamination as the maximum fluoride concentration (0.94 mg/L) is below the acceptable limit for fluoride. In the deeper, fractured aquifer (Aquifer-II), which occurs at depths of 35, 70 and 135-139 mbgl, the maximum fluoride concentration was 1.62 mg/L, which is above the permissible limit [10]. Fluoride contamination in the Bankura-II block was also reported by the public health engineering Directorate, the nodal agency for water supply and distribution in the state of West Bengal. However, the comprehensive correlation between aquifer depth and fluoride concentration in groundwater is lacking in the area. To assess the quality of the groundwater with special reference to fluoride and iron, the samples were analyzed at the NABL-accredited chemical laboratory of CGWB, Kolkata (Table 4).

pH	EC (µS/cm) at 25°C	Concentration (mg/L)												
		TH (as $CaCO_3$)	Ca	Mg	Na	K	Cl	TA (as $CaCO_3$)	HCO_3	SO_4	NO_3	F	TDS	Fe
7.31	391.3	165	28	23	10.6	1.2	25	170	207	0.83	0.92	0.59	217	1.29
TH: Total Hardness; TA: Total Alkalinity; TDS: Total Dissolved Solids														

Table 4: Groundwater quality, Narrah test site.

The hydrochemical data show that all parameters are below the acceptable limit of the drinking water guidelines, except for the high iron content (1.29 mg/L). Fluoride contamination in groundwater is not observed at the Narrah test site, which indicates spatial variability of fluoride in the deeper aquifer (Aquifer-II) on a regional scale. The presence of iron in groundwater above the desirable limit (>0.3 mg/L) has caused discolouration of dishes in nearby households, an elementary school, and a high school. When the groundwater is used for drinking, it is aesthetically unpleasant as it has a bittersweet aftertaste due to its high iron content. As the geological record does not contain any iron-bearing minerals, the possibility of iron contamination through the interaction between water and rock has been ruled out. Iron contamination in the fractured Bankura anorthosite is attributed to the growth of iron-oxidising bacteria. During the field investigation, the proliferation of iron-oxidizing bacterial colonies was observed as floating, reddish-brown layers in village ponds in and around the test site (Figure 6).

Figure 6: Iron contamination due to proliferation of iron-oxidizing bacterial colony (marked in yellow) in a pond about 100 m North-West of the test site.

The hydrogeochemistry of anorthositic aquifer system with reference to the water-rock interaction was studied with special reference to the Platinum Group Elements (PGE) in the Sittampundi anorthosite complex, Tamil Nadu [26]. The study revealed a positive correlation between iron and palladium (r^2=0.05) in the Sittampundi layered anorthosite complex. The authors have concluded that Pd may be effectively used as a pathfinder element due to its high geochemical mobility in the low Eh-high pH environment typically found at deeper levels where fractured anorthosite aquifer is tapped for rural water supply. Due to the high iron content in the Bankura anorthosite aquifer at the Narrah site and the positive correlation between iron and Palladium (Pd) in the fractured aquifers, the test site may become strategically important for the exploration of the PGE using Pd as a pathfinder element. A detailed hydrogeochemical study on the modelling of trace elements and the PGE may be useful in mineral exploration of the precious PGE in this part of Rarh Bengal.

Bacteriological analysis of groundwater at the Narrah site will be required to confirm the role of iron-oxidising bacteria for iron contamination in groundwater due to the organic source [28]. Sharma et al. have demonstrated the removal of excess iron in groundwater by aeration or chemical oxidation followed by rapid sand filtration [29]. The suggestion of a novel method of excess iron removal by application of limestone filters was studied by Aziz et al. [30]. However, given the poor socio-economic situation of the villagers, only government-funded water supply systems are feasible. The concentration of major ions and heavy metals in groundwater indicates its suitability for drinking at the village level.

Discussion

The characterization of the fractured rock aquifer system in the Bankura anorthosite at the Narrah test site revealed saturated fractures at deeper levels (135-138 mbgl) with moderately high groundwater potential. During the preliminary yield test, the aquifer proved to be viable and suitable for supplying water to the local community. The lithological contact between gneissic rock of the CGGC and the Bankura anorthosite is a potential groundwater zone. Pumping tests showed that the anorthosite aquifer has a sustainable discharge of ~4 L/s (345.60 m^3/day) using an air compressor of 250 PSI. The discharge was found to be sustainable for five hours during the test pumping. Using a 10 HP submersible pump, the expected discharge would be ~6.0 L/s (518.40 m^3/day) with an average daily running of five hours. The daily water supply potential of the test well is estimated at 1.08×10^5 litres (108 m^3).

The basic hydrochemical analysis and heavy metal analysis have shown that the groundwater is suitable for drinking except for the high iron content. Although fluoride contamination in groundwater is reported at a regional scale (at block level), at the Narrah test site fluoride in the fractured rock aquifer (0.59 mg/L) is found to be below the acceptable limit (1.0 mg/L) as per revised guidelines on drinking water of the Bureau of Indian Standards (BIS, IS:10500, 2012) [31]. As far as iron contamination in the fractured Bankura anorthosite aquifer is concerned, the release of iron during water-rock interaction is ruled out due to the absence of iron-bearing minerals in the geological log of the piezometer. Iron contamination in groundwater is attributed to the colonial growth of iron-oxidising bacteria in village ponds near the test site. The installation of government-funded iron removal plants would solve the problem of iron contamination in groundwater, thereby meeting the water supply guidelines recommended by the Jal Jeevan mission in terms of quantity and quality. Due to a strong positive correlation between Iron (Fe) and Palladium (Pd), the spatial distribution of Pd in groundwater can be utilised for mineral exploration of Platinum Group Elements (PGE) using Pd as a pathfinder element. Comprehensive hydrogeochemical investigations including geochemical modelling of trace elements and PGEs are recommended in and around the Narrah test site.

The socio-cultural and socio-economic conditions in the study area are closely related to the existing rural water supply position. The estimated village population is 16923 (projected population for 2024 based on 2011 census data), which receives economic support through the Backward Region Grants Fund (BRGF) sponsored by the Government of India. The BRGF aims to redress "regional imbalances in development". In the Narrah Gram Panchayat, four water supply projects in Matranga, Ailta, Pratappur and Balarampur were approved as part of phase I of the BRGF. Socio-cultural analysis reveals that mainly the literate population is enjoying the benefit of the groundwater potential and easy accessibility of the anorthositic aquifer system in both village and community development block levels. Although the water supply projects have been approved by the state level scheme sanctioning committee set up by the government of West Bengal, they are not yet operational. Based on the discharge of the bore well at Narrah and considering the recommended water supply of 55 litres per capita per day for rural areas under the Jal Jeevan Mission–Har Ghar Jal scheme, the bore well would meet the daily water requirement of a population of 1964 persons or cater to 491 families of a four-member family. The bore well would also serve as a sustainable source of drinking water for 20 hamlets in Narrah village. A government-sponsored water supply system based on a 'model well', as demonstrated through test pumping in Narrah, would solve the prevailing problem of water scarcity through the sustainable utilisation of the fractured Bankura anorthosite aquifer. The assured water supply to rural households will improve the Composite Development Index (CDI) and thus improve the socio-economic conditions of the rural community and make the area "well developed" from socio-cultural and socio-economic aspects.

Conclusion

The sustainable water management is a key to solving the water crisis in the drought-prone study area. The socio-economic conditions of the study area are relatively poor with a Composite Development Index (CDI) of 0.44 at block level. About 37% of the village population in Narrah belongs to the scheduled caste and scheduled tribe category and 38.48% of the families in Bankura-II block belong to below poverty line category. The sustainability of the Bankura anorthosite aquifer for rural water supply is of great importance given the prevailing water scarcity. Following the success of the Narrah test well, additional wells tapping the fractured Bankura anorthosite aquifer are feasible at a regional scale. The battery of such wells would be an invaluable source of sustainable drinking water supply for the rural community. By improving the Water Supply Development Index (WS-DI) and the resulting increase in Composite Development Index (CDI), the water-scarce, moderately developed area is expected to transform into a socio-economically developed area. The successful implementation of rural water supply schemes through supply-side management of the fractured Bankura anorthosite aquifer can be replicated in similar drought-prone areas of the Rarh region.

Conflict of Interest

The authors declare no competing interests.

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Author Contribution

First Author: conceptualization, methodology, preparation of figures, data analysis and interpretation, original manuscript preparation, finalization of the manuscript; Second Author: visualization, manuscript revision, supervision. Both authors reviewed the final manuscript and agreed to submit it to the journal.

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