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ORIGINAL ARTICLE

Subsurface Geophysics and Hydrogeology at the Gun Carriage Factory, Jabalpur, Madhya Pradesh, India

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ABSTRACT

India is at the brink of facing severe water scarcity situation. To overcome the challenge, the country plans to implement a mega managed aquifer recharge (MAR) scheme in pan-India scale with huge monetary investment, but for the scheme to succeed, it is essential that the MAR sites are favourable for recharge. The real challenge will be when the 10.6 million rooftop water harvesting structures under the scheme will be constructed in about 8000 towns and 500 urban agglomerates of India. Site-specific study will be essential for these structures to deliver their optimum performance. At present, many of these structures are constructed without adequate hydrogeological and subsurface geophysical investigations. As a result, demarcation of the exact depth of release of harvested rainwater in the aquifers becomes difficult. In an attempt to exemplify how these investigations could be carried out to effect favourable groundwater recharge, a case study has been taken up at the Gun Carriage Factory, Jabalpur, Madhya Pradesh in central India. Unlike similar geophysical studies carried out elsewhere with vertical electrical soundings, this technique was employed to decipher fracture depths, which were determined at a depth of about 15-35 m and confirmed subsequently by an on-the-spot recharge experiment. Fracture zones are porous and permeable horizons where harvested rainwater could be released at depth. This work recommends similar investigations to be carried out in specific areas where any kind of MAR scheme is envisaged so that the investments made deliver their optimum results.

INTRODUCTION

As India experiences water scarcity problems in different parts of the country, the Government of India plans to implement of a variety of schemes to augment the depleting groundwater resources. In urban areas, the campaign is primarily focused on rooftop rainwater harvesting (RTRWH), a supply-side option. It is envisaged that in the coming few years, about 8000 towns and 500 urban agglomerates (CoI, 2011) across the country shall have 10,613,793 numbers of RTRWH structures with an investment of about 368 billion Indian rupees (CGWB, 2020). This is about 28% of the total investment of the 1335.30 billion Indian rupees, the Government is likely to spend on supply-side management options for sustainable management of the groundwater resources in the country.

Indian hydrogeology is very complex, and the geological features rapidly vary from place to place. Many urban agglomerates sit on relatively hard rock or semi-consolidated terrains where it is often difficult to locate suitable fractures or porous horizon at a convenient depth for discharging the harvested water to recharge the groundwater table through gravity. Citizens in connivance with the untrained engineers and contractors often implement the rooftop harvesting schemes under compulsion to abide by the Government's regulatory norms without proper hydrogeological and geophysical investigations. There are many cases where there is rejection of recharge even in unconsolidated formations (Naik et al., 2017). Therefore, it is essential that the subsurface geophysics and hydrogeological conditions are examined well before trying to release the harvested water at certain depth below the ground.

There could be two ways to decide on such a depth, i.e., either by drilling a test piezometer to understand the subsurface features unless there are no other litholog data available nearby or by subsurface geophysical techniques such as vertical electrical sounding (VES). An attempt has been made in this contribution to decipher fractures at a suitable depth through VES technique at the Gun Carriage Factory (GCF), Jabalpur, Madhya Pradesh, India for recharging the aquifers with harvested rainwater. These fracture zones are considered porous and permeable zones for smooth transmission of injected water into the aquifers.

A team from Rajiv Gandhi National Ground Water Training and Research Institute, Raipur, India carried out the field investigations for installation of RWH structures in 16 of GCF's buildings and recommended to discharge 60,000 m^3 of harvested rainwater underground per year to augment the groundwater table in the area (Naik et al., 2016). Since there was no suitable exploratory borewell or test piezometer available nearby, VES was conducted at five different locations inside the GCF premises to decipher suitable fractures at appropriate depth for releasing the harvested rainwater. The present contribution summarizes the results of these five VES and the prevailing hydrogeological conditions.

In fact, there are many applications of geophysics in groundwater hydrology (Kiesch, 2006). In studies related to rainwater harvesting, subsurface geophysics is usually used world-wide for a variety of purposes, such as for characterizing the aquifers (Venugopal, 2010; Prasad, 2011; Raju, 2015), determining the depth and thickness of saturated aquifer zones (Ali et al., 2015; Gaber et al, 2020), quantifying the depth of alluvium thickness (Sass, 2007, Vouillamoz et al., 2007) or depth of various rock layers and bedrock surfaces (Dhakate et al, 2013; Mahmoud and Alazba, 2014; Sreedevi et al., 2015; Rahaman et al., 2019; Singh et al., 2021) and even for determining the variation of water quality with depth (Choudhury et al, 2001; Pujari et al., 2019). However, none of these studies have used subsurface geophysics for determination of fractures at depth so that the rainwater harvested could be discharged safely without causing any deleterious effect on the harvesting structures or the surrounding environment in terms of overflowing of recharge wells etc. as it happened in case of Bahrain (Naik et al., 2017). This work, therefore, is unique in the way that VES technique has been used for deciphering fracture depths in the aquifers for causing favourable recharge.

METHODS

Study Area

The Gun Carriage Factory is a large defence establishment occupying a geographical area of 6.975 km^2 (1723.56 acres) at the outskirts of the city of Jabalpur, a tier-2 city in the State of Madhya Pradesh, India. The area falls under the Survey of India Toposheet Nos. 55M/16 and 64 A/4 and is coordinated by 23°09'46.52" N to 23°11'22.2" N and by 79°58'19.38" E to 79°59'44.34" E. The main GCF factory premises cover an area of 157.005 acres (0.635 km^2) (Fig. 1). It is a unit of Ordnance Factory Board under the Department of Defence Production, Ministry of Defence, Govt. of India, established in 1904 as the first Ordnance Factory of central India. With a mission "Production of State of the-Art Battlefield Equipment", it has been providing the much-needed latest armaments and weapons for the past more than 100 years to the country (GCF, 2022).

Modus Operandi

Meetings were held with the authority of the GCF to discuss the project. Geological and meteorological information were collected from the local offices of the Geological Survey of India and India Meteorological Department, respectively. Geological field traverses were then made to understand the local geology and physiography better. Seventeen wells inside the GCF campus were examined to understand the groundwater conditions. Pumping tests were conducted at two locations for estimation of the hydraulic parameters. Six water samples, including one from rainfall, were randomly collected for analysis of chemical parameters.

As part of geophysical survey, five vertical electrical soundings (VES) were conducted using Schlumberger configuration to understand the subsurface geology, depth-wise lithological variation, depth of weathering and fracture pattern (Fig. 1). The indigenous Resistivity meter SSRMP-ATS was used to carry out the survey work. Maximum AB was maintained at 200 m. The data were plotted on a double-log graph paper and interpreted using master curves and auxiliary curves. The interpreted results were further verified by using SCHLUM and IPI2WIN software in computer.

Resistivity variation in lithology with increasing depth is more prominent in VES compared to other geophysical methods (Muralidharan, 1996). However, in certain consolidated terrains, especially in granites (Andrade, 2014), the apparent resistivity field data often do not show significant change in the geoelectric trend posing difficulty in identifying a geoelectric layer. In such a case, the apparent resistivity data is treated differently by a procedure called 'Factor Analysis'. The term 'factor' is the ratio of the apparent resistivity of a particular AB/2 separation to the cumulative apparent resistivities of the earlier separations. Therefore, if the total number of apparent resistivity scores of a sounding is 'n', then the total number of factor values will be n-1, as there will be no factor value for the first AB/2. In the form of an equation, it can be expressed as follows.

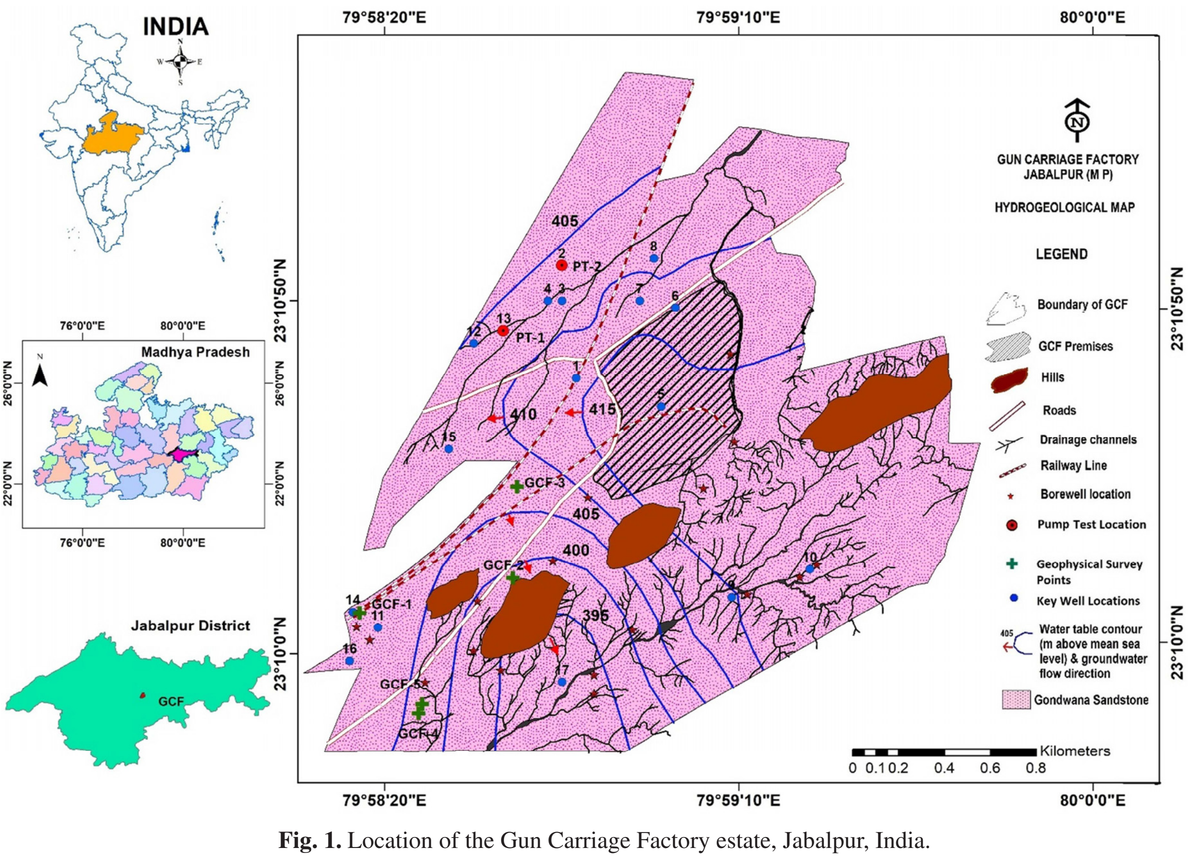

Fig. 1. Location of the Gun Carriage Factory estate, Jabalpur, India.

$$F\rho_a^{15} = \rho_a^{15} \Big/ \sum_{\rho_a^{2}}^{\rho_a^{12}}$$

The factor values generally result in decimal numbers. From the obtained factor values, wherever two consecutive readings of AB/2 shall have the same or nearly the same factor values, they will indicate a fracture at that depth. Therefore, not to take a chance to miss any fracture in the present investigation, factor analysis procedure was applied to the apparent resistivity values of the five vertical electrical soundings (please see Table 3 for details).

RESULTS AND DISCUSSION

Physiography and Drainage

Jabalpur area is hilly and undulating in nature with elevations varying between 402 and 470 metres above mean sea level (mamsl) (Fig. 1). The hills present in the GCF estate are Bara-Simla hills, Chhota- Simla hills and Patbaba Temple hills. The area is a part of Narmada basin. The Narmada River flows in SW-NE direction and takes a sudden turn south of Jabalpur and flows in E-W direction. The Pachperi nala in the south of the study area flows in NE-SW direction. As the area is underlain by fine sediments of Lameta beds which are impervious, the drainage density is high and of dendritic nature. The northern part is drained by the Kalapathar nala that flows in SW-NE direction; its flow direction is opposite to that of the Pachperi nala.

Hydrometeorology

Jabalpur experiences a hot summer and general dry climate except during the rainy season. Minimum temperature of about 10°C occurs in the month of December, while May has the highest temperature of 42°C. June to September is the Southwest monsoon period that has an annual normal of about 1315 mm, which is 90% of the total annual average of 1461 mm (data collected from the observatory of the local India Meteorological Department, August 17, 2016). Maximum rainfall of about 468 mm is received in the month of July while a minimum of 4 mm in the winter month of December. Wind velocity is maximum in the month of June (8.2 km/hr) and minimum in December (2.6 km/hr).

Regional Geology

Jabalpur has a special mention in the geology of central India. Some of the early workers who carried out geological investigations in this area include Adam (1842), Oldham et al. (1901) and Matley (1922). Since the first report of dinosaur bones from Jabalpur by Captain Sleeman in 1928 (Sleeman, 1944), the area has drawn the attention of many paleontologists. Most recently, Khosla et al. (2020), Lal et al. (2023) and Dhiman et al. (2023) studied the area from paleontological perspective. Rao et al. (2011) discussed the seismicity of this region. Based on these studies, the area around Jabalpur exposes a stratigraphic sequence ranging from Paleo-Proterozoic to Recent. The oldest rocks exposed in the area belong to Mahakoshal Group. They are intruded by granite (Madan Mahal Granite), basic and ultrabasic dykes and quartz veins (Dhurandhar and Ranjan, 2020). Mahakoshal Group of rocks has been deposited on the presumably gneissic basement in ENE-WSW trending linear narrow rift basin between Sone Narmada North Fault (SNNF) in the north and Sone Narmada South Fault (SNSF) in the south (Ghosh and Singh, 2013). The area north of SNNF is occupied by Vindhyan Super Group of rocks which are overlain by Lameta Group and Deccan Traps. The area to the south of SNSF is occupied mostly by Lametas and Deccan Basalts. The rocks of Gondwana Super group (Jabalpur Formation - Upper Gondwana) overlie Mahakoshal Group and underlie Lametas on either side of SNSF. The Quaternary sediments are represented by Narmada alluvium. The generalized litho-stratigraphic succession of the area is given in Table 1.

Table 1. Generalized litho-stratigraphic succession of Jabalpur area, India

Age	Supergroup/Group	Formation
Pleistocene - Holocene	Narmada Alluvium	Ramnagar Hirdepur Banetha Surajkund Dhansi Pilikarar
Cretaceous to Palaeocene (~40 - 100 million years: MY)	Deccan Traps	
Cretaceous	Lameta Group	
Triassic-Cretaceous (~100 MY)	Gondwana Supergroup	Jabalpur
Meso-Proterozoic (1800 MY)	Madan Mahal Granite	
Paleo-Proterozoic (~2500 MY)	Mahakoshal Group	Parsoi Agori
		Basement not exposed

Local Geology

Locally, GCF area is characterized by sandstone of upper Gondwana which is underlain by porphyritic granite and granite gneiss of Mahakoshal Group of Precambrian Age (Sengupta et al., 2012). This Gondwana sandstone is also called 'Jabalpur Formation' (Casshyap et al., 1993; Tewari, 1998; Mukhopadhyay et al., 2010) in Indian stratigraphy. These sandstones are fine to medium grained, mostly poorly sorted and sometimes moderately sorted. The shape of the grains is generally subangular to subrounded. The average composition of the sandstone is quartz, feldspar, and micas with minor occurrences of heavy minerals such as epidote, tourmaline, garnet, rutile, staurolite and tremolite-actinolite etc. A few field photographs are shown in Fig. 2.

At Patbaba temple, which is located on a hillock, Lametas are exposed at the top, which are buff coloured, hard, clayey, cherty having calcareous concretions. Sometimes clay layers of 30 cm thickness are present. The thickness of Lametas is about 10 m. Below Lametas, sandstones are exposed which are hard and reddish in colour. From the Lameta Formation, dinosaur clutches, isolated eggs and eggshell fragments have been reported from the Chui Hill and Bara Simla Hill (including Patbaba Temple area) within the GCF estate (Saha et al., 2010; Khosla et al., 2020; Dhiman et al., 2023).

Subsurface Geophysics

The results of the five VES (Fig. 1) are described briefly below.

VES No. GCF-01: The VES is located in front of the GCF Guest House with N latitude 23°10'09.2" and E longitude 79°58'09.8". It is a 4-layer sounding curve (Fig. 3, Table 2). The topmost soil cover is 1.2 m thick with resistivity of 24.5 Ohm-m. The second layer is weathered with a resistivity of 8.6 Ohm-m and extended down to 5.4 m. The thickness of the third layer is 20.5 m that extends down to 25.9 m with resistivity of 160 Ohm-m, which is hard in nature. The last layer below 25.9 m is fractured with resistivity of 50 Ohm-m. From the factor analysis it seems that fractures may occur between 12 and 15 m below the ground at this point.

VES No. GCF-02: This VES is near the residential Quarters No. 25 of GCF with coordinates 23°10' 09.8" N latitude and 79°58'38.7" E longitude . This sounding reveals four subsurface layers (Fig. 3, Table 2). The first layer is topsoil cover with resistivity of 25.5 Ohm-

Lametas exposed at Patbaba Temple hill, adjacent to GCF.

Sandstone exposed at Patbaba Temple hill, adjacent to GCF.

Sandstone exposure at New Colony area within the GCF estate.

Lametas overlying sandstone at Patbaba Temple hill, adjacent to GCF.

Fig. 2. Field photographs around the Gun Carriage Factory (JCF) area, Jabalpur, India.

m and thickness is 2.4 m. The second layer resistivity is 11 Ohm-m and is extended down to 6.5 m. The third layer below 6.5 m extends down to 19.5 m with resistivity of 65 Ohm-m indicating fractured nature of the formation. The last layer too is fractured in nature with resistivity of 14 Ohm-m. From the factor analysis it seems that fractures may occur between 20 and 25 m below the ground at this point.

VES No. GCF-03: This VES is near the Patbaba Mandir at 23°10'3.7" N and 79° 58'38.7" E. This sounding reveals four subsurface layers (Fig. 3, Table 2). The first layer is topsoil cover with resistivity of 64 Ohm-m and thickness is 1.7 m. The resistivity of the second layer is 40 Ohm-m that extends down to 14.7 m. The third layer is from 14.7 m to 51.7 m with resistivity of 140 Ohm-m indicating hard nature of the formation. The last layer below 51.7 m is fractured in nature with resistivity of 50 Ohm-m. From factor analysis it seems that fractures may be between 50 and 60 m below the ground at this point.

Table 2. Results Vertical electrical sounding at the GCF premises, Jabalpur, India.

VES No.	ρ_1	ρ_2	ρ_3	ρ_4	d_1	d_2	d_3	H_1	H_2	H_3
GCF-01	24.5	8.6	160.0	30.0	1.2	4.2	20.5	1.2	5.4	25.9
GCF-02	25.5	11.0	65.0	14.0	2.4	4.1	13.0	2.4	6.5	19.5
GCF-03	64.0	40.0	140.0	50.0	1.7	13.0	37.0	1.7	14.7	51.7
GCF-04	40.0	14.5	98.0	33.0	1.2	2.2	32.0	1.2	3.4	35.4
GCF-05	38.5	16.5	103.0	35.0	1.2	2.3	31.5	1.2	3.5	35.0

VES No. GCF-04: This VES is near the Cricket playground of the GCF campus situated at N latitude 23°09'51.6" and E longitude 79°58' 24.8". This sounding also reveals four subsurface layers (Fig. 3, Table 2). The first layer is topsoil cover with resistivity of 40 Ohm-m and a thickness is 1.2 m. The resistivity of the second layer is 14.5 Ohm-m that extends down to 3.4 m. The third layer is from 3.4 m to 35.4 m with resistivity of 98 Ohm-m indicating hard nature of the formation. The last layer below 35.4 m is fractured in nature with resistivity of 32 Ohm-m. From factor analysis it seems

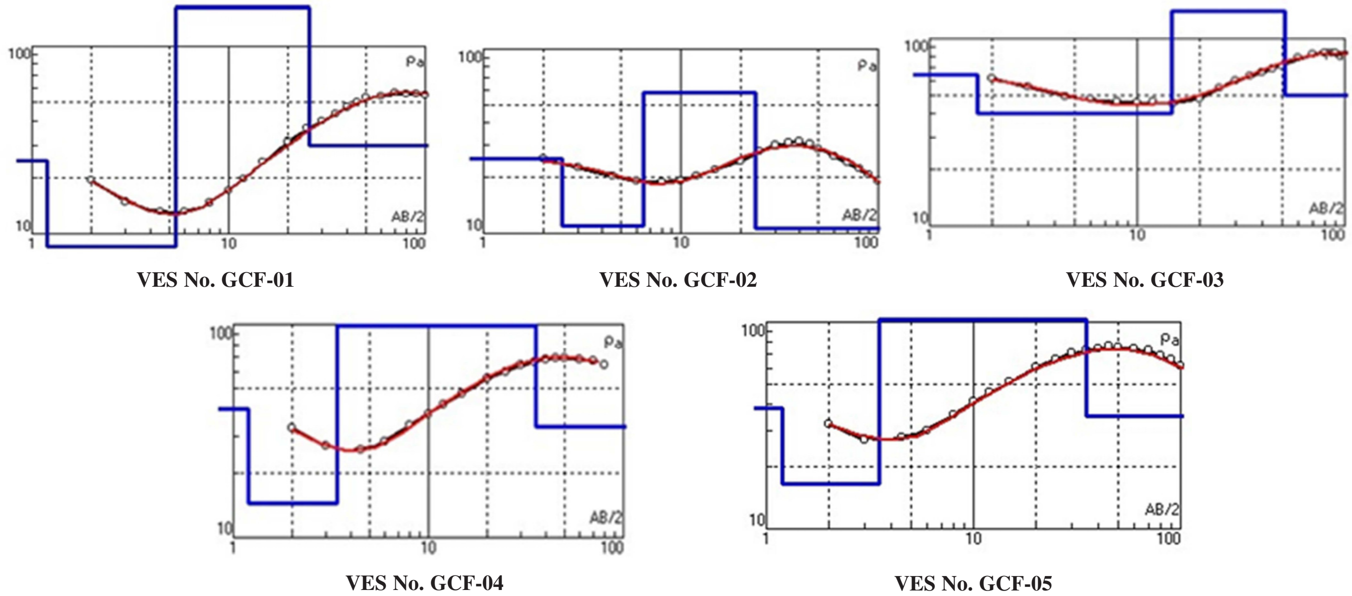

Fig. 3. Field Curves of vertical electrical soundings (VES) around the Gun Carriage Factory premises, Jabalpur, India

that fractures may be in between 15 and 20 m below the ground at this point.

VES No GCF-05: This VES is near the Cricket playground of the GCF campus with coordinates 23°09'52.9"N and 79°58'25.3" E. This sounding also reveals four subsurface layers (Fig. 3, Table 2). The first layer is topsoil cover with resistivity of 38.5 Ohm-m and thickness of 1.2 m. The resistivity of the second layer is 16.5 Ohm-m that extends down to 3.5 m. The third layer is from 3.5 m to 35 m with resistivity of 103 Ohm-m indicating hard nature of the formation. The last layer below 35 m is fractured in nature with resistivity of 35 Ohm-m.

Inferences from the VES curves

After interpretation of all the VES curves, it is observed that at VES No. GCF-03, there is a possibility of fractures between 50 to 60 m. At VES No-GCF-03, a bore well may be drilled up to 100 m depth. At VES No. GCF-01, VES No. GCF-02 and VES No.GCF-04, fracture depths are shallow (15-25 m). Managed aquifer recharge structures may be constructed at these points. Interpretation of field curves is given in Table 3.

Hydrogeology

Hydrogeology of the study area is mainly controlled by geomorphological and geological setup. The composition and structure of the geological formations influence the inherent properties such as porosity and permeability and hence the water holding and water yielding capacity of the aquifers, thereby playing a vital role in the hydrogeological regime.

Table 3. Vertical Electrical Sounding data and Factor in GCF estate, Jabalpur, India

VES No. GCF-01 Date:16.02.15, Direction: N-215° Lat: 23°10'09.3"N Long: 79°58'09.9" E			VES No. GCF-02 Date:16.02.15, Direction: N-190° Lat: 23°10'27.7" N Long: 79°58'38.7" E			VES N. GCF-03 Date:16.02.15, Direction: N-265° Lat:23°10'23.7" N Long: 79°58'38.7"E			VES No. GCF-04 Date :17.02.15, Direction: N-15° Lat: 23°09'51.6" N Long: 79°58'24.8" E			VES No. GCF-05 Date :17.02.15, Direction: N-290° Lat: 23°09'52.9" N Long: 79°58'25.3" E		
AB/2 (m)	Apparent Resistivity (Ohm-m)	Factor	AB/2 (m)	Apparent Resistivity (Ohm-m)	Factor	AB/2 (m)	Apparent Resistivity (Ohm-m)	Factor	AB/2 (m)	Apparent Resistivity (Ohm-m)	Factor	AB/2 (m)	Apparent Resistivity (Ohm-m)	Factor
2	19.3		2	25.3		2	61.6		2	32.6		2	32.0	
3	15.0	0.77353	3	22.8	0.90015	3	55.4	0.89935	3	26.8	0.82129	3	27.0	0.84266
4.5	13.2	0.38360	4.5	20.4	0.42394	4.5	49.2	0.42051	4.5	25.6	0.43205	4.5	27.7	0.46920
6	13.3	0.27963	6	19.2	0.28020	6	47.5	0.28580	6	28.2	0.33149	6	29.9	0.34493
8	14.6	0.24010	8	18.8	0.21431	8	46.5	0.21759	8	33.4	0.29545	8	35.5	0.30436
10	17.0	0.22587	10	19.3	0.18118	10	45.9	0.17640	10	38.0	0.25931	10	41.1	0.26989
12	19.7	**0.21311**	12	20.6	0.16372	12	46.2	0.15093	12	42.1	0.22819	12	45.5	0.23552
15	24.1	**0.21574**	15	22.0	0.15025	15	45.2	0.12830	15	47.1	**0.20766**	15	51.3	0.21489
20	31.0	0.22745	20	24.7	**0.14665**	20	47.5	0.11950	20	55.4	**0.20232**	20	60.3	0.20812
25	36.4	0.21803	25	28.0	**0.14483**	25	54.6	0.12270	25	59.3	0.18020	25	66.3	0.18928
30	40.0	0.19668	30	30.2	0.13650	30	59.4	0.11890	30	64.1	0.16492	30	71.0	0.17043
35	43.6	0.17904	35	31.1	0.12366	35	63.0	0.11270	35	66.3	0.14650	35	73.5	0.15069
40	47.1	0.16401	40	31.4	0.11135	40	66.0	0.10611	40	68.6	0.13223	40	74.8	0.13322
45	50.0	0.14960	45	30.5	0.09731	45	69.0	0.10029	45	69.2	0.11779	45	76.7	0.12061
50	52.6	0.13699	50	29.0	0.08413	50	71.3	**0.09419**	50	69.2	0.10538	50	76.0	0.10671
60	54.0	0.12362	60	26.2	0.07027	60	78.9	**0.09526**	60	68.6	0.09452	60	74.8	0.09479
70	55.9	0.11385	70	24.2	0.06049	70	82.1	0.09053	70	66.9	0.08417	70	73.5	0.08511
80	55.4	0.10134	80	22.4	0.05287	80	84.3	0.08518	80	64.6	0.07502	80	69.2	0.07388
90	55.4	0.09202	90	20.6	0.04627	90	83.5				0.07782	90	65.7	0.06535
100	54.9	0.08355	100	19.2	0.04123							100	61.4	0.05728

Table 4. Lithology of piezometer at Jabalpur (23°09'4.30" N, 79°57'13.01"E)

S. No.	Lithology	Depth Range (m)	Thickness (m)
1	Sandstone- red and weathered	0.0-3.05	3.05
2	Sandstone- highly weathered, white, and weathered	3.05-12.20	9.15
3	Sandstone-semi weathered, yellow and weathered	12.20-29.60	17.40
4	Sandstone-mild hard, brown	29.60-35.70	6.10
5	Granite-granodiorite - brown and massive	35.70-38.75	3.05
6	Granite-gneiss - brown	38.75-81.45	42.70
7	Granite-gneiss - pink	81.45-87.55	6.10
8	Granite gneiss - pink	87.55-90.00	2.45

Depending upon the geological setup, water bearing and water yielding properties, two major regional hydrogeological units have been identified in the area i.e., (i) the semi-consolidated formation comprising of sandstones of Super Gondwana Group and (ii) consolidated formation comprising of granite gneiss of Mahakoshal Group. The consolidated formations are generally found at depth below the semi-consolidated formations in the GCF estate. The water receiving or yielding capacity in these formations largely depends on the extent of fracturing, openness and size of fractures and their interconnection with the near surface weathered zones. These interconnected joints and fractures in the underlying hard rocks facilitate circulation of ground water and in turn form deeper aquifers. A typical litholog of a piezometer showing both these hydrogeological units is shown in table 4 and figure 4.

The semi-consolidated formations of Super Gondwana Group are the most predominant rock types occupying undulating terrain and low-lying areas and are represented by medium to coarse grained, loosely compacted, cross-bedded sandstones of varying colours that indicate their changing depositional environments (Fig. 2). These sandstones are characterised by dual porosities. Primary porosity is developed in the form of inter-granular voids and contact between the two layers (bedding planes) at the time of their deposition. These contacts and interconnected voids serve as the flow paths for ground water movement, besides the secondary porosity occurring in the form of fractures and joints due to tectonic activities.

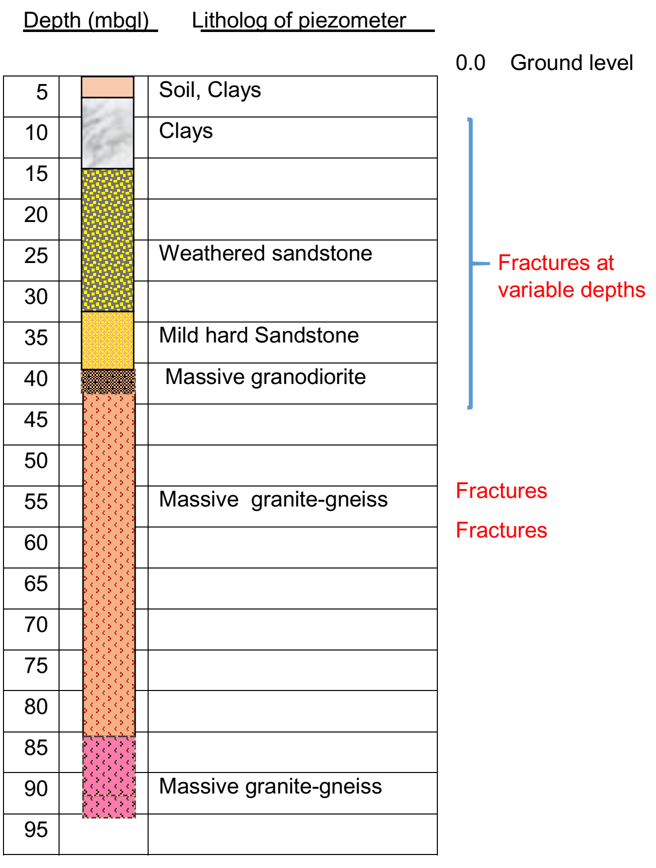

Fig. 4. Graphical representation of the litholog of a piezometer around Jabalpur, India.

Depth to Water Level

Seventeen key observation wells, as shown in figure 1, were selected for measuring the depth to water levels (DTW) in the GCF campus. Only winter-time water levels were measured during the month of January 2015. DTW varies from 11.20 m below ground level (mbgl) to 18.60 mbgl with an average of 13.85 mbgl. A DTW map is shown in figure 5.

Well Hydraulics

Jabalpur Formation is known for its high yielding wells (Adyalkar and Radhakrishna, 1975). During groundwater exploration programme

Table 5. Results of pumping tests in Gun Carriage Factory estate, Jabalpur, India.

Particulars	Pumping Test 1	Pumping Test 2
Location	Key Well No. 13 (BW No-8, Madras Pump House)	Key Well No. 2 (BW No-5, near Vidya Nagar Gate)
Formation	Sandstone and Granite Gneiss	Sandstone and Granite Gneiss
Depth	60	60
Water Level (mbgl)	18.54	11.19
Duration (min)	150	120
Discharge (m^3/hr)	27	16.2
Pumping Water Level (m)	21.55	11.988
Draw Down (m)	3.01	0.798
Δ S = m	1.1	0.68
Transmissivity (m^2/day)	107.86	104.62
Specific capacity (l p m / m)	149.50	338.35

Table 6. Drawdown data of the test wells during the pumping tests at Jabalpur

Pumping Test 1 Key Well No. 13 (BW No-8, Madras Pump House)			Pumping Test 2 Key Well No. 2 (BW No-5, near Vidya Nagar Gate)		
Time (min) since pump started (t)	DTW (m)	Drawdown (m)	Time (min) since pump started (t)	DTW (m)	Drawdown (m)
0	18.54	0	0	11.19	0
1	19.44	0.9	1	11.2	0.01
3	19.78	1.24	3	11.22	0.03
5	20.04	1.5	5	11.258	0.068
10	20.35	1.81	7.5	11.27	0.08
15	20.56	2.02	12.5	11.34	0.15
20	20.68	2.14	20	11.453	0.263
25	20.79	2.25	30	11.572	0.382
30	20.88	2.34	40	11.645	0.455
35	20.95	2.41	53	11.728	0.538
40	21.02	2.48	60	11.765	0.575
60	21.24	2.7	70	11.815	0.625
70	21.27	2.73	80	11.845	0.655
80	21.32	2.78	90	11.884	0.694
90	21.39	2.85	100	11.925	0.735
100	21.48	2.94	110	11.956	0.766
110	21.52	2.98	120	11.988	0.798
120	21.55	3.01			
150	21.55	3.01			

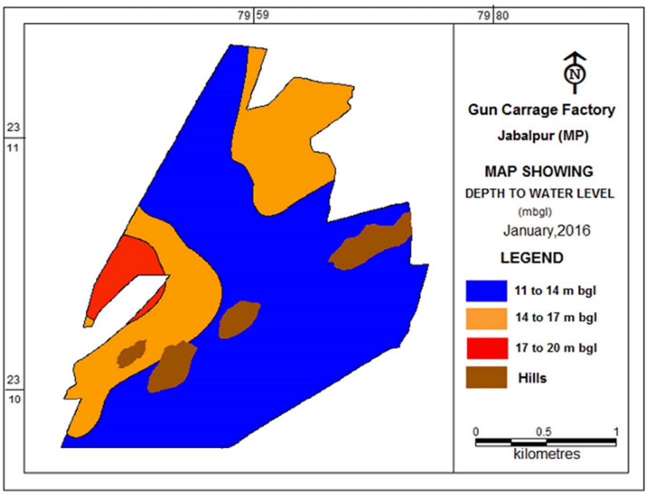

Fig. 5. Depth to water level map in the Gun Carriage Factory estate, Jabalpur, India.

of the Geological Survey of India, Roy (1957) found its yield to be varying between 22 to 55 m^3/hour. During the present investigation, the well yield was found to be in the order of 16 to 35 m^3/hour. There is continuous pumping from the water supply wells 24 hours a day to cater to the water requirements of the GCF and its domestic premises.

To examine the aquifer characteristics of Jabalpur Formation around the GCF area, two pumping tests were conducted during this field investigation. Although these wells were not ideally designed for aquifer performance tests (CGWB, 1986, 1992), the details of these wells along with the results obtained by applying the Jacob's formula are given in table 5. The drawdown data from these wells during the tests along with their graphical plots are shown in table 6 and figure 6, respectively, for reference purposes. From these tests, the average value of the Transmissivity of the Jabalpur Formation in GCF estate is estimated at 106.24 m^2/day and that of specific capacity at 243.93 lpm/min/m.

Chemical Quality of Groundwater

Analytical results of the four groundwater samples show that concentration values of the quality parameters generally lie within the prescribed drinking water standards defined by the Bureau of Indian Standards (BIS, 2012) (Table 7). Only one sample collected at the Madras Pump House shows a total hardness (TH) concentration of 210 mg/L, little above the prescribed 200 mg/L. The sample in the New Colony area too shows a TH value of 195 mg/L, a little below the acceptable limit. The samples indicate that groundwater in a few wells in the area is slightly harder by nature. The only sample of rainwater has a pH value of 5.51 indicating acidic nature, which generally is the case in rainwater (WSS, 2019). However, the acidity gets normalized once the water enters the ground surface due to buffering effects of substances like calcium carbonate, clay, humus and aluminium oxides present in the soil (NIPHE, 2014).

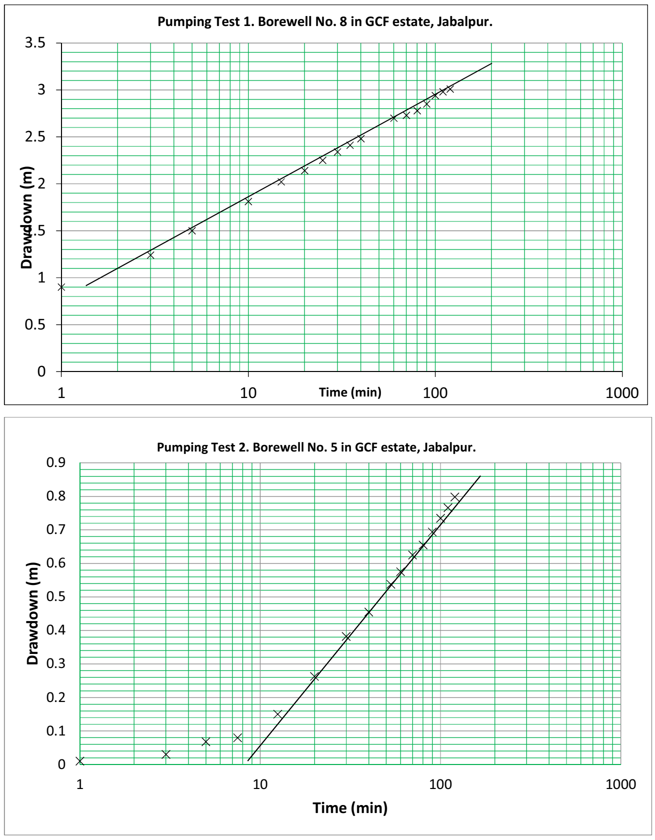

Fig. 6. Drawdown vs. time plots of the pumping tests at GCF estate, Jabalpur, India.

CONCLUSIONS

Conducting subsurface site investigations is essential before implementation of any supply-side management option aimed at augmenting the depleting groundwater resources. Within the Gun Carriage Factory (GCF) premises, Jabalpur, India, where rooftop rainwater harvesting scheme was attempted, since there was no suitable exploratory well with clear litholog available, geophysical investigations were essential to decipher the facture depths so that harvested rainwater could be discharged into the host aquifers. This was supported by the local hydrogeological surveys that included geological investigations, well inventory, pumping tests and a litholog available nearby. The shallower nature of the fractures within a depth of 15-35 m shows that harvested rainwater could possibly be discharged within a depth of 25-35 m. This was confirmed by a special recharge study carried out by a team constituted by the Ministry of Water Resources, Government of India, on request by the GCF authority (Dharma Rao, 2018). This study recommended an optimum depth of 30 m for release of the harvested rainwater in the host aquifer. A typical design of a recharge well is shown in figure 7.

India is already poised to implement a mega managed aquifer recharge scheme in pan-India scale to mitigate its water scarcity. Therefore, it is essential that all sites, where construction of various

Table 7. Chemical quality of groundwater around the Gun Carriage Factory premises, Jabalpur, India

S. No.	Location	Source	pH	EC in µS/cm	CO_3	HCO_3	Cl	F	SO_4	Na	K	Ca	Mg	TH
					Concentrations in mg/L									
1	Rainwater- GCF	RW	5.51	11	0	12	7	0.2	2	0.2	0.2	4	2.4	20
2	Key Well No. 1	BW	7.89	392	0	128	35	0.6	36	21.9	0.8	46	7.2	145
3	Key Well No. 2 (near Vidya Nagar Gate)	BW	7.83	420	0	177	35	0.4	33	23.1	1.2	46	12	165
4	Key Well No. 13 (Madras Pump House)	BW	7.67	656	0	171	71	0.6	40	56.6	5.2	60	14.4	210
5	Key Well No. 10 (New Colony)	BW	8.05	395	0	226	11	0.4	6	8	0.2	70	4.8	195

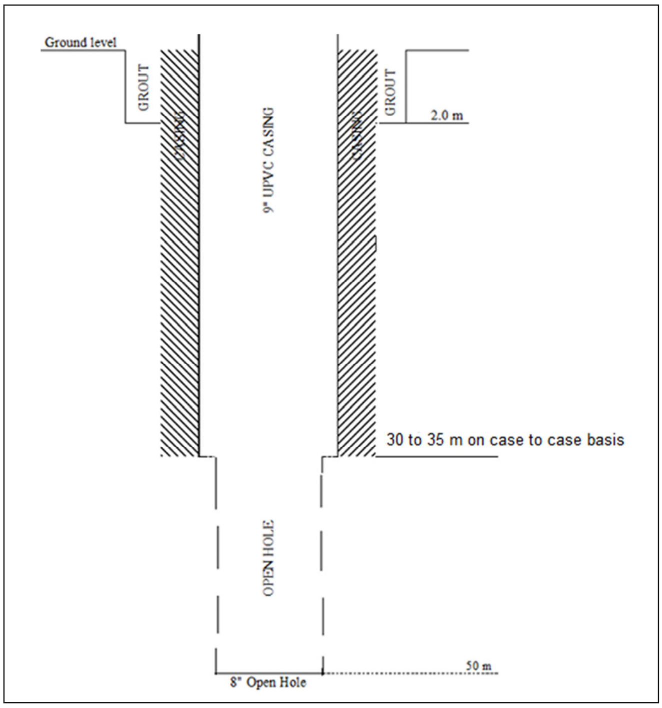

Fig. 7. A typical design of a recharge well in Gun Carriage Factory, Jabalpur, India.

recharge structures are envisaged, are investigated three-dimensionally from hydrogeological perspectives so that the country gets a value-for-money return from this project. The current National Aquifer Mapping (NAQUIM) program of Central Ground Water Board, Ministry of Jal Shakti, Government of India is aimed at drawing a three-dimensional picture of the aquifers in pan-India scale (CGWB, 2022), but the investigations related to NAQUIM are not site-specific. The present work is an example of how such investigations can be attempted in limited available space within a restricted time frame.

References

Adam, D.J. (1842) Memoranda on the geology of Bundelkhand and Jabalpur. Jour. Asiatic Soc. Bengal, v.11, 293p.

Adyalkar, P.G. and Radhakrishna, T.S. (1975) Hydrogeology of the Jabalpur Sandstone of Jabalpur District, Madhya Pradesh. Jour. Geol. Soc. India, v.16(1), pp.86-89.

Ali, H.Y., Priju, C.P. and Prasad, N.N. (2015) Delineation of groundwater potential zones in deep midland aquifers along Bharathapuzha river basin, Kerala using geophysical methods. Aquatic Procedia, v.4, pp.1039-1046.

Andrade, R. (2014) Delineation of fractured aquifer using numerical analysis (factor) of resistivity data in a granite terrain. Internat. Jour. Geophys., doi:10.1155/2014/585204.

BIS (Bureau of Indian Standards) (2012) Indian Standard Drinking Water Specification (second revision) IS 10500:2012. Bureau of Indian Standards, New Delhi, 11p.

Casshyap, S.M., Tewari, R.C. and Khan, A. (1993) Alluvial fan origin of the Bagra Formation. Jour. Geol. Soc. India, v.42(3), pp.269-279.

CGWB (Central Ground Water Board) (1986) Manual on analysis of pumping test data of large diameter wells. Ministry of Water Resources, Government of India.

CGWB (Central Ground Water Board) (1992) Evaluation of aquifer parameters. Ministry of Water Resources, Government of India.

CGWB (Central Ground Water Board) (2022) Aquifer information and management system. htpps://aims-cgwb.org. Retrieved 17 September 2022.

CGWB (Central Groundwater Board) (2020) Master plan for artificial recharge to groundwater in India – 2020. Ministry of Water Resources, Government of India, 190p.

Choudhury, K., Saha, D.K. and Chakraborty, P. (2001) Geophysical study for saline water intrusion in a coastal alluvial terrain. Jour. Appl. Geophys., v.46(3), pp.189-200.

Census of India (CoI) (2011) Provisional population totals: Urban agglomerations and cities – data highlights. Census of India, Government of India.

Dhakate, R., Rao, V.V.S., Raju, B.A., Mahesh, J., Rao, S.T. and Sankaran, S. (2013) Integrated approach for identifying suitable sites for rainwater harvesting structures for groundwater augmentation in basaltic terrain. Water Resour. Managm., v.27(5), pp.1279-1299.

Dharma Rao, C.V.D. (2018) Report of site visit to water recharge experiment in GCF, Jabalpur. National Water Mission, Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India.

Dhurandhar, A.P. and Ranjan, R. (2020) Imaging and integration of hydrogeochemical data for characterization of groundwater quality around Jabalpur, India. Bull. Engg. Geol. Environ., v.79(1), pp.109-131.

Gaber, A., Mohamed, A.K., El Galladi, A., Abdelkareem, M., Beshr, A.M. and Koch, M. (2020) Mapping the groundwater potentiality of West Qena Area, Egypt, using integrated remote sensing and hydro-geophysical techniques. Remote Sensing, v.12(10), pp.1559.

GCF (Gun Carriage Factory) (2022) Gun Carriage Factory Jabalpur. htpps://ddpdoo.gov.in/units/GCF. Retrieved 17 September 2022.

Ghosh, G. K. and Singh, C. L. (2013) Intrusion and upliftment of Mahakoshal rocks between Vindhyan and Gondwana in Narmada Son lineament, Central India. Jour. Geol. Soc. India, v.81, pp.556-564.

Khosla, A. and Lucas, S.G. (2020) Geology and stratigraphy of dinosaur eggs and eggshell-bearing Infra- and Intertrappean beds of peninsular India. *In:* Khosla, A. and Lucas, S.G. (Eds.), Late Cretaceous dinosaur eggs and eggshells of peninsular India, Topics in Geobiology, International Publisher (Springer Nature, Switzerland AG), v.51, pp.57-115. doi:10.1007/978-3-030-56454-4_3

Kirsch, R. (Ed.) (2006) Groundwater geophysics: A tool for hydrogeology. Berlin, Heidelberg: Springer Berlin Heidelberg.

Lal, R., Padhan, T., Jangra, B., Chauhan, P.R., Sahu, S. and Patnaik, R. (2022) New field observations on the Quaternary geology and vertebrate paleontological occurrences in the Narsinghpur Region of Narmada Valley (Central India). Geol. Soc. London, Spec. Publ., v.515, pp.145-168. doi:10.1144/ SP515-2020-243.

Mahmoud, S.H. and Alazba, A.A. (2015) Geomorphological and geophysical information system analysis of major rainwater-harvesting basins in Al-Baha region, Saudi Arabia. Arab. Jour. Geosci., v.8(11), pp.9959-9971.

Matley, C.A. (1921) On the stratigraphy, fossils and geological relationships of the Lameta beds of Jubbulpore. Rec. Geol. Surv. India, v.53, pp.142-169.

Mukhopadhyay, G., Mukhopadhyay, S. K., Roychowdhury, M. and Parui, P.K. (2010) Stratigraphic correlation between different Gondwana basins of India. Jour. Geol. Soc. India, v.76, pp.251-266.

Muralidharan, D. (1996) A semi-quantitative approach to detect aquifers in hard rocks from apparent resistivity data. Jour. Geol. Soc. India, v.47(2), pp.237-242.

Naik, P.K., Mojica, M., Ahmed, F. and Al-Mannai, S. (2017) Stormwater injection in Bahrain: pilot studies. Arab. Jour. Geosci., v.10, pp.452. doi:10.1007/s12517-017-3232-5.

Naik, P.K., Prasad, G., Mondal, K.C. and P.K. Naik (2022) Feasibility study on roof top rainwater harvesting at Gun Carriage Factory, Jabalpur, Madhya Pradesh. Rajiv Gandhi National Ground Water Training and Research Institute, Central Ground Water Board, Ministry of Water Resources, River Development & Ganga Rejuvenation, Govt. of India.

NIPHE (National Institute for Public Health and the Environment - RIVM) (2014) Changes in rainwater and groundwater quality as a result of atmospheric emission reductions: Acidification and eutrophication, 1989 – 2010, RIVM Report 680720007/2014, RIVM, The Netherlands.

Oldham, R.D., Datta, P.N. and Vredenberg, E.W. (1901) Geology of the Son valley in the Rewa state and parts of the adjoining districts of Jabalpur and Mirzapur. Mem. Geol. Surv. India, v.31(1), pp.1–178.

Prasad, N.N. (2011) Geophysical investigation for groundwater exploration in Lakshadweep Islands–A case study. Jour. Indian Geophys. Union, v.15(4), pp.221-227.

Pujari, P.R., Padmakar, C., Quamar, R., Deshpande, L., Janipella, R., Balwant, P., Jyothi, V., Dhyani, S., Verma, P., Reddy, D.V. and Labhasetwar, P. (2019) In-situ treatment of fluoride in a hard rock setting by rooftop

rainwater harvesting recharge scheme. *In:* 1st Indian Near Surface Geophysics Conference & Exhibition (v.2019, no. 1, pp. 1-6), European Association of Geoscientists & Engineers.
Rahaman, M.F., Jahan, C.S. and Mazumder, Q.H. (2019) Rainwater harvesting to alleviate water scarcity in drought-prone Barind Tract, NW, Bangladesh: a case study. Sustain. Water Resour. Managmt., v.5, pp.1567–1578. doi:10.1007/s40899-019-00311-8.
Raju, N.J. (2015) Rainwater harvesting systems to recharge depleted aquifers. Jour. Appl. Geochem., v.17(3), pp.327-334.
Rao, G.V., Nitish, S. and Kumar, P.S. (2020) Geophysical Investigation Of Groundwater Potential In VIIT, Visakhapatnam, Andhra Pradesh-A Case Study. PalArch's Jour. Archaeology of Egypt/Egyptology, v.17(7), pp.7334-7345.
Rao, N. P., Kumar, M. R., Seshunarayana, T., Shukla, A. K., Suresh, G., Pandey, Y., Raju, R. D., Pimprikar, S. D., Das, C., Gahalaut, K., Mishra, P.S. and Gupta, H. (2011) Site amplification studies towards seismic microzonation in Jabalpur urban area, central India. Physics and Chemistry of the Earth, Parts A/B/C, v.36(16), pp.1247–1258.
Roy, A.K. (1957) Exploratory drilling for groundwater in the Narmada valley, Madhya Pradesh, India. Internat. Assoc. Scient. Hydrol. Bull., v.2(4), pp.27-45. doi: 10.1080/0262666570949308.
Saha, O., Shukla, U.K. and Rani, R. (2010) Trace fossils from the late cretaceous Lameta Formation, Jabalpur area, Madhya Pradesh: Paleoenvironmental implications. Jour. Geol. Soc. India, v.76., pp.607-620.
Sass, O. (2007) Bedrock detection and talus thickness assessment in the European Alps using geophysical methods. Jour. Appl. Geophys., v.62(3), pp.254-269.
Sengupta, N., Sengupta, P. and Sanyal, S. (2012). Occurrence of fluorine-bearing minerals in granite and a plausible mode of transport of fluorine into hydrological system: an example from Jabalpur Dist Madhya Pradesh, India. Indian Jour. Geosci., v.66(4), pp. 231-222.
Singh, P., Anand, A., Srivastava, P.K., Singh, A. and Pandey, P.C. (2021) Delineation of groundwater potential zone and site suitability of rainwater harvesting structures using remote sensing and in situ geophysical measurements. *In:* Pandey, P.C. and Sharma, L. (Eds.), Advances in Remote Sensing for Natural Resource Monitoring, pp.170-188.
Sleeman, W.H. (1844). Rambles and Recollections of an Indian Official. Volume I. London: J. Hatchard.
Sreedevi, P.D., Sarah, S., Alam, F., Ahmed, S., Chandra, S. and Pavelic, P. (2015) Investigating geophysical and hydrogeological variabilities and their impact on water resources in the context of meso-watersheds. *In:* Integrated Assessment of Scale Impacts of Watershed Intervention (pp. 57-83). Elsevier.
Tewari, R.C. (1998) Channel sandstone bodies in fluvial Permian-Triassic Gondwana succession of peninsular India. Jour. Geol. Soc. India, v.51, pp.747-754.
Venugopal, K. and Ghosh, N. (2010) Rooftop rainwater harvesting at CWPRS, Pune; Maharashtra – a case study. Jour. Appl. Hydrol., v.XXIII(1 & 2), pp.12-16.
Vouillamoz, J.M., Chatenoux, B., Mathieu, F., Baltassat, J.M. and Legchenko, A. (2007) Efficiency of joint use of MRS and VES to characterize coastal aquifer in Myanmar. Jour. Appl. Geophys., v.61(2), pp.142-154.
WSS (Water Science School) (2019) Acid rain and water. https://www.usgs.gov/special-topics/water-science-school/science/acid-rain-and-water, August 2, 2019. Retrieved 15 June 2022.

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Prachi Gupta offered general technical assistance and prepared figures through GIS and MapInfo software. She was one among the ten women officers across India selected to participate in the India Young Professional Programme implemented in collaboration with Australia Water Partnership.