Sustainable solution for drinking water supply in rural India affected by groundwater pollution

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The present study explores sustainable solutions for providing safe drinking water in an area currently served only by groundwater. Groundwater development here has reached criticality and is contaminated with fluoride and uranium. As there are only a few small seasonal streams in the area, roof-water harvesting and utilization of tank/lake water are tested as alternative approaches for drinking water supply. The study area is in the Chikkaballapura district of eastern Karnataka, India, where the average annual rainfall is 700 mm. The quantity of roof water that can be harvested from the built structures in the study area can adequately meet the drinking water requirements, although not the entire domestic water needs. A nearly perennial lake located in the upper reaches of the micro-watershed stores 301 million litres of water that needs only routine filtration and chlorination. This study shows that sustainable water management practices such as roof-water harvesting and lake water utilization can replace the contaminated groundwater for drinking purposes.

Keywords: Drinking water, perennial lakes, polluted groundwater, roof-water harvesting, sustainable solutions.

A major problem for more than three billion rural residents across the world is access to safe water for drinking and domestic purposes[1]. A sustainable approach to supplying safe water should meet the requirements both in quantity and quality. In India, 0.9 billion people out of a total population of 1.4 billion, i.e. 64% of the population live in rural regions, and most of them are affected by a lack of access to safe drinking water[2]. The rural drinking water requirements of the country are being managed under the Jal Jeevan Mission (JJM) of the Government of India (GoI). Eighty-five per cent of the public water supply is met by groundwater. Also, groundwater in large tracts of India is affected by geogenic or anthropogenic pollution[3]. To supply safe drinking water, several approaches are in practice. In villages facing health issues due to groundwater pollution and in the command areas of irrigation or multi-purpose projects, surface water supply from canals is being implemented. Reverse osmosis (RO) units have been installed in thousands of villages where groundwater is contaminated. These approaches have limitations: (i) surface water does not always reach remote villages in the command areas, and (ii) RO processing results in the expulsion of enormous amounts of wastewater, which is more contaminated than the water that has been treated and returned to the ground[4].

Therefore, there is a need to adopt more sustainable approach(es) to meet the drinking water requirements in such villages. In this study, we provide a sustainable solution for drinking water supply in a Gram Panchayat in eastern Karnataka, India. This case study relates to the Ganjigunte Gram Panchayat, which consists of 18 villages in the Chikkaballapura district of eastern Karnataka. The area is in a water-stressed zone where groundwater exploitation has exceeded the quantum of recharge[3]. Groundwater samples from 16 borewells which supply drinking water to the 18 villages in this Gram Panchayat are found to contain high amounts of uranium going up to 3000 μg/l, which is far greater than the World Health Organization (WHO) or Atomic Energy Regulatory Board (AERB) recommended limits for drinking water[5,6]. Additionally, in nearly 50% of the borewells, the amount of fluoride in groundwater also exceeds the permissible limit of 1.5 mg/l (Table 1)[7]. After identifying the quality issues associated with groundwater and the unsatisfactory performance of RO intervention[4], we have examined the feasibility of roof-water harvesting and using lake water for providing a safe and sustainable drinking water supply in this Gram Panchayat. The quantity of water available by roof-water harvesting and from nearby perennial lakes in the proximity is estimated in the study. The quality of water in the lakes has been evaluated to decipher whether it is possible to use it for drinking after routine treatment, as commonly adopted in municipal water supplies.

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Table 1. Range of uranium and fluoride concentrations in the groundwater of Ganjigunte Gram Panchayat, Chikkaballapur district, Karnataka, India

		Fluoride (mg/l)		Uranium concentration (μg/l)	
Village	Sample code	Minimum	Maximum	Minimum	Maximum
Ganjigunte	GNG	1.3	1.5	578.7	2,991.9
Gangahalli	GAH	1.5	1.6	1,656.2	2,447.2
Chokkanahalli	CHKH	1.6	1.8	92.8	191.3
Poolakuntlahalli	PUL	1.7	2.3	55.9	55.9
Hakkipikki Colony	HK	2.2	2.2	16.8	65.6
Kyasagere	KYS	1.7	2.0	274.5	477.0
Vemagal	VEM	0.7	0.8	1,272.3	2,032.8
Balegowdanahalli	BGH	2.0	2.0	129.5	220.8
Kondarajanahalli	GKDJ	1.4	1.4	435.3	1154.7
Dhoddabandragatta	DBG	1.3	1.3	452.5	775.7
Lakkenahalli	LAK	1.5	1.5	642.1	912.2
Haleganjigunte	HGA	2.2	2.2	271.7	824.3
Devaguttahalli	DEV	2.2	2.6	150.2	678.1
Nagitreddyhalli	NRHL	0.8	1.6	81.8	97.4
Brahmanarahally	BRH	1.5	2.4	148.0	3,218.0
Chikkabandaragatta	CBG	0.7	0.7	1,027.8	1,040.6
Permissible value		1–1.5 mg/l (BIS 2012)[7]		30 μg/l (WHO 2012)[5] 60 μg/l (AERB 2004)[6]	

*BIS, Bureau of Indian Standards; WHO, World Health Organization; AERB, Atomic Energy Regulatory Board.

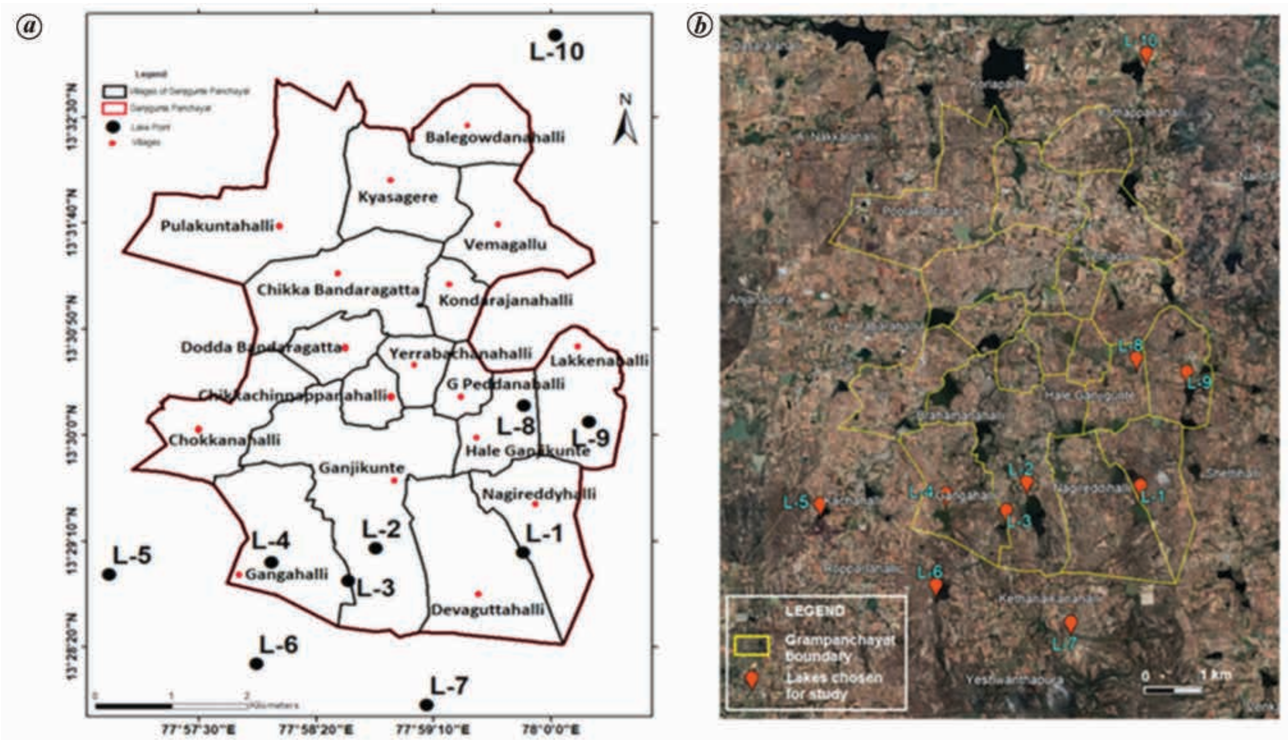

Figure 1. ***a***, Map of the Ganjigunte Gram Panchayat area, Chikkaballapura district, Karnataka, India showing locations of various villages and ten lakes (L-1 to L-10). ***b***, Google Earth imagery of the Ganjigunte Gram Panchayat area and its immediate surroundings showing the distribution of lakes (L-1 to L-10).

Study area

The Ganjigunte Gram Panchayat (a Gram Panchayat is an administrative unit of a group of villages), Shidlaghatta taluk, Chikkaballapura district, Karnataka, is located between lat. 13°28′20″ and 13°32′30″N and long. 77°57′30″ and 78°E. It is spread over an area of 33.5 km^2. The Gram Panchayat consists of 18 villages; Figure 1 *a* shows their locations. In the study area, there are no rivers which can serve as water resources. In general, the slope of the ground is from south to north, and many water tanks are fed by small seasonal streams (Figure 1 *b*). The inhabitants of these villages rely only on groundwater from public or private borewells as a drinking water source.

The study area is located over a hard-rock terrain consisting of Archean granitic gneiss and granodiorite, which are intruded by pegmatite veins and dolerite dykes. Groundwater has been overexploited in the area to meet the agricultural and domestic water needs, and has reached a critical stage of development[3]. Preliminary water quality studies of this area indicate that most villages have groundwater with increased levels of uranium and fluoride (Table 1)[4,8].

Methodology

This study includes (i) field investigations to determine the rooftop area of buildings in the Village Panchayat area, (ii) estimation of storage capacity of the lakes, and (iii) chemical analysis of groundwater, and chemical and biological analysis of surface water of the lakes.

Determination of rooftop area

A quick estimation of rooftop area was done with open-source Google Earth Explore imagery. Polygons were drawn over the observable structures at the highest zoom level. The constructed polygons were imported into the ArcGIS software as a shape file, and the total area of all the structures was computed. Since there are not many structures, actual physical measurement of the rooftop area was also carried out. The area obtained by the measured data were compared with that obtained from the Google Earth imagery. There was a large discrepancy between the two measurements. The area obtained from the imagery was larger, probably because of an error arising from somewhat low resolution of the imagery.

Estimation of quantity of water stored in tanks (lakes)

The area and volume of the lakes were determined using Sentinel-1A GRD imagery, which was downloaded from the Scihub Copernicus Eu site. SNAP (Sentinel Application Platform) software from the European Space Agency (ESA) was used to demarcate the lakes as a digital elevation model (DEM) file. ArcGIS 10.4 was used for mapping and computing the area and volume from the DEM file using both the Clip and Extract-by-mask methods. The Clip method is supported by both vector and raster datasets, while the Extract-by-mask method is supported only by raster data. Therefore, the Clip method is preferred over the Extract-by-mask method in this study.

Perennialism of water in the lakes

To confirm the perennialism of water in the lakes in and around the Ganjigunte Gram Panchayat, time-series data from 2013 to 2023 were studied using Google Earth Engine software. Additionally, images were captured using a time-lapse dataset that used the precise latitudes and longitudes of the lakes. Using the Google Earth Engine Data Catalogue for the period 2013–2023, a program was developed utilizing the Landsat-8 dataset. Landsat-8 surface reflectance (SR) data with blue, green, red, NIR, SWIR-1 and SWIR-2 bands were obtained from the Java Script on the Google Earth Engine code editor. These six bands, coupled with the panchromatic band, offer a ground resolution of 30 m and a fine resolution of 15 m. The program utilized the modified normalized difference water index (MNDWI) method using green and SWIR-1 and NIR and SWIR-1 to detect the presence of water. Other factors, such as cloud cover, were filtered. A positive MNDWI indicates the presence of water, whereas a negative MNDWI indicates its absence. The DEM in ArcGIS was used to obtain bathymetric information to calculate the volume of water.

Water quality determination

The Ganjigunte Gram Panchayat administers 18 villages and borewells in 16 villages supply drinking water to all the villages. These borewells have been generally drilled to depths of 200 m or more. The uranium and fluoride contents in more than a hundred groundwater samples collected during the pre- and post-monsoon seasons from these borewells were analysed at the Centre for Advanced Research in Environmental Radioactivity (CARER), Mangalore University, and the Indo-French Centre, Indian Institute of Science (IISc), Benglauru respectively, following the procedure described by Srinivasan *et al.*[4,8]. For uranium, analysis was performed using a LED fluorimeter (Quantalase LF-2a, India). Fluoride content was determined using ion chromatograph (Metrohm COMPACT 861, Switzerland). The precision of the reported concentrations for uranium is ±0.05 μg/l and for fluoride ±5%. In addition, water samples were collected from the interior parts of lakes near the spillway in clean polythene bottles for geochemical analysis and in sterilized glass bottles to determine biological contaminants. These lake water samples were analysed at the Ramaiah Advanced Testing Laboratory, Bengaluru, for physico-chemical, chemical, and biological quality parameters within 24 h after collection. The colour of water was determined following the procedure given in IS 3025 (Part 4) using colour development method and Shimadzu UV–visible spectrophotometer (UV-1601, USA). The odour was determined following the procedure given in IS 3025 (Part 5); pH and total dissolved solids were determined at the Indo–French Centre, IISc using sensor WTW probe (German make); turbidity was measured using a turbidity meter (Systronics 132, India); calcium, chloride, fluoride, magnesium, nitrate and sulphate contents were determined using Metrohm COMPACT 861; total hardness and alkalinity as $CaCO_3$ were determined by titration method; concentration of barium, boron, copper,

Table 2. Estimated water demand in the Ganjigunte Gram Panchayat for drinking and domestic purposes

Village	Total population (Panchayat office)	Domestic water demand at 55 lpcd* as recommended by Jal Jeevan Mission	Drinking water component at 2.5 l/person/day
Ganjigunte	2,575	141,625	6,438
Gangahalli	445	24,475	1,113
Chokkanahalli	513	28,215	1,283
Poolakuntlahalli	402	22,110	1,005
Hakkipikki Colony	362	19,910	905
Kyasagere	591	32,505	1,478
Vemagal	427	23,485	1,068
Balegowdanahalli	336	18,480	840
Kondarajanahalli	129	7,095	323
Doddabandragatta	260	14,300	650
Lakkenahalli	580	31,900	1,450
Haleganjigunte	427	23,485	1,068
Devaguttahalli	447	24,585	1,118
Nagireddyhalli	20	1,100	50
Brahmanarahally	448	24,640	1,120
Chikkabandaragatta	354	19,470	885
Yarrabachenahalli	107	5,885	268
G Peddanahalli	13	715	33
Total water demand (l/day)	8,436 (total population)	463,980	21,090
Total water demand (million litres/yr)		169.4	7.7

*lpcd, Litres per capita per day.

iron, manganese, selenium, silver, zinc, lead, mercury, nickel, arsenic, chromium and cadmium was determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Shimadzu model 2030, USA); *Escherichia coli* and coliform bacteria, were determined following the procedure given in IS 15185, 2016; *Staphylococcus aureus* and *Clostridium* were determined following IS 5887 (Parts 7 and 2 respectively), *Pseudomonas aeruginosa* following the procedure given in Annexure D of IS 13428-2005 (RA 2018); yeast and mould following the procedure given in IS 5403:1999 (RA 2018), and *Salmonella* and *Shigella* following the procedure in IS 5887 (Part 3 section 1 and Part 7 respectively).

Results

Problem with groundwater in the Ganjigunte Gram Panchayat

Sixteen of the 18 villages in the Ganjigunte Gram Panchayat have one dedicated public borewell each for supplying drinking water. Table 1 shows the range of fluoride and uranium concentration in the groundwater collected from these 16 borewells. Except in four villages, the fluoride content is 1.5 mg/l or greater. In all the villages, uranium abundance exceeds the permissible limit of 60 μg/l (Table 1). These contaminants are derived from minerals in late Archean potassic granites, granodiorites and the pegmatites intruding them, which are widely distributed in the area. The hard-rock granitic aquifer releases fluoride and uranium due to rock–water interaction. Fluoride may have been derived from accessory biotite, amphibole, fluorite and apatite; uranium may have been derived from allanite and sphene, which are common accessories in the granitoids and pegmatites. These rock formations in the area have been affected by oxidic weathering, which has resulted in red soils. Oxidation of uranium to the hexavalent state promotes its dissolution in the circulating groundwater. Contact/residence time of groundwater in the hard-rock aquifer enhances the concentration of the contaminants. In such areas, groundwater without any treatment is not desirable for drinking. This problem has been addressed by the Government through provision of RO plants. An earlier study showed that the RO units in operation can reduce uranium concentration by 95% and fluoride concentration by 93% (ref. 4). Even with this maximum efficiency of the RO system, the permeate would still contain much more than 60 μg/l uranium when its abundance in groundwater exceeds 1000 μg/l. Therefore, it appears that a sustainable drinking water supply in the Gram Panchayat should consider the use of surface water. In the following, we consider the feasibility of harvesting rainwater from the roofs and the use of tank (lake) water in the Ganjigunte Gram Panchayat.

Quantity of water required for drinking and domestic purposes

The United Nations (UN) recommends drinking 2.5 litres of water per capita per day (lpcd). JJM, GoI, aims to provide 55 lpcd for domestic use in rural India, including water for drinking. The population of Ganjigunte Gram Panchayat

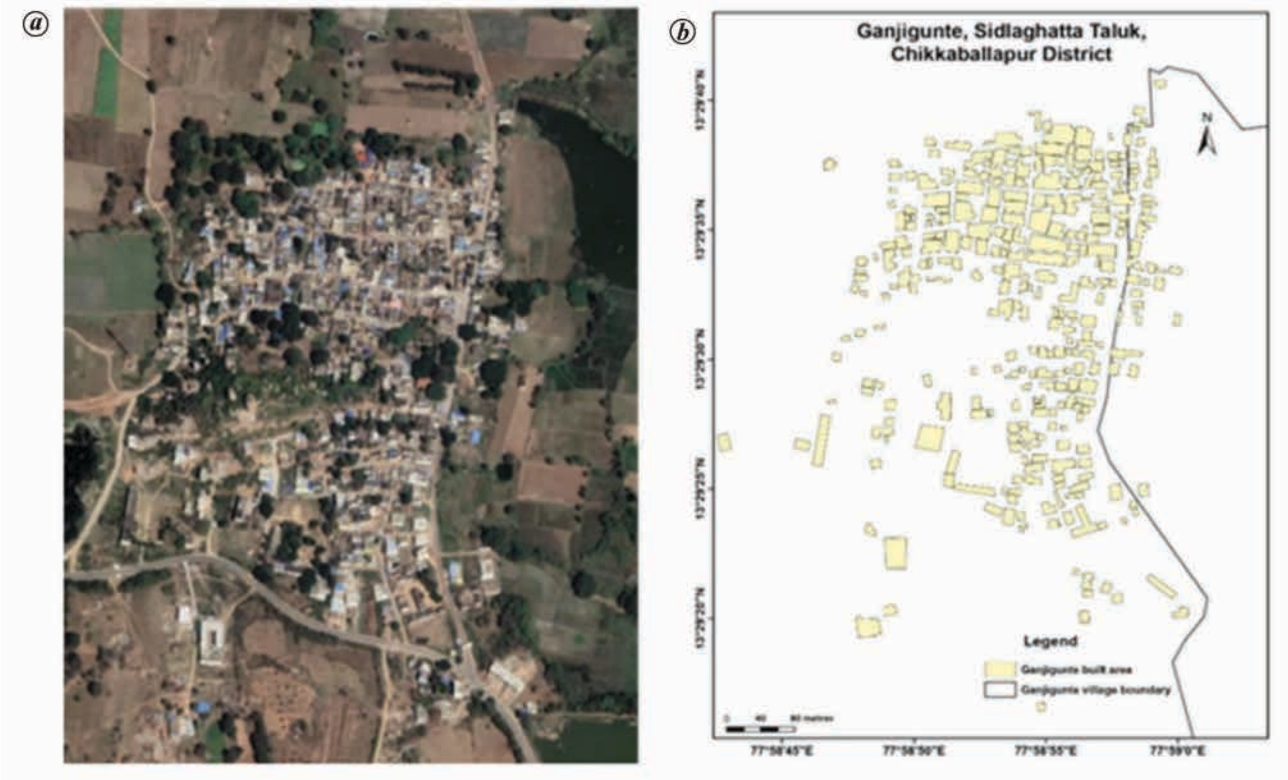

Figure 2. ***a***, Google Earth imagery of the Ganjigunte village showing built structures. ***b***, Rooftop area inferred from the imagery.

as of 2022 was 8426. Therefore, the total daily water requirement for domestic use is 0.46 million litres (ML) per day or 169.4 ML per year. The quantity of water for drinking alone would be 7.7 ML/yr (Table 2).

Whether roof-water harvesting and tank water can meet this requirement is analysed in the following section.

Roof-water harvesting

Figure 2 *a* and *b* show the Google Earth imagery of Ganjigunte village and the extracted rooftop area.

The Supplementary Figure 1 *a–d* shows the extracted rooftop areas for other villages in this Gram Panchayat. Field survey and physical observation of the condition of buildings in the 18 villages of the Ganjigunte Gram Panchayat revealed that the total number of built structures was 1426, of which 1188 structures were suitable for roof-water harvesting. The built structures in all the villages of the Gram Panchayat account for a total roof area of 66,387 m^2. Average rainfall data estimated from the 100-yr database in the Ganjigunte Gram Panchayat was 694 mm/annum (ref. 8). Since climate change significantly impacts rainfall patterns, the average rainfall during the last ten years based on India Meteorological Department data was evaluated and found to be 834.2 mm/annum. The minimum rainfall during the last 100 years was 492 mm/annum; in the previous ten years, it was 499 mm/annum. The amount of rainwater that can be harvested from the rooftops was determined using these data and corrected for losses of approximately 10% during harvesting. Whether minimum rainfall can produce enough water from the roofs to meet the drinking water requirements of the population was verified. Table 3 gives the volume of rainwater that can be harvested based on the minimum and average rainfall.

In the years with minimum rainfall, 29.4 ML can be harvested, while in those with average rainfall, 41.5 ML can be harvested. During the last ten years, the minimum rainfall could yield is 29.8 ML, and the average rainfall could yield 49.8 ML. As the drinking water quantity required per annum is only 7.7 ML, the harvested roof water is much more than that required for drinking purposes. However, if domestic water requirement is considered, which is 169.3 ML/annum, the harvested roof water quantity falls short of the requirement. Therefore, it is necessary to consider alternative water sources that can supplement or substitute the harvested roof water.

Surface water resources

The surface water resources in the Ganjigunte Gram Panchayat are mainly in the form of tanks (inland lakes). The tanks in the area were studied for quantity and quality of water.

Tanks in the Gram Panchayat: Google Earth imagery of the Ganjigunte Gram Panchayat shows a number of water bodies

Table 3. Computed quantity of rainwater that can be harvested from the rooftops in the study area

Village	Number of houses	Rooftop area (m^2)		Quantity of rainwater that can be harvested (l) based on average rainfall between 1901 and 2015		Quantity of rainwater that can be harvested (l) based on average rainfall during the last 10 years (2013–2022)	
		Using software	Actual measurement	492 mm/yr (minimum)	694 mm/yr (average)	499 mm/yr (minimum)	834 mm/yr (average)
Ganjigunte	361	45,718.4	22,075.7	10,861,244	15,320,536	11,015,784	18,415,566
Poolakuntalahalli, Hakkipikki Colony*	137	6,866.7	4,052.9	1,994,027	2,812,713	2,022,412	3,380,954
Kyasagere	99	6,917.4	5,613.2	2,761,694	3,895,561	2,800,962	4,682,490
Vemagal	68	7,748.3	5,587.0	2,748,804	3,877,378	2,787,908	4,660,667
Balegowdanahalli	63	2,596.2	1,865.2	917,678	1,294,449	930,735	1,555,950
Kondarajanahalli	33	1,435.2	1,116.7	549,416	774,990	557,248	931,576
Doddabandragatta	53	3,010.0	2,067.5	1,017,210	143,4845	1,031,678	1,724,700
Haleganjigunte	86	5,430.9	2,424.2	1,192,706	1,682,395	1,209,691	2,022,293
Devaguttahalli	73	8,049.6	3,669.4	1,805,345	2,546,564	1,831,011	3,060,980
Chikkabandaragatta	67	5,207.2	2,578.1	1,268,425	1,789,201	1,286,447	2,150,609
Yarrabachenahalli	19	1,958.2	934.8	459,922	648,751	466,455	779,794
G Peddanahalli	4	117.7	81.9	40,295	56,839	40,868	68,321
Lakkenahalli	82	7,479.5	6,106.4	3,004,349	4,237,842	3,047,114	5,093,992
Gangahalli	76	3,836.1	2,630.2	1,294,058	1,825,359	1,312,465	2,194,105
Chokkanahalli	106	7,052.7	3,391.0	1,668,372	2,353,354	1,692,089	2,828,739
Nagireddyhalli	5	227.0		0	0	0	0
Brahmanarahally	94	6,538.4	2,192.7	1,078,808	1,521,734	1,094,177	1,829,184
Measured rooftop area and estimated quantity of rainwater harvested (l)	1,426 (total)	120,189.4	66,386.9	32,662,355	46,072,509	33,127,043	55,379,919
Estimated quantity of rainwater with 10% correction (million litres)	1188 (actually measured)	108,170.4	59,748.2	29.4	41.5	29.8	49.8

*Hakkipikki Colony is an extension of Poolakuntalahalli. Therefore, the number of houses is presented together.

(Figure 1 *b*). A study of the imagery and topographic map prepared by the Survey of India shows that the natural gradient in the Gram Panchayat is from south to north. As we are searching for water sources for drinking and domestic purposes, it is necessary to select tanks with less polluted water. Therefore, the tanks were examined with reference to their location in relation to anthropogenic activities such as agriculture and sewage disposal.

Figure 1 *a* shows the location of the ten lakes in the Ganjigunte Gram Panchayat and their immediate surroundings. In this study, the lakes are grouped into three categories: (1) lakes in natural setting in the upper reaches of the micro-water sheds, where they are bordered by less than 20% agricultural fields in the catchment and where no visible sewage outlets are reaching the lakes, (2) lakes with agricultural fields rimming approximately 50% of their margins generally located downstream of category-1 lakes, and (3) lakes surrounded by agricultural fields located in the valleys. Lakes in categories (2) and (3) have the possibility of receiving surface run-off that carries agrochemicals such as nitrogen, phosphorus and potassium (NPK) fertilizers and some insecticides and pesticides that degrade the quality of water in them[9]. Therefore, utilization of water from category-1 lakes for drinking and domestic purposes is desirable. Figure 3 *a* and *b* provide an example of a category-1 lake in the Ganjigunte Gram Panchayat. This lake, called Reddykere, is in the upper reaches of the micro-water shed and is largely surrounded by natural rock and soil, as seen in the imagery. Three lakes shown as L-1, L-2 and L-4 in Figure 1 satisfy similar criteria and are considered potential drinking and domestic water sources. We verified the perennialism and quality of water in these and other lakes of the Gram Panchayat for further evaluation of the suitability of these lakes for water supply.

Quality of lake water: For drinking purposes, the quality of water is of utmost importance. Lake water is prone to pollution from natural and anthropogenic sources. Therefore, we examined the water quality parameters, comparing them with the permissible standards of WHO[11] and BIS[7]. The methods used to determine water quality parameters have already been described earlier. The physical, chemical, and biological quality parameters are given in the Supplementary Table 1. A perusal of Supplementary Table 1 shows that the colour of the lake water and total dissolved solids (TDS) are within acceptable limits in all the lakes. The turbidity of water in six out of the ten lakes is less than 1 NTU, as required by the standards for drinking water. In the case of L-1, L-7, L-8 and L-10, turbidity exceeds the acceptable limit. The TDS concentration is

Figure 3. ***a***, Google Earth imagery of Reddykere lake (L-2) located in a natural setting with rock outcrops reaching up to the margin of the lake and less than 20% area of agricultural fields at its margin. No sewage water disposal into the lake is evident. ***b***, View of the lake. ***c***, Bathymetric map of the Reddykere lake prepared using digital elevation model and Arc GIS.

less than 500 mg/l, which is the permissible limit for drinking water. Aluminium exceeds the permissible limit of 0.03 mg/l in two lakes (L-1 and L-3). Barium, boron, calcium, chloride, copper, fluoride, magnesium, manganese, nitrate, selenium, silver, zinc, nickel, sulphate, arsenic, chromium, mercury and cadmium are within the permissible limits in all the studied lakes. Iron exceeds the permissible limit in L-1 and L-4. Lead concentration exceeds the permissible limit in L-1. The water in all the lakes is soft, with total hardness ranging from 44 to 196 mg/l. The total alkalinity is within the permissible limit of 200 mg/l. There is no lake water in the area that does not contain *E. coli*. Three lakes, namely, L-1, L-2 and L-4, are identified as potential sources of drinking water based on their location and quantity of water they store. Water from L-1 has more lead than the permissible limit in addition to coliform bacteria, *Staphylococcus*, yeast and mould. Due to the high lead content, it may be ruled out as a drinking water source. Water from L-2 has no trace elements contamination, but consists of *E. coli*, coliform bacteria and yeast. Water from L-4 has high yeast and mould contamination. Among the three lakes, water from L-2 appears to be better than that from other two lakes. The common factor is *E. coli* and bacterial contamination. The lake water needs filtration and chlorination treatment before supplying for drinking purposes. Since this is a routine practice in all public water supply systems, it should be possible to adopt the same in the study area, and L-2 water can be utilized.

Perennialism: For a lake to be a sustainable water resource, it must be perennial. Perennialism is studied from time-series satellite images of the lakes in a region. Google Earth Engine timelapse images since 1984 with maximum magnification were examined. Figure 4 *a* shows images of Reddykere and Narayanareddykere lakes from 2014 to 2022. Examination of the surface reflectance of these lakes was carried out using two different band combinations, viz. B3 and B6, and B5 and B6, to determine the presence of water. Figure 4 *b* shows differences in the reflections. The LANDSAT-8 imageries for the period 2013–2023 were studied using the MNDWI method to test perennialism[12,13]. The time-series graphs demonstrate that the water level was low during 2014 and 2015, which is further supported by the fact that 2013 and 2014 were very low-rainfall years (Supplementary Figure 2). This study revealed that lakes L-1, L-2, L-3 and L-4 in the southern elevated part of the Ganjigunte Gram Panchayat are nearly perennial, except that three of them (L-1, L-2 and L-4) became nearly dry during the severe drought spell between 2013 and 2015 (ref. 13). L-3 did not go dry even during this period of drought (Figure 4 *a* and *b*).

L-3 is a small lake whose storage would not be adequate for water supply. Therefore, lakes L-1, L-2 and L-4 were considered for supplying water. The quantity of water in these three large lakes was estimated.

Quantity of water available: The quantity of water in the ten selected lakes was estimated using remote sensing methods. DEM in ArcGIS environment was used to obtain bathymetric information to calculate the volume of water. The area and volume were estimated using the clip and extract methods. The values estimated by the clip method, since they are supported by GPS, are preferred. Table 4 shows the area and maximum quantity of water in the ten selected lakes corrected for dead storage taken as 15%.

Figure 3 *c* and the Supplementary Figures 3–11 show bathymetric maps of all the selected lakes. The estimated volume of water in the lakes ranged from 2.0 to 396.5 ML. L-10 and L-2 are the largest lakes in the Gram Panchayat, followed by other lakes, which are given in the order of abundance of water as follows: L-10 > L-2 > L-7 > L-4 > L-5 > L-6 > L-1 > L-9 > L-8 > L-3. Although L-10 has the largest water spread, physical examination shows that it is largely silted. Furthermore, L-10 is in the lower part of the study area, and any water that needs to be used from this area requires more energy for pumping to the

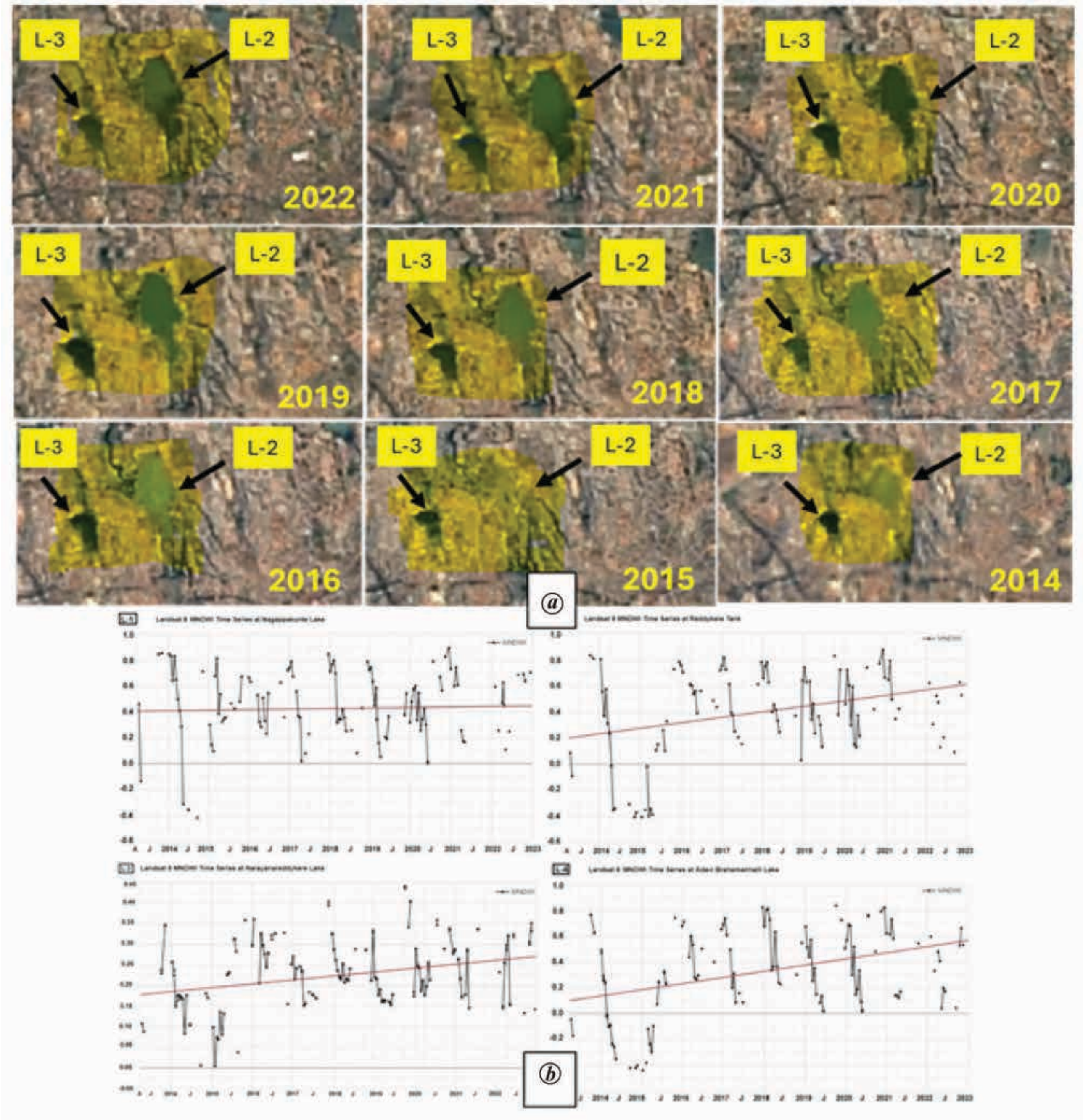

Figure 4. ***a***, Google Earth Engine timelapse images with maximum zoomed-in images of Reddykere lake (L-2) and the adjacent Narayanareddykere lake (L-3). ***b***, Modified normalized difference water index plots for lakes L-1, L-2, L-3 and L-4 from LANDSAT-8 surface reflectance data.

southern elevated part where the maximum number of people are living. Its water is also contaminated with lead. Therefore, L-2 is the preferred lake for drinking water supply. The lake has 301.2 ML of water and it can easily meet the drinking water requirement of 7.7 ML. However, it cannot meet domestic water requirements. Therefore, people living in the Ganjigunte Gram Panchayat must depend on groundwater (except for drinking) for domestic needs. L-2 can be considered only for drinking water supply.

Discussion and conclusion

The objective of this study was to find an alternative sustainable source of drinking water in an area where groundwater has reached a critical stage of exploitation and is strongly contaminated by fluoride and uranium[8]. RO intervention for purifying the groundwater, an initiative taken by the Government to provide healthy drinking water, has not been satisfactory[4]. This is because: (i) RO units have

Table 4. Computed area and quantity of water in the lakes corrected for dead storage

Tank code	Tank	Area ($10^3 \times m^2$)		Quantity of water (million litres) (*A*)		Dead storage (15%) (*B*)		Net quantity of water that can be used when the tank is 100% full (million litres) (*A* – *B*)	
		Clip	Extract	Clip	Extract	Clip	Extract	Clip	Extract
L-1	Nagappakunte	46.6	46.4	127.5	127.0	19.1	19.0	108.4	107.9
L-2	Reddykere	115.9	116.3	354.3	356.1	53.1	53.4	301.2	302.6
L-3	Narayanareddykere	2.8	2.8	2.4	2.4	0.4	0.4	2.0	2.0
L-4	Adavi Brahmanahalli	70.5	70.6	309.8	310.0	46.5	46.5	263.3	263.5
L-5	Kuchahalli	26.6	26.7	128.5	131.5	19.3	19.7	109.2	111.7
L-6	Near Kethanaikanhally	48.7	48.8	157.5	158.9	23.6	23.8	133.8	135.0
L-7	Kethanaikanahally	44.7	45.6	212.2	211.3	31.8	31.7	180.3	179.6
L-8	Kothakunte	19.4	19.6	9.6	9.9	1.4	1.5	8.2	8.5
L-9	Chikkalakunte	37.7	38.0	77.7	78.7	11.6	11.8	66.0	66.9
L-10	Kuthappanahalli	99.8	94.6	466.4	454.3	70.0	68.1	396.5	386.1

not been able to remove contaminants to acceptable levels when the level of contamination is high, and (ii) these units are wasting three times the water they recover for drinking in an area where groundwater resources are already in a critical stage of exploitation. Further, the RO wastewater, which is more contaminated with pollutants, is found to return to the groundwater regime. Therefore, supplying water from the RO units may not be a sustainable solution in the long run. Under such critical circumstances, it has become imperative to consider roof-water harvesting or exploiting surface water from tanks to sustainably meet the drinking and domestic water requirements.

The area of rooftops of houses in the villages is adequate for harvesting the required quantity of water for drinking, although not for the entire domestic water use. Similarly, the study has shown that the surface water bodies (tanks/lakes) near the villages are nearly perennial and can easily supply the required amount of water for drinking. They also do not seem to satisfy the entire domestic water requirement.

This study indicates that the conjunctive use of harvested rainwater, as well as surface and groundwater is inevitable for sustainable supply of domestic water in the Ganjigunte Gram Panchayat. Effective management of water resources is necessary. However, both roof and lake water need purification by filtration and chlorination to eliminate harmful bio-contaminants, as in any other public water supply system.

Desert countries like Israel or Saudi Arabia[14] have demonstrated how even the small amount of rainfall they receive can be harvested and used to meet the drinking water demands. Rajasthan is one of the states in India that has shown how water harvested during the rainy season can be stored and utilized for drinking for many months in a year[15–17].

It is worthwhile studying the engineering aspects of supplying water from either rooftop water harvesting or lake water use in areas where groundwater exploitation has reached criticality and/or is contaminated, as in the present study area. A common sump for storing water from either or both sources and water purification units are necessary for Gram Panchayats of the type studied here.

The case study presented here can be considered as an approach in areas located far away from the perennial sources of water for drinking water supply. The benefits and broader implications of the study are as follows:

- Sustainability in terms of water quantity and quality: This approach promotes sustainable water management in a water-stressed zone by utilizing available water resources in the neighbourhood.
- Applicability: The findings of this study can be applied to other regions facing similar challenges, such as groundwater overuse and contamination. This approach encourages proper utilization of available resources and effective management.
- Alignment with SDGs: This study aligns with the UN Sustainable Development Goals (SDGs), particularly SDG-6, which focuses on ensuring access to water and sanitation for all. By promoting sustainable water management, it contributes to long-term water security and improved living conditions.
- This study is relevant to the dedicated efforts of the Government of Karnataka and GoI to implement water projects like Jaladhare and JJM to fulfil the drinking water needs of rural areas. Schemes based on surface water sources are being undertaken by multi-village drinking water programmes under the National Rural Drinking Water Programme. Measures are being taken to provide clean and safe water by purifying the surface water from various water sources to the habitats where the groundwater is affected with high nitrate, iron, TDS, fluoride, arsenic, uranium and other elements. Under the National Drinking Water scheme, based on surface water sources, initiatives have been taken to find a permanent solution to the drinking water issues.

Conflict of interest: The authors declare that there is no conflict of interest.

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