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Assessment of Toxic Environmental Loading in Drinking Water Sources of a Cancer-Affected Region in Andhra Pradesh, India

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Abstract:	An increase in reported cancer cases raises concerns regarding the potential influence of environmental factors on public health in India. The study has been undertaken to evaluate groundwater and surface water quality to identify possible contamination sources and assess associated human health risks in a densely populated village (Balabhdarapuram), reported as a cancer hotspot region in Andhra Pradesh State, India, where numerous industrial activities are present. Groundwater samples from shallow wells, deep wells including public water supply sources, and surface water samples from canals and ponds were collected in January 2026 and analyzed for major ions and heavy metals. Elevated iron concentrations (>550 µg/L), associated with chloride concentrations exceeding 250 mg/L, were observed in a cluster of wells, including a public water supply source, suggesting combined influence of geogenic processes and local anthropogenic inputs such as wastewater infiltration and septic leakage. Elevated lead concentration in the same public water supply source indicates a potential concern for drinking water safety in the study area. Moderate to high contamination levels (MI: 2.40–7.49; Cd: 1.2–4.0) are also observed in public water supply sources. Non-carcinogenic risk remained within acceptable limits for adults (HI<1), whereas children showed comparatively higher exposure. Carcinogenic risk assessment using Total Cancer Risk (TCR) identified elevated to potential cancer risk (TCR > 1×10^{-4}) at three public water supply schemes. These locations require priority attention and should be provided with safer alternative public drinking water supply sources where acceptable cancer risk levels have been observed. The study emphasizes the need for effective water treatment, implementation of heavy-metal

	removal technologies, continuous groundwater quality monitoring, and improved drinking water security in the study area.
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Title Page

Assessment of Toxic Environmental Loading in Drinking Water Sources of a Cancer-Affected Region in Andhra Pradesh, India

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ABSTRACT

An increase in reported cancer cases raises concerns regarding the potential influence of environmental factors on public health in India. The study has been undertaken to evaluate groundwater and surface water quality to identify possible contamination sources and assess associated human health risks in a densely populated village (Balabhdarapuram), reported as a cancer hotspot region in Andhra Pradesh State, India, where numerous industrial activities are present. Groundwater samples from shallow wells, deep wells including public water supply sources, and surface water samples from canals and ponds were collected in January 2026 and analyzed for major ions and heavy metals. Elevated iron concentrations (>550 µg/L), associated with chloride concentrations exceeding 250 mg/L, were observed in a cluster of wells, including a public water supply source, suggesting combined influence of geogenic processes and local anthropogenic inputs such as wastewater infiltration and septic leakage. Elevated lead concentration in the same public water supply source indicates a potential concern for drinking water safety in the study area. Moderate to high contamination levels (MI: 2.40–7.49; Cd: 1.2–4.0) are also observed in public water supply sources. Non-carcinogenic risk remained within acceptable limits for adults (HI<1), whereas children showed comparatively higher exposure. Carcinogenic risk assessment using Total Cancer Risk (TCR) identified elevated to potential cancer risk ($TCR > 1 \times 10^{-4}$) at three public water supply schemes. These locations require priority attention and should be provided with safer alternative public drinking water supply sources where acceptable cancer risk levels have been observed. The study emphasizes the need for effective water treatment, implementation of heavy-metal removal technologies, continuous groundwater quality monitoring, and improved drinking water security in the study area.

Keywords: Groundwater quality; Heavy metals; Health risk assessment; Total cancer risk; Public water supply

1. Introduction

Groundwater is one of the most important freshwater resources supporting drinking, domestic, agricultural, and industrial sectors worldwide and plays a critical role in sustaining public health, food production, and economic development (Mohammadi et al. 2019). In India, groundwater is the principal source of drinking water, particularly in rural regions, and therefore, groundwater quality directly influences human health (Shah et al. 2023). However, increasing agricultural intensification, industrialization, urban expansion, and population growth have resulted in growing pressure on groundwater resources, affecting both groundwater quantity and quality (Laoye et al. 2025). Groundwater contamination due to wastewater discharge and inadequate sanitation has become an increasing environmental concern in both urban and rural areas. Groundwater systems are highly vulnerable to contamination because pollutants introduced at the land surface can infiltrate through the unsaturated zone and eventually reach underlying aquifers (Sravani et al. 2018). In rural and peri-urban areas, improper disposal of domestic wastewater, seepage from septic tanks, open drains, and inadequate sanitation infrastructure are among the major causes of groundwater quality deterioration (Barathkumar et al. 2025). Wastewater seepage commonly introduces dissolved salts, chloride, nitrate, organic matter, pathogens, and trace contaminants into groundwater (Saleh et al. 2019). Similarly, poor drainage systems and stagnant wastewater accumulation may increase groundwater recharge containing contaminants, particularly during rainfall events. In densely populated urban areas, leakage from sewer networks, improper wastewater disposal, and reduced infiltration control further contribute to groundwater contamination (Nawale et al. 2021).

Continuous wastewater infiltration may alter groundwater hydrochemistry and increase concentrations of indicators such as chloride, nitrate, total dissolved solids (TDS), iron, manganese, and microbial contaminants (Surekha et al. 2015; Adimalla 2018). Elevated chloride concentrations are often used as an indicator of anthropogenic recharge because chloride is highly mobile and conservative in groundwater systems (Singha et al. 2025). Long-term contamination resulting from inadequate sanitation and wastewater discharge may reduce groundwater suitability for drinking purposes and increase potential human health risks in both urban and rural areas (Selvam et al. 2017). When untreated or partially treated wastewater infiltrates into the subsurface, contaminants may migrate into shallow and deep aquifers and subsequently enter drinking water supplies . Wastewater infiltration commonly introduces pathogenic microorganisms, dissolved salts, nutrients (particularly nitrate), organic matter, heavy metals, and other contaminants into groundwater (Bhuiyan et al. 2010, Hinton et al. 2024). Consumption of contaminated groundwater may lead to a range of health effects. Long-term exposure to groundwater affected by wastewater infiltration may also increase concentrations of heavy metals and other toxic elements, potentially resulting in adverse effects on the nervous system, kidney function, liver function, cardiovascular health, and child development (Singh et al. 2014). In areas experiencing continuous contamination, prolonged exposure may increase both non-carcinogenic and carcinogenic health risks, depending on contaminant type, concentration, exposure duration, and population vulnerability (Kumar et al. 2024). Children, elderly individuals, and populations dependent on untreated groundwater are generally more vulnerable to these health effects (Bhuiyan et al. 2010; Kouser and Verma 2024). The World Health Organization (WHO 2017) revised guideline for Pb (10 µg/L) emphasizes that no safe threshold exists below which no adverse effect occurs, and IARC (2012) confirms chromium (Cr) and cadmium (Cd) as Group 1 carcinogens and Pb as Group 2A, with groundwater ingestion as a primary chronic exposure route. Smith et al. (2000) documented the Bangladesh-West Bengal arsenic disaster, describing it as one of the largest mass poisonings in history, affecting more than 35 million people and clearly linking chronic arsenic exposure with cancers of the bladder, skin, and lung. Similar contamination problems have been identified in Nepal, China, Chile, Argentina, and several Indian states, showing that heavy-metal pollution is not isolated but a widespread public health issue. Parida and Patel (2023) examined the systemic toxicity of lead, cadmium, chromium, arsenic, and mercury, emphasizing their role in cancer development. Rao et al. (2009) reported that groundwater in an industrial area of Hyderabad, India is heavily contaminated with heavy metals and showing strong industrial land waste-dumping influence. Sankhla et al. (2016) reviewed heavy metal contamination in water sources such as groundwater, surface water, and tap water in Vijayawada, Andhra Pradesh, showing that local industrial effluents are an important source of contamination. The authors concluded that better waste control and regular monitoring are needed to reduce health risks.

Balabhadrapuram Village in the East Godavari district, Andhra Pradesh, India, is home to approximately 11,000 people and is grappling with a rise in cancer cases during recent years. A recent health department survey has identified 38 cancer cases in the village, and more than 200 residents have been diagnosed with various forms of cancer. Reports in the print and electronic media indicated that the observed incidence rate in the village was considerably higher than the Andhra Pradesh State average and exceeded the national average, leading to public concern and initiation of environmental and health investigations. This unprecedented health situation raised concerns regarding possible environmental and lifestyle-related factors contributing to the increase in reported cases and has affected the social and economic well-being of local communities (The Hindu, 2025). Special Medical Camps were arranged by the East Godavari District Collector, who deployed 31 teams comprising doctors and cancer specialists to conduct house-to-house surveys and screenings (Fig.1). These teams gathered information on family medical histories, dietary habits, and lifestyle factors. Suspected cancer patients are undergoing detailed screening tests to confirm diagnoses. Residents are suffering from multiple types of cancer, including throat, brain, colon, and breast cancers. Alongside these cases, there is also a notable prevalence of liver-related diseases among newborns and other individuals. The root cause of this health crisis remains unclear, prompting investigations into possible environmental triggers. The environmentalists stated that, in India, the spread of cancer is one per thousand population and eight per 10,000 population in Andhra Pradesh. At Balabhadrapuram, the number of cancer cases reported by March 2025, is almost three times more than the State's average, signaling the state of alarm on the rate of spread of cancers in the village (The Hindu, 2025). The NGOs and other organizations suspect that the proximity of Balabhadrapuram to industrial facilities, such as the Grasim factory, means that pollutants from these operations are affecting water quality and air purity. Balabhadrapuram's health crisis underscores the need for environmental monitoring and healthcare interventions in rural areas. Therefore, the immediate action required to prevent further suffering and mitigate any potential environmental hazards that may be contributing to this crisis in the Balabhadrapuram and the neighbouring villages to determine to elevated cancer is localized in Balabhadrapuram or indicative of broader environmental issue.

Experts and activists urge MoEFCC to investigate 'environmental pollution' causing high cancer rates near Grasim Industries' Chlor-Alkali unit at Bhalabhadrapuram in Andhra Pradesh

The factory is reportedly being allowed to use PFOA (Perfluorooctanoic Acid), which causes cancer. Hence, the government environment protection agencies should inspect the factory and initiate measures to prevent further spread of cancer cases at the village, says former IICT scientist

Updated - March 24, 2025 08:39 pm IST - BHALABHADRAPURAM (EAST GODAVARI)

T. APPALA NAIDU

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Locals being screened for various cancers at a medical camp organised at Bhalabhadrapuram in East Godavari district on Monday. | Photo Credit: BY ARRANGEMENT

Scientists for People seeks thorough probe into Balabhadrapuram cancer cases, writes to APPCB

In addition to an investigation into the matter, the organisation also sought accountability for the "inaccurate" public statements made by the government officials and demanded that the gravity of the situation be acknowledged.

Published - March 31, 2025 03:20 am IST - VIJAYAWADA

THE HINDU BUREAU

READ LATER

Doctors conducting a door-to-door survey to identify cases of various cancers at Bhalabadrapuram village of Bikkavolu Mandal in East Godavari district. | Photo Credit: BY ARRANGEMENT

Fig. 1. Newspaper report highlighting concerns regarding increasing cancer incidence in Balabhadrapuram village (Source: The Hindu, 24 March 2025; 31 March 2025).

Although groundwater quality assessments and comparison with drinking water standards have been conducted in parts of East Godavari district, no significant studies have specifically focused on Balabhadrapuram village and its surrounding habitations despite increasing public concern regarding reported cancer incidence in the area. Earlier studies evaluated groundwater contamination only in terms of chemical exceedance, without quantifying the potential human health implications approaches. The information is unavailable regarding the domestic wastewater seepage, and sanitation-related contamination on heavy metal distribution and associated health risks in the study area. Therefore, the present study focuses on a comprehensive assessment of groundwater and surface water quality in Balabhadrapuram and surrounding villages through hydrochemical characterization, heavy metal analysis, pollution assessment and human health risk evaluation. The study further aims to identify priority drinking water sources, evaluate potential exposure pathways for adults and children, and recommend scientifically based mitigation and drinking water management measures for reducing long-term health risks and ensuring safe water supply in the study area.

2. Study Area

Balabhadrapuram village and its surrounding villages, are considered as the study area (Fig.2), covering hydrological boundaries. The study area lies within the geographical coordinates of approximately 16°55′30″ to 17°01′34″ N latitude and 81°58′44″ to 82°04′48″ E longitude. The region falls under the administrative jurisdiction of two mandals, namely Biccavolu and Rangampet. The study area is situated approximately 12 km from Rajahmundry city, the East Godavari district headquarters. A Godavari delta canal, namely the Samalkot main canal, pass through the south of the village. The main crop is paddy under canal irrigation. The study area experiences a dry, sub-humid climate with oppressive summers and seasonally distributed rainfall. The normal annual rainfall in the study area ranges from 900 to 1100 mm (IMD, 2015). Approximately 70% of the total annual rainfall occurs during the Southwest Monsoon season (June to September), with the remaining 30% distributed across the Northeast Monsoon (October–December) and minimal dry-season precipitation (CGWB 2024). Balabhadrapuram village has a population of approximately 11,000 residents. The community is predominantly dependent on groundwater through piped public water supply from two Overhead Tanks (OHT), namely Yellampeta OHT and Tatanagram OHT, for drinking and domestic use to all households.

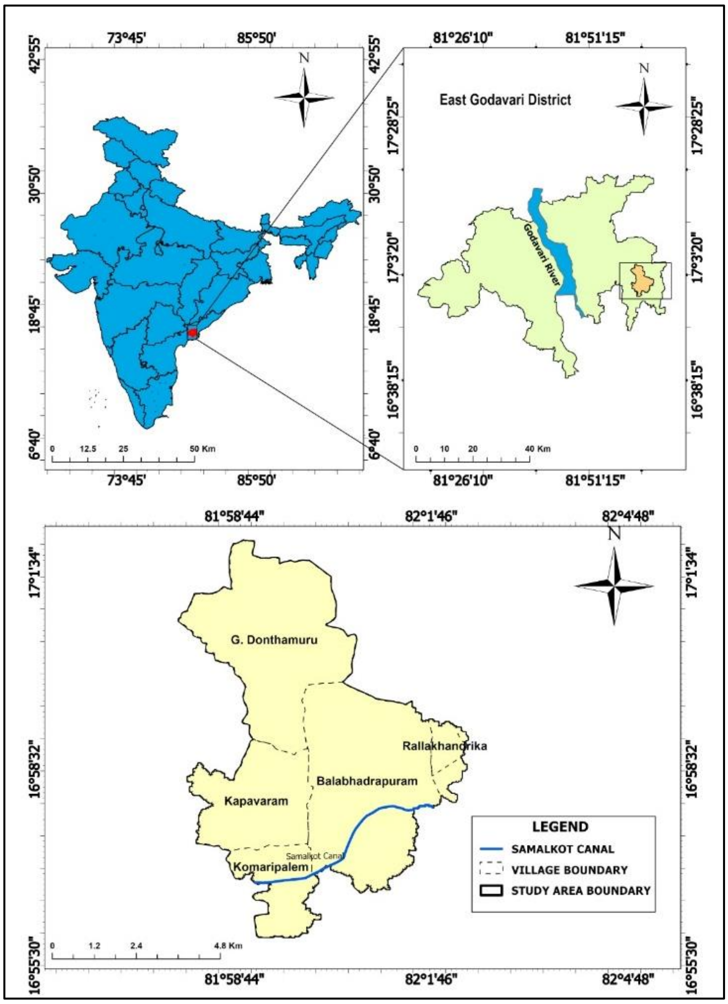

Fig. 2. Location map of study area in East Godavari District, Andhra Pradesh, India showing administrative boundaries of village

2.1. *Physiography and Topography*

The Digital Elevation Model (DEM) indicates that ground elevations in the study area vary from approximately 7 m to 78 m above mean sea level (Fig. 3a). The higher elevation zones are predominantly distributed in the northern and north-central parts, while relatively lower elevations occur in the southern and southeastern parts. The elevated northern sector generally corresponds to the Rajahmundry Sandstone terrain, whereas the lower elevation areas are associated with floodplain deposits. The gradual reduction in elevation from north to south suggests a regional topographic gradient that supports groundwater movement toward lower-lying areas. The lower elevation zones may also act as areas of groundwater accumulation and could be more susceptible to contaminant transport from upgradient recharge regions. The slope map (Fig. 3b) shows that the study area is predominantly characterized by nearly level to gently sloping terrain. Most parts of the study area fall within the 0–2° slope category, indicating low surface gradients and relatively slow runoff conditions. Moderately sloping zones (2–5°) occur locally in the central and northern portions, while isolated steep slope patches (5–13°) are observed mainly in elevated northern areas. The combination of low relief and gentle slopes in the central and southern portions may promote longer residence time of infiltrating water and facilitate movement of dissolved contaminants into shallow groundwater systems (Lapworth et al., 2017).

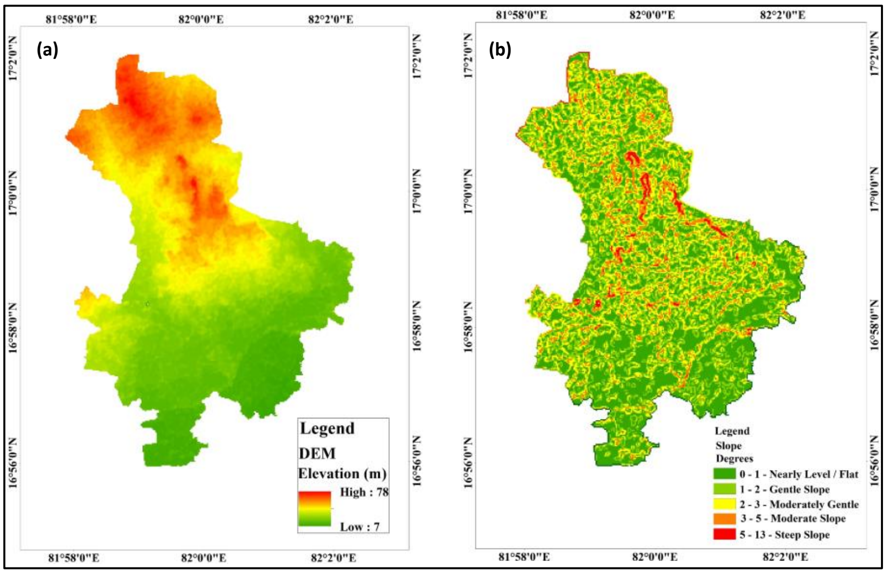

Fig. 3. (a) Elevation map (b) Slope map of the study area

2.2. *Geology and Soils*

The geology map (Fig. 4a) indicates that the study area is mainly occupied by two geological units, namely Rajahmundry Formation (Rajahmundry Sandstones) and floodplain deposits. The Rajahmundry Formation occupies the major portion of the study area, particularly in the northern, central, and western regions, while floodplain deposits are distributed mainly in the southern and south-eastern parts. Due to the unconsolidated nature of floodplain deposits and relatively shallow groundwater conditions, floodplain areas are often more susceptible to contamination from surface activities including agriculture, domestic wastewater seepage, and sanitation-related recharge (Lapworth et al., 2017; CGWB 2025). The soil map (Fig. 4.3b) shows that the study area is predominantly covered by Red Clayey Soils, with limited occurrence of Saline Sodic Soils in the south-eastern portion of the study area. The Red Clayey Soil forms the dominant soil type across most of the study area and iron-rich composition responsible for its reddish colour (Brady and Weil, 2017; Bhaskar et al., 2026).

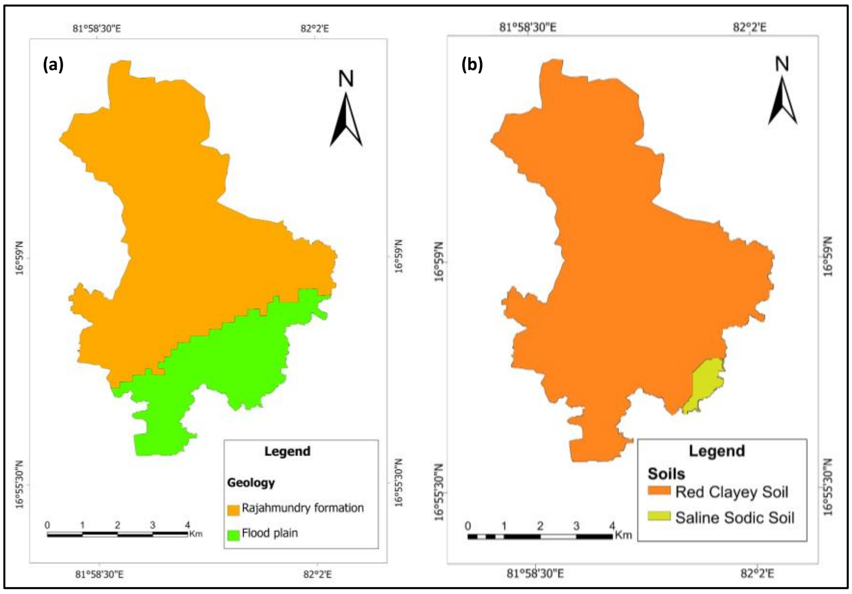

Fig. 4. (a) Geology map (b) Soil map of the study area

2.3. *Industrial Features*

Several industries and agro-industrial establishments encircle the study area. Fig.5 presents the spatial distribution of major industrial and poultry farms identified within the study area. One of the major industrial units present in the study area is the GRASIM industry, located within the northern–central sector. In addition, fertilizer-related industries and agrochemical activities are distributed in and surrounding the area of Balabhadrapuram. These industrial activities involve handling, storage, and processing of raw materials and chemicals that may contribute to localized environmental loading through surface runoff, wastewater discharge or seepage under inadequate containment conditions.

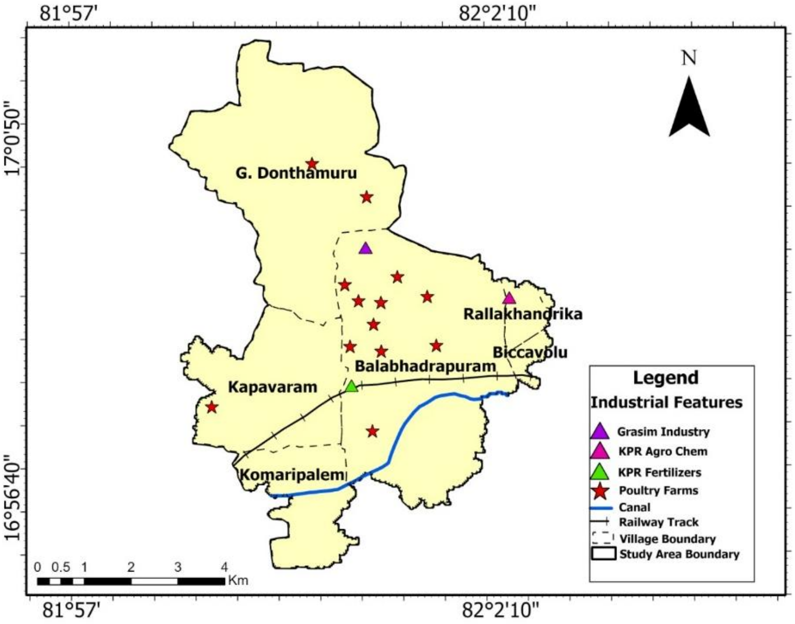

Fig. 5. Distribution of major industrial features and poultry farms in and around Balabhadrapuram Village

The study area is also characterized by numerous poultry farms, particularly concentrated around Balabhadrapuram and nearby villages. Poultry activities generate organic waste, wash water, nutrients, and dissolved salts, which may infiltrate into shallow groundwater systems if proper waste management practices are not maintained. Continuous accumulation of poultry litter and wastewater may increase nutrient concentrations and alter groundwater chemistry through recharge (Bolan et al., 2010; Hubbard et al., 2020). Therefore, the industrial and land-use setting provides an important framework for understanding the observed hydrochemical variations, heavy metal occurrence, and health-risk patterns identified in the study area.

3. Materials and Methods

The hydrological investigations of the study area have been evaluated using available groundwater monitoring information using piezometer well network with the Andhra Pradesh State Ground Water & Water Audit Department (APSGW&WAD). Groundwater elevation contour maps were prepared using Surfer software (Golden Software, 2026) to delineate the spatial distribution of groundwater levels, identify hydraulic gradients, and infer the predominant direction of groundwater flow within the study area (Todd and Mays 2005; Fetter, C.W. 2018). Field investigations were carried out during January 2026. A total of 25 water samples were collected, comprising 6 Shallow wells (dug wells), 15 deep wells (including public water supply sources and Overhead Tank systems), 3 Surface water samples (2 Village ponds and 1 Canal), and 1 RO water sample was also collected. Sampling locations were selected to represent residential areas, agricultural zones, public water supply systems, and locations influenced by surrounding anthropogenic activities. Water samples were collected using standard groundwater sampling procedures (APHA, 2017). Prior to sampling, wells were purged sufficiently to obtain representative groundwater samples. Samples for heavy metal analysis were collected in acid-washed polyethylene bottles and preserved using nitric acid (HNO_3) to maintain sample integrity. Collected water samples were analyzed for major hydrochemical parameters, including pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), major cations, and major anions in the Water Quality Laboratory, Deltaic Regional Centre, National Institute of Hydrology (NIH), Kakinada, Andhra Pradesh. Water samples were collected following standard sampling procedures to obtain representative groundwater and surface water quality conditions. Physico-chemical parameters such as pH, EC, and TDS were measured using standard laboratory instruments and analytical procedures. Major cations and anions were determined using standard water quality analytical methods following established laboratory protocols. The analytical results were subjected to quality checks to ensure data reliability and consistency. Major ion concentrations were compared with the Beuro of Indian Standards (BIS) for drinking water quality (BIS 2012) to evaluate the suitability of water for drinking purposes. Hydrochemical characteristics of shallow and deep groundwater were interpreted separately, considering possible variations in groundwater chemistry with depth. Spatial distribution maps using ArcGIS software were used to evaluate groundwater quality variations and identify possible contamination zones.

The collected water samples were analyzed for selected heavy metals including Chromium (Cr), Iron (Fe), Manganese (Mn), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Arsenic (As), Selenium (Se), Cadmium (Cd), Antimony (Sb), Mercury (Hg), Thallium (Tl), and Lead (Pb) in the Water Quality Laboratory, Environmental Hydrology Division, NIH, Roorkee, Uttarakhand. Water samples were collected in pre-cleaned polyethylene bottles and preserved immediately after collection by acidification with ultrapure nitric acid (HNO_3) to maintain dissolved metal stability and minimize adsorption onto container walls. Prior to analysis, samples were filtered through 0.45 µm membrane filters to remove suspended particles and obtain dissolved metal concentrations. Heavy metal concentrations were determined using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS), which is a highly sensitive analytical technique capable of detecting trace and ultra-trace concentrations of metals in water samples (Linge 2005; USEPA 2014). In ICP–MS analysis, the water sample is introduced into a high-temperature argon plasma where elements are ionized and subsequently separated and quantified based on their mass-to-charge ratio (m/z) using a mass spectrometer. Instrument calibration was performed using certified multi-element standard solutions, and analytical quality control was maintained through calibration verification, procedural blanks, duplicate samples, and standard reference checks to ensure precision and accuracy of the analytical results. The measured concentrations were reported in micrograms per litre (µg/L) and subsequently compared with BIS drinking water standards in **(**BIS 2012) and used for pollution and health-risk assessment.

3.1. Heavy Metal Pollution Assessment

To evaluate groundwater contamination due to heavy metals, the following indices were calculated from the United States Environmental Protection Agency (USEPA) standard methods (USEPA, 1989; 2011).

Metal Index (MI)

The Metal Index (MI) is a water quality assessment tool used to evaluate the overall level of heavy metal contamination in water (Caeiro et al., 2005; Tamasi and Cini, 2004). It provides a single numerical value that represents the combined effect of multiple heavy metals present in water relative to their maximum allowable concentrations. The Metal Index directly compares the concentration of each metal with its corresponding acceptable limit and sums their ratios to determine the overall contamination level as shown in the below formula.

$$MI = \sum \frac{C_i}{MAC_i}$$

Where, Ci = Measured concentration of the i^{th} heavy metal (µg/L) and MACi = Maximum Allowable Concentration (BIS standard)

Based on the MI classification, groundwater quality is categorized into six levels. Groundwater with MI values less than 0.3 is considered very pure**,** indicating negligible heavy metal contamination. MI values between 0.3 and 1.0 represent pure groundwater with minimal contamination. Groundwater having MI values between 1.0 and 2.0 is classified as slightly affected. MI values ranging from 2.0 to 4.0 indicate moderately affected groundwater, reflecting a noticeable level of heavy metal contamination. MI values between 4.0 and 6.0 are classified as strongly affected**.** Groundwater with MI values equal to or greater than 6.0 is considered seriously affected**,** representing severe heavy metal pollution.

Contamination Index (Cd)

The Contamination Index (Cd) is a water quality assessment tool used to evaluate the overall degree of heavy metal contamination. It measures the cumulative effect of multiple contaminants by comparing their observed concentrations with the corresponding permissible standards (Caeiro et al., 2005). Unlike MI, the Contamination Index focuses on the extent to which each parameter exceeds its permissible limit and then combines these exceedances into a single value. The formula for Cd is as follows

$$Cd = \sum C_f$$

Where:

$$C_f = \frac{C_A}{C_N} - 1$$

C_f = Contamination Factor; C_A = Measured concentration of the metal; C_N = Standard permissible concentration

Groundwater with Cd < 1 is classified as having low contamination. Cd values ranging 1 ≤ Cd < 3, indicate medium contamination. Groundwater with Cd ≥ 3, is classified as having high contamination, reflecting significant heavy metal pollution that may adversely affect groundwater quality and pose potential risks to human health.

3.2. Human Health Risk Assessment

Human health risk associated with groundwater consumption was evaluated using the drinking water ingestion pathway separately for adults and children.

Hazard Quotient (HQ)

The Hazard Quotient (HQ) is a health risk assessment parameter used to evaluate the potential non-carcinogenic health risks caused by exposure to heavy metals through contaminated groundwater. It compares the amount of a contaminant entering the human body with the safe exposure level established by the United States Environmental Protection Agency (USEPA, 1989; 2011). The formula for the Hazard Quotient (HQ) is as follows

$$HQ = \frac{CDI}{RfD}$$

Where, CDI = Chronic Daily Intake (mg/kg/day) and RfD = Reference Dose (mg/kg/day)

The Chronic Daily Intake (CDI) estimates the amount of a contaminant consumed daily per unit body weight through drinking water for adults and child.

$$CDI = \frac{C \times IR}{BW}$$

The parameters include the metal concentration in water (C, mg/L), the ingestion rate (IR), assumed as 2 L/day for adults and 1 L/day for children, and the average body weight (BW), considered as 70 kg for adults and 15 kg for children. An HQ value less than 1 indicates that the estimated exposure is below the reference dose and is therefore unlikely to cause significant non-carcinogenic adverse health effects. In contrast, an HQ value greater than 1 ($HQ > 1$) suggests that the exposure exceeds the acceptable threshold and may pose potential non-carcinogenic health risks.

Hazard Index (HI)

The Hazard Index (HI) is used to evaluate the combined non-carcinogenic health risk arising from exposure to multiple heavy metals through drinking water (USEPA, 1989; 2011). It is calculated as the sum of individual Hazard Quotient (HQ) values as shown in the following formula

$$HI = \sum HQ_i$$

Where, HI = Hazard Index; HQ_i = Hazard Quotient of each individual heavy metal

The Hazard Index provides an estimate of the cumulative health risk due to simultaneous exposure to multiple contaminants. Based on the HI values, groundwater health risk is classified into four categories. $HI < 1$ indicates no significant non-carcinogenic health risk. $HI=1$ represents the threshold level, indicating that exposure has reached the maximum acceptable limit. $HI > 1$ indicates potential non-carcinogenic health risk, implying that prolonged exposure to contaminated groundwater may result in adverse health effects. $HI > 10$ represents high non-carcinogenic health risk.

Cancer Risk Assessment

Cancer risk assessment was carried out to evaluate the potential lifetime carcinogenic health risks associated with long-term exposure to heavy metals through drinking groundwater (WHO 2022). Unlike Hazard Quotient (HQ) and Hazard Index (HI), which assess non-carcinogenic effects, Cancer Risk (CR) estimates the probability of an individual developing cancer during their lifetime due to continuous ingestion of contaminated drinking water. Carcinogenic risk assessment was performed separately for adult and child populations, considering differences in water ingestion rate and body weight (USEPA, 1989; 2011). The assessment was carried out for selected carcinogenic heavy metals commonly associated with groundwater contamination, namely Chromium (Cr), Nickel (Ni), Arsenic (As), and Cadmium (Cd) (IARC 2012; USEPA 2024) . Initially, the Chronic Daily Intake (CDI) of each carcinogenic metal through ingestion was estimated using measured metal concentrations in groundwater and standard exposure assumptions. The estimated CDI values were subsequently multiplied by the corresponding Cancer Slope Factor (SF) to determine the individual Cancer Risk (CR) using the following equation

$$CR = CDI \times SF$$

Where, CDI = Chronic Daily Intake (mg/kg/day) and SF = Cancer Slope Factor ((mg/kg/day)$^{-1}$

The SF value for arsenic (As) is 1.5, cadmium (Cd) is 6.1, chromium (Cr) is 0.5, and nickel (Ni) is 0.84.

The Total Cancer Risk (TCR) for each sample was estimated by summing the individual cancer risk values of all carcinogenic metals considered in the study as follows

$$TCR_{Adult} = CR_{Cr} + CR_{Ni} + CR_{As} + CR_{Cd}$$

Total Cancer Risk represents the cumulative probability of developing cancer over a lifetime due to simultaneous exposure to multiple carcinogenic heavy metals through groundwater ingestion.

A TCR $< 1.0 \times 10^{-4}$ indicates acceptable cancer risk, suggesting that the lifetime probability of developing cancer due to groundwater consumption is within the accepted limit and is considered tolerable. The TCR values, 1.0×10^{-4} - 2.0×10^{-4} indicate elevated cancer risk, suggesting that the probability of developing cancer is higher than the acceptable level and warrants continued monitoring and appropriate risk management measures. A TCR value $> 2.0 \times 10^{-4}$ indicates potential cancer risk, implying that long-term consumption of the contaminated groundwater may pose a significant carcinogenic health concern.

Locations exhibiting elevated and potential cancer risk were identified as priority areas requiring further monitoring, drinking water management, and mitigation measures to reduce long-term human exposure to carcinogenic contaminants. The alternative water supply options, treatment requirements, and long-term monitoring recommendations are discussed to support safe drinking water management in the study area. The flow chart (Fig. 6) illustrates the sequential methodology followed in the present study.

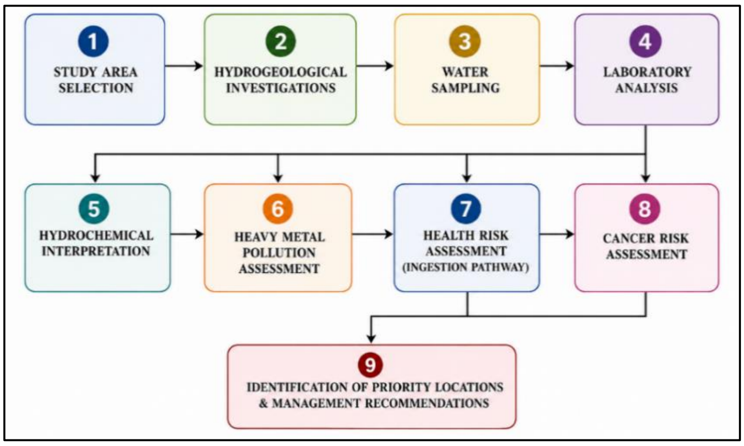

Fig. 6. Flow chart showing the methodology adopted for the study

4. Results and Discussions

4.1. Land use/land cover Classification

The land use/land cover (LU/LC) pattern of the study area has been analyzed to understand the present status of the existing land-use pattern and the spatial distribution of surface features. For this purpose, Sentinel satellite imagery of the year 2025 (May) with a spatial resolution of 10 m was utilized for land use/land cover classification

(Drusch 2012; ESA 2024). The satellite imagery was interpreted through supervised classification techniques and subsequently validated through detailed field checks.

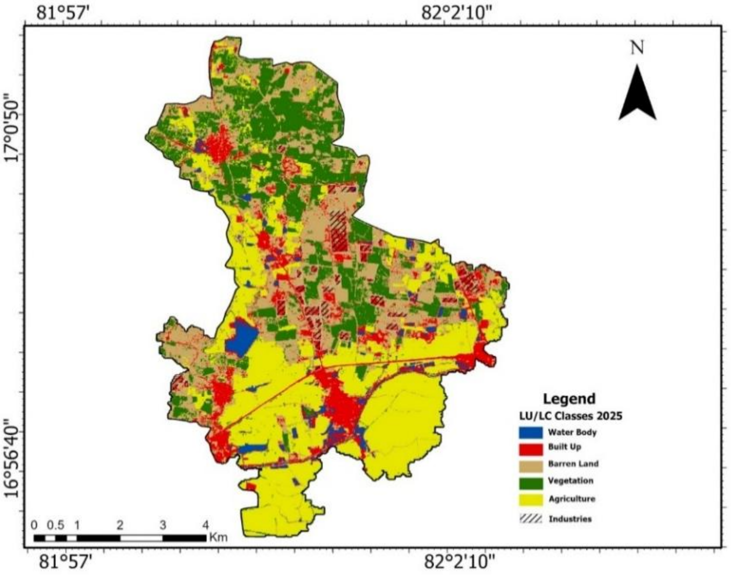

Fig.7. LU/LC classification of the study area

The spatial distribution of the various land use/land cover classes is presented in Fig. 7, while the corresponding area statistics, including the area (km²) and percentage coverage of each class, are summarized in Table 7. The LU/LC analysis of the study area reveals that agricultural land is the dominant land-use category, occupying 9.63 km² (21.13%) of the total geographical area of 45.59 km^2. Paddy is the principal crop cultivated in this category, predominantly in the southern part of the study area, which lies within the command area of the floodplain region and provides favourable conditions for agriculture. Vegetation is the most extensive land-use class, covering 15.44 km² (33.89%). This category mainly comprises palm oil plantations and other vegetation types, which are predominantly distributed in the northern and central parts of the study area. These areas are largely associated with the Rajahmundry Sandstone Formation, which supports high yield from deep tube wells.

Barren land occupies an area of 13.32 km² (29.24%), and this category includes vacant lands. The considerable area of industrial land (1.63%), with 3.68% covers an area of and industries, empty lands utilized for various industrial activities, including numerous poultry farms and fertilizer-related industries distributed across the central and northern parts of the study area. The built-up area covers 4.22 km² (9.29%) of the total geographic area and includes the settlements of villages. Water bodies account for 1.35 km² (2.96%), with the major water body, the Samalkota canal, and several village ponds. Overall, the LU/LC pattern indicates that agriculture and vegetation together constitute more than 55% of the study area, highlighting the predominance of agricultural and plantation-based land use, while built-up areas and water bodies occupy relatively smaller proportions.

Table 7. Area and Percentage of Different Features of LU/LC in the Study Area

Class	**Area (km²)**	**Percentage (%)**
Water Body	1.3494	2.96
Built Up (Settlements)	4.228831	9.29
Industrial Land	1.630169	3.58
Barren Land	13.3207	29.24
Vegetation	15.4359	33.89
Agriculture	9.6256	21.13
Total	**45.5906**	**100.00**

4.2. Groundwater Elevation Contour Maps

Groundwater level data (m below ground level; bgl) from seven piezometer monitoring wells located in and around the study area were obtained from the Andhra Pradesh State Groundwater and Water Audit Department (APSGW&WAD) for preparing the groundwater elevation contour maps (Fig.8). Among these monitoring wells, three piezometers (Rangampeta, Valuthimmapuram, and China Doddikolanu) are situated to the north of the study area, three piezometers (Bikkavolu, Anaparthy, and Kuthukuluru) are located to the south of the study area, and one piezometer (Balabhadrapuram) lies within the study area as shown in Fig. 8. Groundwater level data corresponding to the pre-monsoon and post-monsoon seasons of 2024 were used to evaluate regional groundwater flow conditions. The collected groundwater level data were processed and interpolated using Surfer software to generate groundwater level contour maps and to interpret groundwater flow directions across the study area.

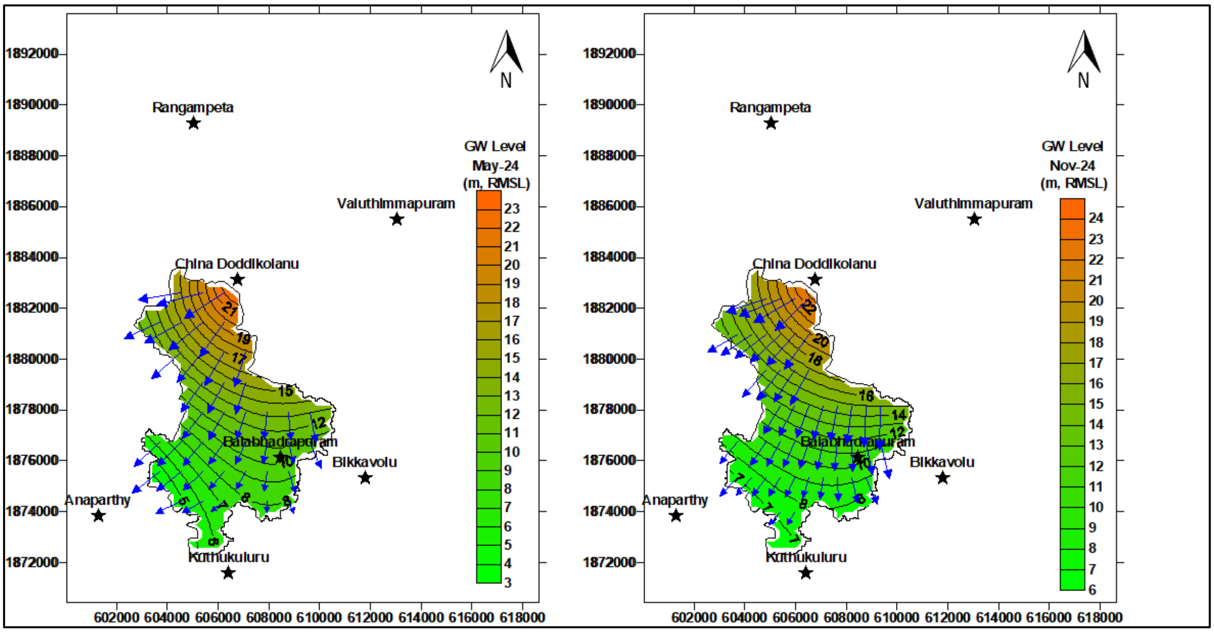

Fig.8 Groundwater elevation maps in the (a) pre-monsoon (b) post-monsoon seasons of 2024

Groundwater elevation contour maps for the pre-monsoon and post-monsoon seasons of 2024 are presented in Fig. 8(a) and Fig. 8(b), respectively. During the pre and post-monsoon seasons, groundwater elevations ranged from about 23 m and 24 m (RMSL) in the northern part of the study area to approximately 3 m and 6 m, reduced to mean sea level (RMSL) in the southern part. The groundwater gradient indicates that the general direction of groundwater flow is towards the southeast and southwest. The groundwater-level contour and vector analyses reveal that the north-eastern part of the study area, particularly around Chinna Doddikolanu, acts as a groundwater recharge zone. Conversely, Balabhadrapuram village appears to represent groundwater discharge or convergence zones, as indicated by the groundwater flow vectors directed towards this location. These findings suggest that groundwater movement within the study area is predominantly from the north-eastern part (recharge area) towards the southern and southwestern parts. Consequently, any contaminants introduced into the groundwater system within the upgradient areas of the central and northern parts may migrate along the prevailing groundwater flow paths and potentially affect the downgradient areas located in the southern part of the study area. Therefore, the southern villages may be vulnerable to groundwater contamination originating from anthropogenic activities occurring in the recharge and intermediate flow zones.

4.3. Assessment of Drinking Water Quality

An extensive field survey has been carried out in January 2026 the locations of groundwater and surface water samples collected are shown in Fig. 9. The sampling network was designed to provide spatial coverage of

Balabhadrapuram village and its surrounding areas, including G. Donthamuru, Kapavaram, Rallakhandrika, and Komaripalem. A total of 25 water samples were collected from different water sources comprising deep wells (tube wells), shallow wells (dug wells), pond water, canal water, and Reverse Osmosis (RO)-treated drinking water to represent different hydrogeological settings, land-use conditions, and exposure pathways associated with water use. Among these, groundwater samples (15 deep wells and 6 shallow wells) constitute the majority of the sampling network and are distributed throughout the study area to identify spatial variation in groundwater quality. Deep well samples are distributed over study area, enabling assessment of regional groundwater quality variations, while shallow well samples are concentrated mainly within Balabhadrapuram and G. Donthamuru villages, where concerns regarding drinking water quality and health issues have been reported. Two pond water samples, and one canal water sample were collected as surface water may influence groundwater quality in the study region.

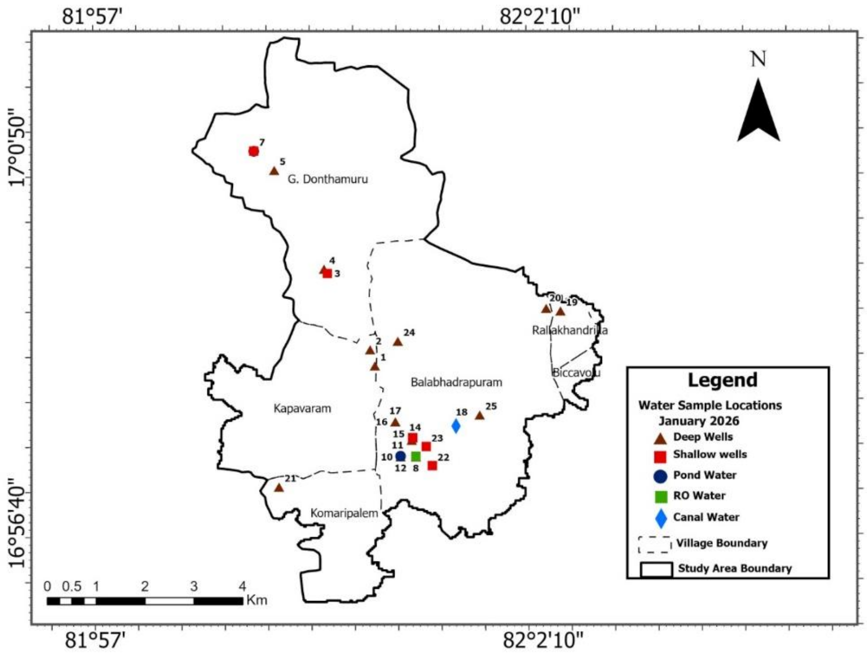

Fig.9. Locations of groundwater and surface water samples in the study area collected in January 2026

The details of groundwater and surface water sampling locations together with their present utilisation pattern in the study area are shown in Table 8. Groundwater samples comprise public drinking water supply wells, domestic wells, agricultural wells, and industrial surroundings, whereas surface water samples represent local village ponds and canal systems. The serial numbers (SID) of collected water samples are shown in Fig.9. Several deep wells, namely SID-4, SID-5, SID-12, SID-16, SID-17, and SID-24, function as public drinking water supply sources, indicating their direct importance for community water supply and human exposure assessment and are shown in Fig.10. The groundwater samples SID-1, SID-20, and SID-21 are presently used for agricultural purposes. Few wells located near poultry farms (SID-2), fertilizer industries (SID-19), and a private RO treatment facility (SID-9). At SID-8, groundwater is abstracted as a raw water source for private RO treatment, while SID-9 represents the treated RO-water supplied commercially for drinking purposes. Surface water sampling included pond water and canal water to evaluate possible contamination pathways and environmental interactions. The fresh water pond at SID-11 is presently used for fish culture, whereas SID-7 (pond water) and SID-18 (canal water) are primarily used for irrigation purposes and are not used as drinking water sources. The locations of two ponds in the study area are shown in Fig.11.

Fig. 10. Public drinking water supply schemes at (a) SID-12 (Yellampeta OHT) (b) SID-17 (Tatanagaram OHT) (c) SID-24 (PMAY-NTR Nagar) in Balabhadrapuram (d) SID-4 in Balavaram (e) SID-5 in G. Dontamuru

Fig. 11. Surface water locations at ponds (a) SID-7 (G. Dontamuru) (b) SID-11 (Balabhadrapuram)

4.3.1. Hydrochemical characteristics of Water Samples

A total of six shallow well samples were collected from G. Dontamuru, and Balabhadrapuram villages during January 2026. All shallow wells are dug wells and out of six shallow wells, four are from Balabhadrapuram and two are from G. Dontamuru village.

Groundwater

The statistical summary of hydrochemical parameters in shallow and deep wells is presented in Table 9. The pH ranges from 6.58 to 7.61 with a mean value of 7.08 and a low coefficient of variation (CV = 5.8%). The shallow groundwater is therefore neutral to slightly alkaline in nature and falls within the BIS permissible range (6.5–8.5). The low variability suggests that regional geochemical processes control pH throughout the shallow aquifer. TDS ranges from 380 to 1347 mg/L, with a mean of 916 mg/L. The relatively high CV values (~35%) indicate significant spatial variation in groundwater mineralization/contamination. The TDS values exceed the BIS desirable limit of 500 mg/L but remain within the permissible limit of 2000 mg/L. One shallow well sample (SID-6**)** exhibits the lowest TDS value (380 mg/L) obtained in G. Dontamuru village, indicating comparatively fresh groundwater, while the highest TDS values were recorded at SID-13 (1347 mg/L), SID-22 (1026 mg/L) and SID-14 **(**1002 mg/L), which are clustered in the Centre of the Balabhadrapuram village. Total hardness varies between 148 and 548 mg/L, with a mean value of 351 mg/L. According to BIS classification, the highest hardness is attributed to SID-13 (548 mg/L). Except for (SID-6), the remaining shallow wells that exceed BIS standards represent hard to very hard water. The elevated hardness is mainly attributed to high concentrations of calcium and magnesium derived from aquifer materials. The high CV values for sodium (61%) and potassium (83%) indicate strong localized influences on groundwater quality. The highest sodium (121 mg/L), potassium (107 mg/L) and chloride (316 mg/L) concentrations were observed at SID-13, located at the center of the Balabhadrapuram village, indicating possible contributions from domestic wastewater infiltration. The statistical analysis indicates that the shallow aquifer is more vulnerable to anthropogenic influences than the deeper aquifer. The elevated TDS, alkalinity, hardness, sodium, potassium, magnesium, and chloride concentrations are observed in SID-13, SID-14, and SID-22 within Balabhadrapuram village. These results suggest that, localized human activities are contributing to the deterioration of shallow groundwater quality in parts of the study area.

Table 9. Statistical Summary of Hydrochemical Parameters in Shallow and Deep Groundwater

Parameter	**Deep Groundwater**					**Shallow Groundwater**				
	Min	**Max**	**Mean**	**SD**	**CV (%)**	**Min**	**Max**	**Mean**	**SD**	**CV (%)**
pH	6.58	7.61	7.08	0.41	5.77	6.82	7.80	7.16	0.34	4.69
TDS	380	1347	915.67	321.34	35.09	213	1270	651.07	310.68	47.72
Alkalinity	184	764	486.67	205.38	42.20	116	440	302.13	84.22	27.87
Hardness	148	548	350.67	127.89	36.47	124	396	246.13	79.01	32.10
Na^+	17.7	121.0	66.57	40.71	61.16	2.2	181	43.09	45.32	105.18
K^+	4.9	107.0	48.97	40.75	83.21	0.8	53.6	17.20	18.36	106.73
Ca^{2+}	20	75	53.67	21.91	40.84	32	90	50.27	16.60	33.02
Mg^{2+}	23	96	52.00	26.72	51.39	6	70	28.47	17.57	61.73
SO_4^{2-}	36	80	61.00	15.49	25.40	7	113	40.40	28.89	71.52
Cl^-	124	316	213.33	69.59	32.62	60	360	171.73	91.48	53.27
NO_3^-	3	31	10.67	10.44	97.91	2	87	24.47	24.06	98.33
CO_3^{2-}	16	112	61.33	35.75	58.28	0	68	44.27	18.42	41.61
HCO_3^-	168	652	425.33	171.46	40.31	116	372	257.87	68.72	26.65

Note: except pH, all parameters are in mg/L

A total of 15 deep-well samples were collected from Balabhadrapuram, G. Dontamuru, Biccavolu, and Komaripalem villages. The statistical analysis indicates that the groundwater pH ranges from 6.82 to 7.80, with a mean value of 7.16, reflecting neutral to slightly alkaline hydrochemical conditions. The low coefficient of variation (CV = 4.69%) suggests a relatively uniform distribution of pH throughout the deep aquifer system, indicating that pH is primarily controlled by regional hydrogeochemical processes rather than localized influences. Total Dissolved Solids (TDS) exhibit spatial variability (CV≈48%), indicating significant differences in groundwater mineralization/contamination across the study area. Most of the deep well samples show TDS concentrations exceeding the BIS acceptable limit of 500 mg/L but remaining within the permissible limit of 2000 mg/L. Elevated chloride concentrations occur in two distinct zones (Fig.12a). The first zone is located in the eastern part of the study area, in and around KPR Fertilisers, Biccavolu (SID-19 and SID-20), which may be attributed to localized anthropogenic influences, including agricultural and industrial activities. The second zone of elevated TDS is observed in the central part of Balabhadrapuram village, where shallow and deep groundwater samples (SID-8, SID-10, SID-12, SID-13, SID-14 and SID-15) exhibit chloride concentrations ranging from 276 to 360 mg/L. The clustering of chloride concentration in the densely inhabited part of the village suggests that local human activities may be contributing to groundwater quality deterioration.

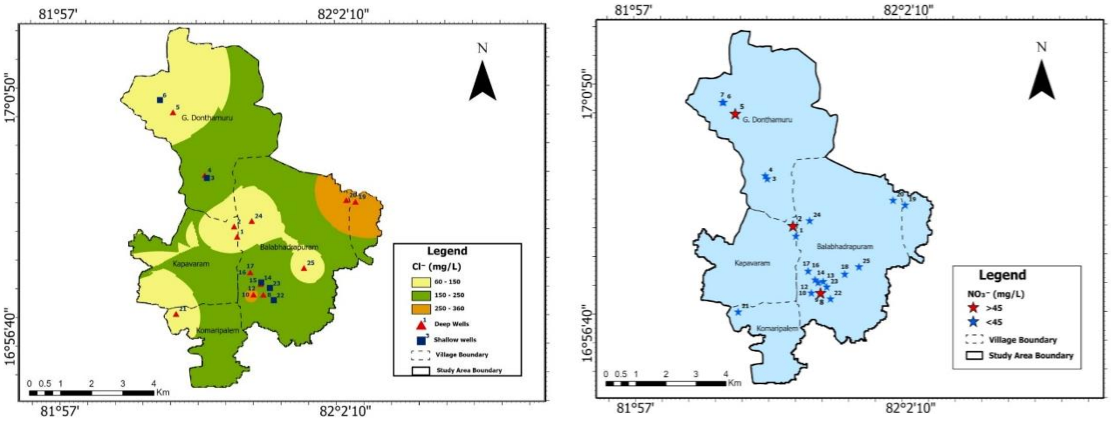

Fig. 12. (a) Spatial distribution of chloride (mg/L) (b) locations of high and low nitrate (mg/L) in groundwater

The distribution of high and low nitrate concentration of shallow and deep groundwater in the study area is shown in Fig. 12(b). A high nitrate concentration of 87 mg/L was observed at SID-8, which exceeds the BIS permissible limit of 45 mg/L for drinking water. Since SID-8 is located within the inhabited area of Balabhadrapuram village, the elevated nitrate concentration indicates localized contamination of the aquifer, which may be resulting from anthropogenic activities such as seepage from septic tanks, domestic wastewater disposal, and inadequate sanitation practices. Elevated nitrate concentrations were also recorded at SID-2 (near the Poultry Farm Complex, Balabhadrapuram) and SID-5 (Public Tap, G. Donthamuru), where nitrate levels exceed the BIS permissible limit. The occurrence of high nitrate concentrations at SID-2 may be associated with the leaching of nitrogen-rich wastes from poultry farming activities, whereas at SID-5, domestic wastewater infiltration and other local anthropogenic sources may contribute to nitrate enrichment in groundwater. These locations are important drinking water sources serving nearby habitations, and a significant number of residents directly consume the groundwater without advanced treatment. Therefore, the presence of elevated nitrate concentrations is a matter of concern, as long-term consumption of nitrate-contaminated drinking water may pose adverse health effects, including methemoglobinemia (blue baby syndrome) in infants, and may also contribute to other health risks among vulnerable populations (Ward et al., 2018; WHO 2022). Regular monitoring of nitrate levels, identification of contamination sources, and implementation of appropriate groundwater treatment measures are needed in these areas.

Surface Water

Two pond water samples (SID-7 and SID-11) were collected from G. Dontamuru and Balabhadrapuram, respectively, during January 2026 to evaluate the quality of surface water and its potential influence on the surrounding groundwater system. The pond located in G. Donthamuru (SID-7) is used for irrigation purposes, while the pond in Balabhadrapuram is utilized for freshwater aquaculture. The pH values range from 6.9 to 8.3, which fall within the BIS acceptable range (6.5–8.5). The pond waters are neutral to slightly alkaline in nature, indicating favorable chemical conditions. The TDS values of SID-7 (391 mg/L) in G. Dontamuru are within the BIS acceptable limit, and SID-11 (631 mg/L) exceeds the acceptable limit. The pond waters can be classified as moderately hard waters (184 to 208 mg/L). Chloride concentrations vary from 96 to 188 mg/L, indicating the absence of significant chloride contamination in the pond waters. Nitrate concentration is 10 mg/L in the pond waters, which is below the BIS permissible limit. The low nitrate concentrations indicate minimal influence of agricultural runoff, sewage contamination, or fertilizer leaching on the pond waters. Sodium concentrations are relatively low (7.8 and 26.8 mg/L), suggesting fresh water conditions. Potassium concentrations (12.9 and 24.7 mg/L) are moderately elevated, particularly in SID-11, which may reflect minor contributions from surface runoff/organic matter decomposition. The canal water sample represents the freshest water source in the study area, characterized by the lowest EC, TDS, hardness, and major ion concentrations among all natural water sources. All measured parameters are well within the BIS acceptable limits for drinking water. The low mineralization indicates limited interaction with geological formations and continuous replenishment by flowing surface water. The canal water likely serves as an important recharge source to the adjacent groundwater system, particularly in the floodplain areas.

4.3.2. Heavy Metal Occurrence and Drinking Water Quality Assessment of Groundwater

The concentrations of heavy metals in both shallow and deep groundwater samples were evaluated collectively with reference to the drinking water standards prescribed by the Bureau of Indian Standards (BIS 2012) to evaluate the overall spatial distribution and identify contamination hotspots across the study area. However, depth-wise variations in heavy metal occurrence were also examined wherever significant differences between shallow and deep groundwater were observed. The analytical results indicate that most of the investigated heavy metals occur at relatively low concentrations and are generally within the permissible limits for drinking water. The heavy metals exceeding the BIS drinking water standards in shallow and deep groundwater samples are presented in Table 10.

Table 10. Heavy Metals Exceeding BIS Drinking Water Standards in Shallow and Deep Well Samples

Heavy Metal	**BIS Limit (µg/L)**	**No. of Samples Exceeding Limit**	**Percentage of Samples Exceeding (%)**	**Sample IDs Exceeding BIS Limit**	**No. of Samples Exceeding Limit**	**Percentage of Samples Exceeding (%)**	**Sample IDs Exceeding BIS Limit**
		shallow wells			**deep wells**		
Iron (Fe)	300	3	50.0	SID-3, SID-13, SID-14	5	33.3	SID-1, SID-4, SID-10, SID-12, SID-15,
Manganese (Mn)	100	4	66.7	SID-6, SID-13, SID-14, SID-23	3	20.0	SID-1, SID-17, SID-19
Lead (Pb)	10	0	0.0	None	1	6.7	SID-12

The analysis of 21 groundwater samples (comprising 6 shallow wells and 15 deep wells) reveals that only a limited number of trace metals, namely iron (Fe), manganese (Mn), and lead (Pb), exceed the prescribed drinking water standards at certain locations. The exceedances are spatially restricted and are not uniformly distributed across the study area. Therefore, the subsequent discussion focuses primarily on these three metals (Fe, Mn, and Pb), which are the principal heavy-metal contaminants of concern in the groundwater system. Their occurrence, spatial distribution, possible sources, and potential implications for groundwater quality and human health are discussed in detail to assess the extent of heavy metal contamination within the study area. Out of the 15 deep-well samples, 5 samples exceed (33.3%) while out of 6 shallow well samples, 3 samples exceed (50.0%) the BIS acceptable limit of 300 µg/L for iron. The highest iron concentration has been recorded at SID-13 with 7544 µg/L followed by SID-15 with 1724.8 µg/L. As shown in the spatial distribution of Iron concentration in the study area (Fig. 13a), these locations are situated within Balabhadrapuram village and its surrounding areas. Most of the elevated iron concentrations are concentrated central part of Balabhadrapuram village, indicating localized iron enrichment in the shallow and deep wells. The occurrence of high iron concentrations is likely associated with the dissolution of iron-bearing minerals and may also be influenced by local hydrogeological conditions. Although iron is not generally considered a major toxic contaminant, concentrations above the BIS limit can impart an unpleasant taste, reddish-brown staining of utensils and plumbing fixtures, and deterioration of the aesthetic quality of drinking water (BIS 2012).

Manganese concentrations remain below the BIS acceptable limit of 100 µg/L in most groundwater samples. However, elevated manganese concentrations were recorded at SID-1, SID-6, SID-13, SID-14, SID-19, and SID-23 (Fig. 13b). The spatial distribution of manganese concentration is shown in Fig. 13(b). Prolonged consumption of water containing elevated manganese concentrations may pose potential neurological and cognitive health risks, particularly among children and elderly populations (Bouchard et al., 2011; WHO 2022). The simultaneous occurrence of elevated iron and manganese concentrations at SID-13 and SID-14 suggests the infiltration of organic-rich wastewater into groundwater. These observations indicate that both geogenic and anthropogenic processes may be influencing groundwater quality in the central part of Balabhadrapuram village.

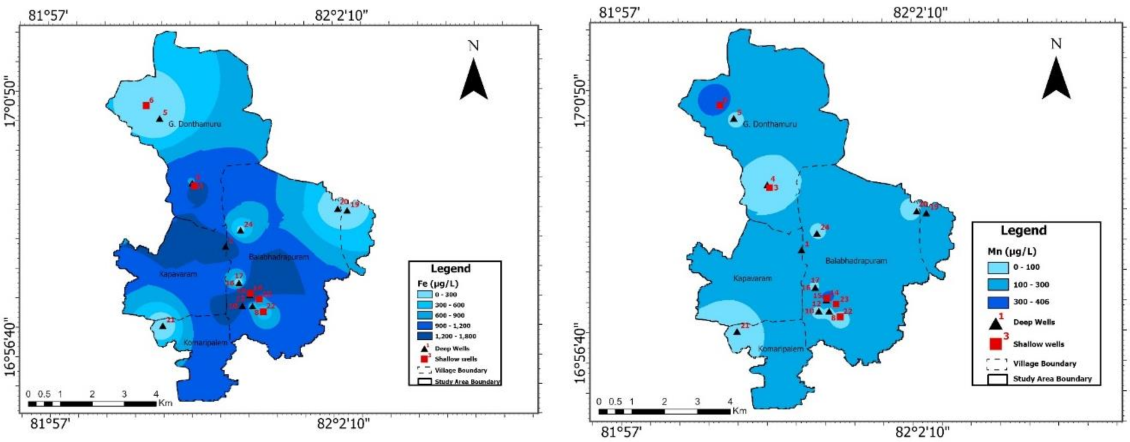

Fig. 13. Spatial distribution of (a) Iron and (b) Manganese concentration (µg/L) in the study area

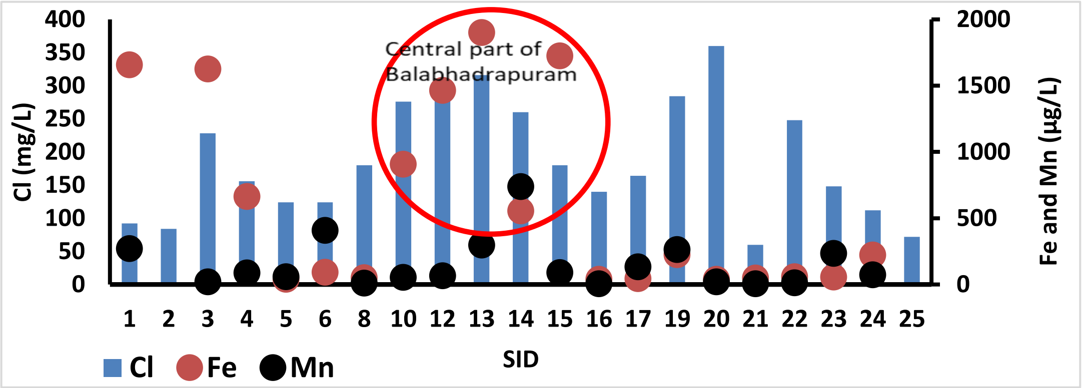

Fig. 14 Comparative distribution of chloride, iron, and manganese in groundwater samples

As chloride (Cl⁻) is generally considered a conservative tracer and is often used to indicate anthropogenic influences, to identify potential sources of groundwater contamination, chloride concentrations were compared with those of iron (Fe) and manganese (Mn) in both shallow and deep groundwater samples (Fig. 14). The graph reveals that elevated iron concentrations (>550 µg/L) are associated with relatively high chloride concentrations (>250 mg/L) in groundwater samples SID-10, SID-12, SID-13, SID-14, and SID-15, all of which are located within the central part of Balabhadrapuram village. Among these, SID-12 and SID-15 exhibit high iron concentrations exceeding 1400 µg/L with high chloride concentrations exceeding the BIS acceptable limit. A shallow well (SID-13) shows exceptionally high iron concentrations (>7000 µg/L) together with high chloride levels, indicating the strong influence of localized contamination. This association suggests that, in addition to natural geogenic sources, anthropogenic recharge, such as domestic wastewater seepage, septic tank leakage, or other sanitation-related activities, may be contributing to groundwater quality deterioration. Therefore, the coexistence of elevated chloride and iron concentrations suggests anthropogenic recharge (Appelo and Postma, 2005; Panno et al., 2006). However, in a hamlet called Balavaram, located within G. Dontamuru village, there are elevated iron concentrations in both the shallow well (SID-3) and deep well (SID-4), where Fe levels exceed 650 µg/L and are associated with low chloride concentrations (< 250 mg/L). The occurrence of elevated iron in both shallow and deep aquifers suggests that iron enrichment may be controlled by natural geogenic processes, such as the dissolution of iron-bearing minerals.

Lead (Pb) exceeded the BIS permissible limit of 10 µg/L in only one sample (SID-12). Although the exceedance is localized, lead is of particular concern because it is a toxic metal that can accumulate in the human body. Chronic exposure to lead through drinking water may adversely affect neurological development, kidney function, and cardiovascular health (NTP 2012; Navas-Acien 2007; WHO 2022). Since SID-12 (Yellampeta OHT, Balabhadrapuram) is a public water supply source, regular monitoring is recommended to verify the observed concentration and identify potential contamination sources. The locations requiring priority attention are presented in Table 11. Except few samples, most of the deep groundwater samples is suitable for drinking purposes with respect to heavy metals. Among the analyzed heavy metals, iron (Fe), manganese (Mn), and lead (Pb) were found to exceed the permissible limits in one or more samples, whereas all other metals, including arsenic, cadmium, chromium, mercury, nickel, selenium, and antimony, remained within the prescribed drinking water standards. An observation from the study is that arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), and nickel (Ni), which are often associated with carcinogenic and chronic health effects, were found to be well within the BIS drinking water limits in all analyzed samples.

Table 11: Priority Groundwater Sources Based on Elevated Heavy Metal Concentrations

SID	Well	Location	Exceeding Metal
1	Deep well	Palmoil Gardens, Balabhadrapuram	Fe, Mn
3	Shallow well	Dr. Ambedkar Statue Centre, Balavaram	Fe
4	Deep well	Public Tap, Balavaram	Fe
6	Shallow well	Banyan Tree Centre, G. Donthamuru	Mn
10	Deep well	Function Hall, Balabhadrapuram	Fe
12	Deep well	Yellampeta OHT, Balabhadrapuram	Fe, Pb
13	Shallow well	Gubbalamma Temple, Balabhadrapuram	Fe, Mn
14	Shallow well	Devi Centre, Balabhadrapuram	Fe, Mn
15	Deep well	Devi Centre, Balabhadrapuram	Fe
17	Deep well	Tata Nagaram OHT, Balabhadrapuram	Mn
19	Deep well	KPR Fertilisers, Biccavolu	Mn
23	Shallow well	Dried Pond, Balabhadrapuram	Mn

4.3.3. Heavy Metal Occurrence in Surface Water and Quality Assessment

The concentrations of heavy metals in the surface water samples were evaluated with reference to drinking water standards. The analytical results indicate that, among the analyzed parameters, the pond water sample collected at G. Dontamuru (SID-7) recorded the highest concentrations of iron (418.2 µg/L) and manganese (115.1 µg/L), both of which exceed the BIS acceptable limits for drinking water. These elevated concentrations indicate localized deterioration of surface water quality which may be attributed to the presence of stagnated water, which promotes the accumulation and decomposition of organic matter that enhance the dissolution of iron and manganese into the water column. In addition, localized anthropogenic activities, including the dumping of domestic waste**,** may further contribute to the enrichment of these metals in the pond water. The pond water sample collected at Balabhadrapuram (SID-11) shows comparatively lower concentrations of Fe (95.6 µg/L) and Mn (60.6 µg/L), and the remaining metals are within BIS drinking water limits, indicating better chemical quality with respect to heavy metals. The canal water sample (SID-18) collected at Balabhadrapuram exhibits low concentrations of all analyzed heavy metals and is well within BIS acceptable limits. The lower metal concentrations in canal water may be attributed to continuous flow conditions. The heavy metal results suggest that surface water quality in the study area is suitable with respect to trace metal contamination, except for localized enrichment of iron and manganese in the pond at G.Dontamuru (SID-7).

4.3.4. Heavy Metal Contamination Assessment of Groundwater and Surface Water

Metal Index (MI) and Contamination Index (Cd) are calculated for all groundwater samples (21 No) and surface water samples (3 No) to evaluate the overall degree of heavy metal contamination and to identify contamination hotspots within the study area.

Metal Index Assessment of Groundwater

Water samples with MI values greater than 1 indicate increasing influence of heavy metals and may require detailed investigation, while samples with MI > 6 are generally considered unsuitable for drinking due to significant heavy metal contamination. The classification of groundwater quality based on the Metal Index (MI) for deep and shallow wells is presented in Table 12. It is observed from Table 10 that three wells (SID-3, SID-13, and SID-14) out of six shallow wells (50%) fall under the seriously affected category (MI > 6), whereas only three wells (SID-1, SID-12, and SID-15) out of thirteen deep wells (~23%) are classified as seriously affected. This indicates that shallow groundwater is more vulnerable to heavy metal contamination than deeper groundwater in the study area. Among all the sampled wells, SID-13 (MI = 29.42) recorded the highest Metal Index value, followed by SID-14 (MI = 9.78) and SID-1 (MI = 9.20), indicating severe heavy metal enrichment at these locations. Based on the Metal Index (MI) assessment, the public water supply sourced from deep wells at SID-4 (MI = 3.95) in Balavaram and SID-24 (MI = 2.40) in Balabhadrapuram falls under the moderately affected category, whereas the public water supply from the deep well at SID-12 (MI = 7.49) in Balabhadrapuram falls under the seriously affected category, indicating potential concerns regarding water quality for public consumption.

Table 12. Classification of Groundwater Quality based on Metal Index (MI) for Shallow and Deep Wells

Groundwater Quality Status (MI Range)	**Shallow Wells (Sample ID; MI)**	**Deep Wells (Sample ID; MI)**
Very Pure (<0.3)	—	—
Pure (0.3–1.0)	—	SID-08 (0.86), SID-16 (0.45), SID-20 (0.63), SID-21 (0.47)
Slightly Affected (1.0–2.0)	—	SID-05 (1.27), SID-17 (1.85)
Moderately Affected (2.0–4.0)	SID-22 (2.04), SID-23 (3.40)	SID-04 (3.95), SID-24 (2.40)
Strongly Affected (4.0–6.0)	SID-06 (5.53)	SID-10 (4.54), SID-19 (5.50)
Seriously Affected (>6.0)	SID-03 (7.01), SID-13 (29.42), SID-14 (9.78)	SID-01 (9.20), SID-12 (7.49), SID-15 (7.62)

The severely affected shallow wells suggest that shallow aquifer systems are more susceptible to contamination due to their direct interaction with surface anthropogenic activities and active recharge processes, including possible domestic wastewater seepage and sanitation-related inputs, which may facilitate metal mobilization into groundwater. In contrast, the occurrence of seriously affected deep wells suggests that heavy metal enrichment may also be influenced by natural geogenic processes and/or prolonged contaminant migration through subsurface pathways. These severely affected wells are predominantly located in the central part of Balabhadrapuram village, indicating that groundwater quality in this area may be controlled by localized contamination or hydrogeochemical reactions.

Metal Index Assessment of Surface Water

Metal Index (MI) and water quality classification of surface water samples are presented in Table 13. The Metal Index was used to evaluate cumulative heavy metal enrichment and classify surface water quality. The MI results indicate that both pond water samples (SID-7 and SID-11) fall under the moderately affected category, suggesting moderate cumulative heavy metal enrichment and deterioration in water quality. The comparatively higher MI value at SID-7 (3.36) in G. Dontamuru indicates greater metal loading than SID-11 in Balabhadrapuram. The canal water sample (SID-18) in Balabhadrapuram exhibited an MI value of 1.02, which falls under the slightly affected category, indicating comparatively lower heavy metal influence and relatively better surface water quality.

Table 13. Metal Index (MI) and Water Quality Classification of Surface Water Samples

Sample ID	Surface water & location	MI	Classification
7	Pond Water, G. Dontamuru	3.36	Moderately Affected
11	Pond Water, Balabhadrapuram	2.09	Moderately Affected
18	Canal Water, Balabhadrapuram	1.02	Slightly Affected

Contamination Index Assessment of Groundwater

Table 14 presents the classification of groundwater contamination based on Contamination Index (Cd) for deep and shallow wells in the study area. The Contamination Index (Cd) results indicate clear differences between shallow and deep groundwater systems. Among the 13 deep wells, the majority (7 wells; ~54%) fall under the low contamination category (Cd<1), suggesting limited heavy metal influence in deeper aquifers. However, three deep wells (SID-1, SID-12, and SID-15) exhibit high contamination (Cd ≥ 3), indicating localized heavy metal enrichment. In contrast, the shallow groundwater system appears more vulnerable, where 4 out of 6 shallow wells (~67%) are classified as highly contaminated. The highest contamination index was observed at SID-13 (Cd = 26.113), followed by SID-14 (Cd = 7.237) and SID-03 (Cd = 4.419), indicating severe localized contamination. These elevated Cd values are mainly attributed to higher concentrations of iron, manganese, and lead relative to BIS drinking water standards. The Cd results suggest that shallow groundwater is more susceptible to heavy metal contamination than deeper groundwater, likely due to greater interaction with surface-derived anthropogenic sources.

Table 14. Contamination Index (Cd) Assessment of Shallow and Deep Groundwater

Contamination Level (Cd Range)	Shallow Wells (Sample ID; Cd)	Deep Wells (Sample ID; Cd)
Low Contamination (Cd < 1)	SID-22 (0.000)	SID-05 (0.000), SID-08 (0.000), SID-16 (0.000), SID-17 (0.321), SID-20 (0.000), SID-21 (0.000), SID-24 (0.000)
Medium Contamination (1 ≤ Cd < 3)	SID-23 (1.337)	SID-04 (1.207), SID-10 (2.023), SID-19 (1.993)
High Contamination (Cd ≥ 3)	SID-03 (4.419), SID-06 (3.067), SID-13 (26.113), SID-14 (7.237)	SID-01 (6.220), SID-12 (4.041), SID-15 (4.749)

Contamination Index Assessment of Surface Water

Contamination Index (Cd) values and contamination levels of surface water samples are presented in Table 15. The calculated Cd values for surface water samples ranged from 0 to 0.545, indicating generally low levels of heavy metal contamination. The results indicate that all analyzed surface water samples fall under the Low Contamination category (Cd < 1), suggesting that cumulative heavy metal concentrations remain below critical contamination thresholds. Among the samples, SID-7 (pond water, G. Dontamuru) recorded the highest Cd value (0.545), indicating comparatively greater heavy metal accumulation than the other surface water samples. Although classified as low contamination, the slightly elevated Cd value may reflect localized influences such as surface runoff, agricultural inputs, domestic wastewater intrusion, sediment–water interaction, or local anthropogenic activities. In contrast, SID-11 (pond water, Balabhadrapuram) and SID-18 (canal water) exhibited Cd values of zero, indicating negligible cumulative heavy metal contamination and suggesting relatively better surface water quality with respect to the selected heavy metals. The Cd assessment suggests that surface water bodies in the study area presently do not exhibit significant heavy metal contamination.

Table 15. Contamination Index (Cd) Values and Contamination Levels of Surface Water Samples

Sample ID	Surface water	Cd Value	Contamination Level
7	Pond Water	0.545	Low Contamination
11	Pond Water	0	Low Contamination
18	Canal Water	0	Low Contamination

4.3.5. Human Health Risk Assessment of Drinking Water

To evaluate possible environmental factors associated with the reported cancer incidence in and around Balabhadrapuram village, the health-risk assessment was restricted to groundwater sources used for drinking purposes. Therefore, Hazard Quotient (HQ), Hazard Index (HI), and Cancer Risk (CR) assessments were restricted to groundwater sources used for drinking water purposes (14 No), including public water supply wells and domestic drinking water wells, since these indices are based on human exposure through water ingestion. Wells used exclusively for agricultural irrigation or other non-potable purposes were excluded from the health-risk assessment to avoid overestimation of population exposure.

Non-Carcinogenic Health Risk Assessment of Groundwater

To evaluate potential impacts on human health, non-carcinogenic risk was estimated using Hazard Quotient (HQ) for individual metals and Hazard Index (HI) for combined exposure through drinking water ingestion. The HQ and HI values are classified to evaluate the non-carcinogenic health risks associated with groundwater consumption. Samples with HQ and HI values less than 1 indicate that adverse health effects are unlikely under long-term exposure conditions, whereas HQ and HI values greater than 1 suggest potential non-carcinogenic health concerns. The formulae for these indices are described in the Methodology section.

Table 16. Hazard Index (HI) and Non-carcinogenic Health Risk Classification of Drinking Water Sources of Groundwater for Adults and Children

SID	HI Adult	Health Risk Assessment Adult	HI Child	Health Risk Assessment Child
3	0.39	No Significant Risk	0.90	No Significant Risk
4	0.84	No Significant Risk	1.97	Potential Risk
5	0.16	No Significant Risk	0.38	No Significant Risk
6	0.27	No Significant Risk	0.64	No Significant Risk
8	0.21	No Significant Risk	0.49	No Significant Risk
10	0.34	No Significant Risk	0.80	No Significant Risk
12	0.61	No Significant Risk	1.41	Potential Risk
13	0.96	No Significant Risk	2.24	Potential Risk
14	0.37	No Significant Risk	0.86	No Significant Risk
15	0.52	No Significant Risk	1.21	Potential Risk
16	0.12	No Significant Risk	0.28	No Significant Risk
17	0.22	No Significant Risk	0.52	No Significant Risk
23	0.46	No Significant Risk	1.07	Potential Risk
24	0.45	No Significant Risk	1.05	Potential Risk

The non-carcinogenic health risk assessment based on the Hazard Index (HI) revealed differences in potential health impacts between adults and children exposed to drinking water in the study area (Table 16). A radar plot for hazard index (HI) for adults and child of each groundwater sample used for drinking purposes is shown in Fig. 15. The results indicate that the HI values for adults ranged from 0.12 to 0.96, and all values remained below the acceptable threshold of HI = 1, suggesting that no significant non-carcinogenic health risk is expected for the adult population through the drinking water pathway. In contrast, the HI values for children ranged from 0.28 to 2.24, indicating relatively higher exposure and susceptibility compared to adults. Among the analyzed samples, SID-4 (HI = 1.97), SID-12 (HI = 1.41), SID-13 (HI = 2.24), SID-15 (HI = 1.21), SID-23 (HI = 1.07), and SID-24 (HI = 1.05) exceeded the acceptable threshold value (HI > 1) and therefore indicate potential non-carcinogenic health risks for children. The high risk has been observed in public water supplies at Balavaram (SID-4) and Balabhadrapuram (SID-12), suggesting that children consuming water from these sources may be more vulnerable to adverse health effects from long-term exposure to heavy metals than adults. The HI findings in the study area demonstrate that although groundwater sources are generally within acceptable non-carcinogenic risk limits for adults, several locations pose potential health risks to children, highlighting the need for regular monitoring and appropriate management measures to ensure a safe drinking water supply in the study area.

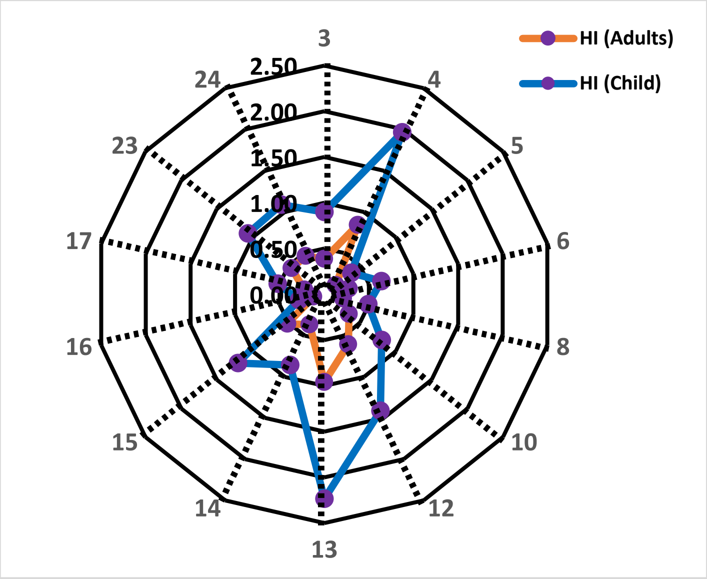

Fig.15. Radar plot for hazard index for adults and child of each groundwater sample used for drinking purposes

Non-Carcinogenic Health Risk Assessment of Surface Water

Hazard Index (HI) and non-carcinogenic health risk classification of drinking water sources of surface water for adults and children indicate that the HI values for adults ranged from 0.06 to 0.455, and all values remained below the acceptable threshold (HI < 1), suggesting that surface water ingestion is not expected to cause significant non-carcinogenic health effects for the adult population. Among the analysed samples, SID-11 (Pond Water, Balabhadrapuram) recorded an HI value of 1.063 for children, which slightly exceeds the acceptable threshold (HI > 1) and falls under the Potential Risk category under the assumed drinking water ingestion scenario. However, because the pond is currently used for fish culture purposes rather than drinking water supply, the calculated HI value reflects a general health risk scenario assuming regular ingestion of pond water and should not be interpreted as an indication of actual human drinking water exposure in the present use conditions.

Cancer Risk Assessment of Groundwater and Surface Water

Cancer Risk (CR) is a health risk assessment parameter used to estimate the probability of an individual developing cancer during their lifetime due to exposure to carcinogenic heavy metals through drinking contaminated groundwater. Table 17 presents the Total Cancer Risk (TCR) values and corresponding carcinogenic risk classifications for adult and child populations for groundwater and surface water in the study area. For the adult population for groundwater consumption, samples SID-3, SID-5, SID-6, SID-8, SID-14, SID-16, and SID-17 exhibit TCR values within the acceptable risk range (10^{-6}–10^{-4}), indicating that long-term groundwater consumption from these locations is unlikely to cause significant carcinogenic health effects. However, groundwater samples SID-4, SID-10, SID-12, SID-13, SID-15, SID-23, and SID-24 exceed the acceptable threshold (TCR > 10^{-4}) and are classified under elevated to potential cancer risk, suggesting possible long-term carcinogenic concerns. Out of these samples, three samples, namely SID-4 (in Balavaram), SID-24 (in Balabhadrapuram) and SID-12 (in Balabhadrapuram), are the public water supplies, and many populations are depending on these drinking water supply systems. For the child population, only SID-5 remains within the acceptable risk category, whereas all remaining groundwater samples exceed the acceptable threshold. The remaining samples fall into the elevated-to-potential cancer risk category. The occurrence of elevated TCR values despite relatively low metal concentrations demonstrates that cumulative lifetime exposure and metal toxicity characteristics can significantly influence carcinogenic risk assessment. These findings suggest that children represent the most vulnerable population group in the study area. The groundwater and surface water locations showing acceptable, elevated, and potential cancer risk categories for adults and children are shown in Fig. 16 (a) and 16 (b).

Table 17. Total Cancer Risk Assessment and Risk Classification of Groundwater and surface water for Adults and Children

Sample ID	TCR Adult	Adult CR Classification	TCR Child	Child CR Classification
SID-3	7.83×10^{-5}	Acceptable Risk	1.83×10^{-4}	Elevated Cancer Risk
SID-4	1.89×10^{-4}	Elevated Cancer Risk	4.41×10^{-4}	Potential Cancer Risk
SID-5	3.59×10^{-5}	Acceptable Risk	8.37×10^{-5}	Acceptable Risk
SID-6	6.81×10^{-5}	Acceptable Risk	1.59×10^{-4}	Elevated Cancer Risk
SID-7	1.62×10^{-4}	Elevated Cancer Risk	3.78×10^{-4}	Potential Cancer Risk
SID-8*	5.72×10^{-5}	Acceptable Risk	1.34×10^{-4}	Elevated Cancer Risk
SID-10	1.32×10^{-4}	Elevated Cancer Risk	3.08×10^{-4}	Potential Cancer Risk
SID-11*	2.22×10^{-4}	Potential Cancer Risk	5.19×10^{-4}	Potential Cancer Risk
SID-12	1.70×10^{-4}	Elevated Cancer Risk	3.97×10^{-4}	Potential Cancer Risk
SID-13	2.31×10^{-4}	Potential Cancer Risk	5.39×10^{-4}	Potential Cancer Risk
SID-14	6.85×10^{-5}	Acceptable Risk	1.60×10^{-4}	Elevated Cancer Risk
SID-15	1.46×10^{-4}	Elevated Cancer Risk	3.40×10^{-4}	Potential Cancer Risk
SID-16	4.69×10^{-5}	Acceptable Risk	1.09×10^{-4}	Elevated Cancer Risk
SID-17	5.18×10^{-5}	Acceptable Risk	1.21×10^{-4}	Elevated Cancer Risk
SID-18*	0.653×10^{-4}	Acceptable Cancer Risk	1.52×10^{-4}	Elevated Cancer Risk
SID-23	1.95×10^{-4}	Elevated Cancer Risk	4.55×10^{-4}	Potential Cancer Risk
SID-24	2.34×10^{-4}	Potential Cancer Risk	5.45×10^{-4}	Potential Cancer Risk

Note: * indicates surface water samples

Among the analyzed surface water samples, SID-11 (Pond Water, Balabhadrapuram) recorded the highest Total Cancer Risk values for both adults and children and was classified under the Potential Cancer Risk category. Although SID-11 pond water shows Potential Total Cancer Risk under direct ingestion scenarios, the pond is primarily used for aquaculture; therefore, the risk assessment represents a potential indirect exposure concern. Since heavy metals can bioaccumulate in fish tissues, there is a possibility of human exposure through fish consumption. However, a definitive dietary cancer risk cannot be established without fish tissue analysis and food-chain risk assessment. Similarly, SID-7 (Pond Water) exhibited an elevated cancer risk for adults and a potential cancer risk for children under the assumed drinking water exposure. However, this pond is not used for drinking water supply and is also not used for fish culture. Therefore, the estimated carcinogenic risk does not represent direct human exposure under existing usage conditions but indicates relative heavy metal enrichment in the surface water body. The canal water sample (SID-18) exhibited comparatively lower TCR values, with Acceptable Cancer Risk for adults and Elevated Cancer Risk for children. Since the canal water is also not used as a drinking water source, the estimated cancer risk values represent only a theoretical ingestion-based assessment and should not be interpreted as an immediate public health concern. although the surface water bodies are not presently used for drinking purposes, the observed TCR values indicate that surface waters, particularly pond systems, may act as local sinks for heavy metal accumulation and therefore require periodic monitoring to prevent future environmental deterioration and indirect exposure pathways.

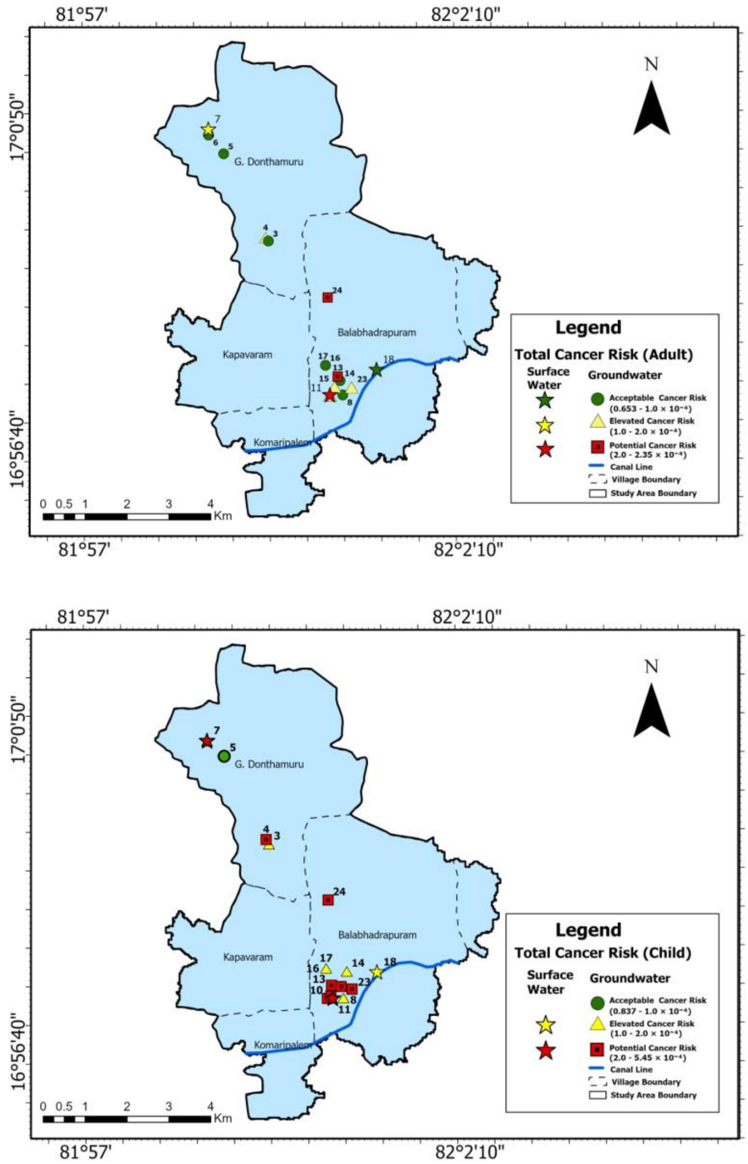

Fig. 16 Distribution of groundwater and surface water locations showing acceptable, elevated, and potential cancer risk categories for (a) adults and (b) children

Table 18. Priority Groundwater Locations based on Total Cancer Risk (TCR) and Recommended Risk Management Measures

Sample ID	TCR Risk Category	Water Source	Sample Location	Present Use	Recommended Immediate Action	Possible Alternative Source	Long-Term Management Option
SID-24	Potential Cancer Risk	Deep Well	PMAY–NTR Nagar, Balabhadrapuram	Public drinking water supply	Supply treated water	Public Water Supply from SID-16 / Tatanagaram OHT (SID-17)	New tube well and periodic monitoring
SID-13	Potential Cancer Risk	Dug Well (Shallow Well)	Devi Centre, Balabhadrapuram	Domestic	Restrict direct consumption	Not recommended as it is located in non-residential area	Improve sanitation and groundwater protection

SID-23	Elevated/Potential Cancer Risk	Dug Well (Shallow Well)	Balabhadrapuram	Domestic	Restrict direct consumption	Not recommended as it is located in non-residential area	Improve sanitation and groundwater protection
SID-4	Elevated/Potential Cancer Risk	Deep Well	Balavaram, G. Dontamuru	Public drinking water supply	Supply treated water	SID-5 (acceptable cancer risk source in G. Dontamuru)	Establish a new safe supply source in Balavaram
SID-14	Elevated/Potential Cancer Risk	Dug well (Shallow Well)	Devi Centre, Balabhadrapuram	Domestic / Drinking	Restrict direct consumption	Nearby public water supply	Improve sanitation and groundwater protection
SID-12	Elevated/Potential Cancer Risk	Deep Well	Market area, Balabhadrapuram	Public water supply from Yellampeta OHT	Supply treated water	New tube well / treated supply	Improve sanitation and groundwater protection

Note: TCR = Total Cancer Risk. Locations shown represent priority groundwater sources identified based on carcinogenic health risk assessment. Recommended measures are precautionary and should be supported through continued groundwater monitoring and verification of water quality before implementation.

Table 18 presents the priority groundwater locations identified based on Total Cancer Risk (TCR) assessment together with recommended risk management and mitigation measures. The priority locations were selected considering the magnitude of carcinogenic risk, present water use, source type, and feasibility of alternative drinking water options. The results indicate that SID-24, SID-13, SID-23, SID-4, SID-14, and SID-12 exhibit elevated to potential cancer risk levels, indicating comparatively greater cumulative exposure to carcinogenic heavy metals under long-term water consumption scenarios. Among these locations, SID-24 (PMAY–NTR Nagar), SID-4 (Balavaram), and SID-12 (Yellampeta OHT) are particularly important because they are currently functioning as public drinking water supply sources, and therefore require priority intervention to reduce long-term human exposure. Risk management measures proposed for public supply systems include supply of treated water, provision of alternative safe drinking water sources, and the reduction of dependence on existing contaminated sources. Long-term management measures include the development of new tube wells, the improvement of groundwater protection practices, sanitation improvement, and periodic water quality monitoring. For shallow domestic wells (SID-13, SID-14, and SID-23), restricting direct consumption and improving local sanitation and groundwater protection measures are recommended to minimize contaminant migration and future exposure. In addition to these wells, the pond water (SID-11) recorded potential carcinogenic risk values. However, this pond is presently used for fish culture rather than as a drinking water source; therefore, the risk values should be interpreted as indicative of environmental contamination potential rather than direct public drinking water exposure.

5. Conclusions

The groundwater elevation (RMSL) contour maps for the pre and post-monsoon seasons of 2024 revealed that groundwater elevations ranged from approximately 23 m in the northern part of the study area, which is occupied by Rajahmundry Sandstones, to about 3–6 m in the southern part, which is characterized by floodplain deposits. The groundwater gradient indicates that the direction of groundwater flow is towards the southeast and southwest. That means, any contaminants introduced into the groundwater system within the upgradient areas of the northern and central parts may migrate along the downgradient area (Balabadhrapuram) located in the southern part of the study area. Groundwater hydrochemistry identified clustering of elevated Total Dissolved Solids (TDS) and chloride (Cl^-) concentrations within the central inhabited part of Balabhadrapuram village, indicating possible influence of anthropogenic recharge. Heavy metal analysis showed that most trace metals remained within the drinking water standards prescribed by BIS (IS 10500:2012), however, iron (Fe), manganese (Mn), and lead (Pb) exceeded permissible limits at few locations. Elevated iron concentrations (>550 µg/L) associated with high chloride concentrations (>250 mg/L) are observed in groundwater samples in the central part of Balabhadrapuram, including public water supply sources (SID-12) suggesting that, in addition to natural geogenic contributions, local domestic wastewater infiltration, septic leakage, and sanitation-related activities may influence groundwater quality. Elevated lead concentration has been observed in the public water supply sample SID-12 (public water supply from Yellampeta OHT), indicating potential concern for drinking water safety.

Heavy metal Pollution using Metal Index (MI) and Contamination Index (Cd) as well as health-risk assessment using Hazard Index (HI), and Cancer Risk (CR) demonstrated that shallow groundwater is more vulnerable to heavy metal contamination compared to deep groundwater. Moderate to high heavy metal contamination with the range of MI values (2.40–7.49) and Cd values (1.2–4.0) has been identified at few locations, including public water supply wells in Balabhadrapuram (SID-12 and SID-24**)** and Balavaram (SID-4). Carcinogenic risk assessment showed that acceptable cancer risk levels were observed at public water supply schemes located at SID-5 (G. Dontamuru) and SID-16 and SID-17 (Tatanagaram OHT, Balabhadrapuram). Potential Cancer Risk for adults and children has been identified at three public drinking water supply wells, namely SID-4 (Balavaram), SID-12 **(**Yellampeta OHT)**,** and SID-24 **(**PMAY–NTR Nagar), as well as in a few shallow groundwater samples located in the central part of Balabhadrapuram village. These public drinking water supply sources exhibiting potential carcinogenic risk should be considered priority locations requiring attention and continued monitoring. Establishment of an appropriate water treatment system (such as heavy metal removal technology) may be considered. Alternatively, if sufficient capacity confirmed, the nearby drinking water source at SID-5 (G. Dontamuru) and SID-16 & SID-17 (Tatanagaram OHT), which exhibits acceptable cancer risk conditions, may be supplied as an alternative source for supplying water to the Balavaram and Balabhadrapuram population. The pond water (SID-11) in Balabhadrapuram also exhibited potential carcinogenic risk values. However, the pond is currently used for fish culture and not as a drinking water source, and therefore, the estimated risk should not be interpreted as direct public drinking water exposure. Instead, the findings indicate the need to evaluate the source of water feeding the pond and assess potential environmental contamination and possible indirect exposure concerns, rather than immediate human exposure through direct consumption of pond water.

The findings highlight the need to evaluate alternative safe drinking water sources from nearby public water supply schemes that exhibit acceptable/potential cancer risk conditions, and to implement appropriate water treatment systems, such as heavy-metal removal technologies, to minimize long-term human exposure and strengthen drinking water security in the study area.

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Field data collection were performed by Y.S. Prasad and G. Surya. Material preparation was performed by Y.S. Prasad. Lab analysis was carried out by R.V. Ramana, V.S. Jeyakanthan. and G. Surya. Interpretation was carried out by Y.S. Prasad, Y.R. S. Rao. Original draft preparation and written by Y.S. Prasad. Review and Editing were performed by Y.S. Prasad and Y.R. S. Rao. Maps were prepared by V.S. Jeyakanthan and K.R. Santhan. All authors read and approved the final manuscript.

Data availability:

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.