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Assessing groundwater quality and its association with child undernutrition in India

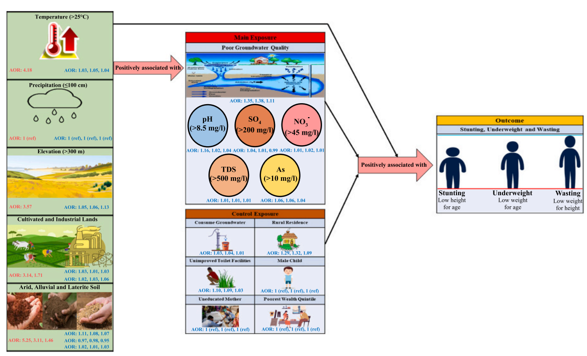
Sourav Biswas [a], Aparajita Chattopadhyay [b,*], Subhojit Shaw [b], Roman Hoffmann [c]

[a] Department of Population and Development, International Institute for Population Sciences, Deonar, Mumbai 400088, Maharashtra, India
[b] Department of Population and Development, International Institute for Population Sciences, Mumbai 400088, Maharashtra, India
[c] International Institute for Applied Systems Analysis (IIASA), Wittgenstein Centre for Demography and Global Human Capital (IIASA, OeAW, University of Vienna), Schloßplatz 1, 2361 Laxenburg, Austria

HIGHLIGHTS

- 26.53 % of India faces groundwater unfit for consumption.
- Poor groundwater quality correlates with higher child undernutrition probabilities.
- High As, pH, Mg, SO_4, NO_3^- linked to increased child undernutrition risks.
- Improved sanitation, sex, wealth, and diet factors influence undernutrition rates.
- Affluent households mitigate the effects of poor groundwater on child undernutrition.

GRAPHICAL ABSTRACT



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ABSTRACT

Background and objectives: Groundwater contamination poses a significant health challenge in India, particularly impacting children. Despite its importance, limited research has explored the nexus between groundwater quality and child nutrition outcomes. This study addresses this gap, examining the association between groundwater quality and child undernutrition, offering pertinent insights for policymakers.

Data and methods: The study uses data from the fifth round of the National Family Health Survey (NFHS) and the Central Groundwater Board (CGWB) to analyze the association between groundwater quality and child nutritional status. The groundwater quality data were collected by nationwide monitoring stations programmed by CGWB, and the child undernutrition data were obtained from the NFHS-5, 2019–21. The analysis included descriptive and logistic regression model. The study also considers various demographic and socio-economic factors as potential moderators of the relationship between groundwater quality and child undernutrition.

Findings: Significant variation in groundwater quality was observed across India, with numerous regions displaying poor performance. Approximately 26.53 % of geographical areas were deemed unfit for consuming

Abbreviations: MDG, millennium development goal; BIS, Bureau of Indian Standards; NFHS, National Family Health Survey; CGWB, Central Groundwater Board; WQI, Water Quality Index.

* Corresponding author.

E-mail addresses: souravbiswas3198@gmail.com (S. Biswas), aparajita@iipsindia.ac.in (A. Chattopadhyay), subhojitshaw93@gmail.com (S. Shaw), hoffmannr@iiasa.ac.at (R. Hoffmann).

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groundwater. Environmental factors such as high temperatures, low precipitation, and arid, alluvial, laterite-type soils are linked to poorer groundwater quality. Unfit-for-consumption groundwater quality increased the odds of undernutrition, revealing a 35 %, 38 %, and 11 % higher likelihood of stunting, underweight, and wasting in children, with higher pH, Magnesium, Sulphate, Nitrate, Total Dissolved Solids, and Arsenic, levels associated with increased odds of stunting, underweight, and wasting. Higher temperatures (>25 °C), high elevations (>1000 m), and proximity to cultivated or industrial areas all contribute to heightened risks of child undernutrition. Children consuming groundwater, lacking access to improved toilets, or living in rural areas are more likely to be undernourished, while females, higher-income households, and those consuming dairy, vegetables, and fruits daily exhibit lower odds of undernutrition.

Policy implications: Policy implications highlight the urgent need for investment in piped water supply systems. Additionally, focused efforts are required to monitor and improve groundwater quality in regions with poor water quality. Policies should emphasize safe sanitation practices and enhance public awareness about the critical role of safe drinking water in improving child health.

1. Introduction

Groundwater is an essential source of drinking water with >2.5 billion people relying only on groundwater for daily water requirements (Gude, 2018). SDG 6.3 aims to improve water quality globally by reducing pollution, minimizing the release of hazardous chemicals, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse (UN, 2015). However, >2.2 billion people still lack access to a safely managed water service (UN, 2019), highlighting the ongoing challenges related to groundwater quality on a global scale, particularly in lower-income countries where insufficient environmental sanitation practices and water quality pose significant challenges (Adelodun et al., 2021). Studies have shown that contaminated water sources and poor sanitation practices are responsible for over 80 % of all human infections (Prüss-Ustün et al., 2019).

In Asia and the Pacific, groundwater abstraction rates are the highest, with countries such as Bangladesh, India, Indonesia, Iran, Pakistan, and Turkey extracting over 60 % of groundwater (UNESCO, 2022). However, excessive groundwater usage raises concerns about resource sustainability, environmental degradation, climate change, and societal well-being (Carrard et al., 2019).

India faces complex challenges in managing its groundwater due to its vast size and population exceeding 1.4 billion. Large population, urbanization, and increasing agricultural demands strain its already stretched water resources. Balancing water allocation is crucial to boost agricultural productivity while ensuring clean water for health survival. Climate change threatens India's groundwater sustainability with shifting rainfall patterns and stronger monsoons (Asif et al., 2023). Natural forests and sustainably managed biodiverse forests are recognized for their critical role in mitigating the impacts of climate change on groundwater quality (Akachi et al., 2009; IPCC, 2022). These forests contribute to reducing surface runoff, thus increasing infiltration to groundwater and improving water quality (IPCC, 2022). The preservation and restoration of such forest ecosystems can provide a natural filtration system that helps to remove pollutants and pathogens from water sources (Saravanan et al., 2021). It is imperative to establish a direct connection between these transformations and groundwater quality to construct a comprehensive theoretical framework that can explain the effects of water on child health and nutritional well-being.

Child undernutrition remains a critical global health concern, with significant implications for physical growth, cognitive development, and overall well-being. Disturbingly, in 2020, approximately 2.37 billion people worldwide lacked access to sufficient food, highlighting the magnitude of the problem (FAO, 2021). South Asia bears a substantial burden with 36 % of children under five experiencing stunted growth (UNICEF, 2020). The causes of child undernutrition are multifaceted, influenced by a combination of poor diets during the crucial first two years of life, inadequate maternal nutrition before and during pregnancy, and environmental factors like poor sanitation, compromised water quality, and air pollution (Vilcins et al., 2018). The prevailing child undernutrition scenario in India necessitates a thorough examination of the available data to understand the magnitude and implications of this critical issue. With 35 % of children under the age of five experiencing stunting (NFHS-5, 2021), India holds the highest number of stunted children globally, amounting to 40.6 million individuals (UNICEF, 2021). This alarming situation calls for action to address the significant burden on India but also to contribute to global nutrition targets.

Groundwater quality is vital for child nutrition in India, where it is heavily used, supplying 85 % of rural domestic water and 65 % of irrigation (Korlakunta, 2022). Earlier studies have theoretically proposed a connection between groundwater and child undernutrition. However, there has not been a comprehensive exploration of this link (Cumming and Cairncross, 2016; Dangour et al., 2013; Hasanain et al., 2012; VanDerslice et al., 1994; Vella et al., 1992). Contaminated groundwater can harm children's health, causing nutritional deficiencies (Pronczuk and Surdu, 2008). The impact is significant in areas heavily reliant on groundwater with contamination from various sources (Li et al., 2021a). Groundwater contaminants like heavy metals, nitrates, pesticides, and pathogens can harm children's health (Madhav et al., 2020). For example, arsenic, lead exposure can lead to stunted growth, impaired cognitive development, and compromised immune function. Microbial contaminants can cause diarrheal diseases and hinder nutrient absorption, resulting in undernutrition (WHO, 2022).

However, evidence-based, published research on groundwater quality assessment and its link with child nutrition is yet to be found in India. The bulk of the studies have been carried out at a micro level, focusing solely on the assessment of groundwater quality without considering health implications (Adimalla and Qian, 2019; Li et al., 2021b; Saleh et al., 2023; Silva et al., 2021; Zhang et al., 2019). Previous studies on child undernutrition only focused on the socio-demographic, maternal and food consumption aspects.

To this end, this research aims to assess groundwater quality and its association with child undernutrition in India, thereby providing empirical evidence on an issue of high national relevance. We utilized official groundwater contaminants data to assess groundwater quality, mapping its spatial distribution by state and quantifying the groundwater situation. In addition, data on children's nutritional status are derived from the NFHS-5, which we combine with the groundwater quality data using regional cluster identifiers. We examined the link between groundwater quality with stunting, underweight, and wasting while analyzing how wealth status, water quality, and drinking water sources moderate the impacts on child nutrition. This study pioneers the mapping of groundwater quality and its correlation with child undernutrition, providing a novel evidence of high relevance for the Indian context.

2. Data and methods

2.1. Geospatial data

The study relies on secondary data gathered from diverse sources.

Groundwater data (2019–21), encompassing information from 29,065 sites across India, was acquired from the Central Groundwater Board (CGWB) (https://cgwb.gov.in/). CGWB collected samples from 29,065 sites once during the summer, rainy, and winter seasons in 2019–21, providing average data. States and UTs have no data, such as Jammu and Kashmir, Ladakh, Himachal Pradesh, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, and Lakshadweep, were excluded from the analysis. Geospatial parameters, including maximum temperature (2019–21), minimum temperature (2019–21), and precipitation (2019–21), were sourced from the Indian Meteorological Department (IMD) (https://mausam.imd.gov.in/). Elevation data was retrieved from EarthExplorer – USGS (https://earthexplorer.usgs.gov/), whereas landcover and landuse data (2019) were accessed through Bhuvan (https://bhuvan.nrsc.gov.in/). Further data sets were provided by ICAR-NBSS&LUP (https://nbsslup.icar.gov.in/) for soil analysis, the Geological Survey of India (GSI) for geological insights (https://www.gsi.gov.in/), and Google Earth Pro was used for identified the industrial locations (2019) (https://www.google.com/earth/about/versions/#earth-pro). The study utilized the averaged mean monthly maximum temperature, minimum temperature, and precipitation data from the years 2019 to 2021.

2.2. Socio-demographic data

The child undernutrition information, derived from the cross-sectional Demographic and Health Survey (DHS) known as the National Family Health Survey (NFHS-5) in India, conducted between 2019 and 2021, reflects the cross-sectional nature of the NFHS-5 survey data we utilized, with each sampled respondent surveyed once during the same period. Stunting, underweight and wasting were considered as the main indicators of under 5 years of child undernutrition. Besides, child undernutrition measurement, various socio-demographic, dietary habits and spatial data were used from the child data file of NFHS-5.

2.3. Merging geospatial data with NFHS-5 data

To merge all parameters of groundwater, maximum temperature, minimum temperature, precipitation, elevation, land cover and land use, soil and industrial locations data with NFHS-5 data, we used the clusters shape file of the NFHS-5 database. We matched the cluster IDs of NFHS-5 data with the raster area of the various geospatial data using GPS coordinates to extract groundwater contaminants data.

2.4. Calculating groundwater quality index

We used the formula of Brown et al. (Brown et al., 1972) and followed the Bureau of Indian Standards as standards for water properties and contaminants for calculating the Water Quality Index (WQI). Table 1 provides an overview of the parameters and limits used by selected countries and organizations (Bouaissa et al., 2021; Chakraborty et al., 2022; Liu et al., 2021).

The Water pH, Calcium (Ca), Magnesium (Mg), Sulphate (SO4), Chloride (Cl^-), Nitrate (NO_3^-), Fluoride (F^-), Total Hardness (TH), Total dissolved solids (TDS), Electrical Conductivity (EC), and Arsenic (As) are the 11 indicators we used for water quality analysis, which are in the dataset. The formula used for Water Quality Index is shown below.

2.4.1. Calculation of the Water Quality Index (WQI)

Step 1: Calculate the unit weight (W_n) factors for each parameter by using the formula

$$W_n = \frac{K}{Sn}$$

$$\text{Where, } K = \frac{1}{\frac{1}{S1} + \frac{1}{S2} + \frac{1}{S3} + \ldots + \frac{1}{Sn}} = \frac{1}{\sum \frac{1}{Sn}}$$ Where

S_n = Standard desirable value of the nth parameters

On summation of all selected parameters unit weight factors, $W_n = 1$ (unity)

Step: 2. Calculate the Sub Index (Q_n) value by using the formula

$$Q_n = \frac{[(Vn - Vo)]}{[(Sn - Vo)]} * 100$$

Where V_n is the mean concentration of the nth parameters, S_n is the standard desirable value of the nth parameters

V_0 = Actual values of the parameters in pure waters (generally V_0 = 0, for most parameters except for pH)

$$QpH = \frac{[(Vn\ pH - V0\ pH)]}{[(Sn\ pH - V0\ pH)]} * 100$$

Step: 3. Combining Step 1 & Step 2, WQI is calculate as follows

Overall WQI= $\frac{\sum WnQn}{\sum Wn}$ (Table 2) (Khatri et al., 2020; Menberu et al., 2021).

Table 2 shows how the Water Quality Index of a site has been calculated. With the help of this method, the Water Quality Index of 29,065 sites has been calculated. And Table 3 shows the WQI rating scale.

The inverse distance weighting (IDW) interpolation method was used for hotspot mapping of 11 water properties and contaminants and groundwater quality mapping. IDW is a deterministic approach for multivariate interpolation with a known scattered collection of points (Ohlert et al., 2023; Selmane et al., 2022). A weighted average of the values available at the known points is used to determine the values allocated to the unknown points. This method also generates spatial weight matrices in spatial autocorrelation investigations (Childs, 2004; Setianto and Triandini, 2013; Yang et al., 2020). The district-level map of groundwater quality was generated using QGIS 2.18.25, with zonal statistics mean applied for analysis

Table 1
Comparison of different parametric standards for drinking water quality.

Sl. no.	Parameter	European Union	United States	China	Canada	WHO	India (BIS)
1.	Water pH				6.5–8.5	6.5–9.2	6.5–8.5
2.	Calcium (Ca)				200 mg/l	75 mg/l	75 mg/l
3.	Magnesium (Mg)				50.0 mg/l	30.0 mg/l	30.0 mg/l
4.	Sulphate (SO_4)					250 mg/l	200 mg/l
5.	Chloride (Cl^-)	250 mg/l				250 mg/l	250 mg/l
6.	Nitrate (NO_3^-)	50 mg/l	10 mg/l	10 mg/l		50 mg/l	45 mg/l
7.	Fluoride (F^-)	1.5 mg/l	0.7 mg/l	1.0 mg/l		1.5 mg/l	1.0 mg/l
8.	Total Hardness (TH)				0–75 mg/l		300 mg/l
9.	Total dissolved solids (TDS)					1000 mg/l	500 mg/l
10.	Electrical Conductivity (EC)	2500 μS/cm				1500 μS/cm	300 μS/cm
11.	Arsenic (As)	0.01 mg/l	0.01 mg/l		0.01 mg/l	0.01 mg/l	0.01 mg/l

Table 2
Calculating Water Quality Index (WQI) at a groundwater site.

Parameters	BIS standards (Sn)	Mean conc. (Vn)	1/Sn	K = 1/(∑1/Sn)	Wn = K/Sn	Ideal Value (V_0)	Vn/Sn	Qn = Vn/Sn*100	WnQn = Wn*Qn
pH	7.5	7.9	0.133	0.76	0.101	7.0	1.8	180.0	18.2
Ca	75	44	0.013	0.76	0.010	0.0	0.6	58.7	0.6
Mg	30	19.44	0.033	0.76	0.025	0.0	0.6	64.8	1.6
SO_4	200	4.3	0.005	0.76	0.003	0.0	0.0	2.2	0.0
Cl^-	250	35.55	0.004	0.76	0.003	0.0	0.1	14.2	0.0
NO_3^-	45	7.2	0.022	0.76	0.016	0.0	0.2	16.0	0.3
F^-	1	0.13	1.000	0.76	0.760	0.0	0.1	13.0	9.9
TH	300	190	0.003	0.76	0.002	0.0	0.6	63.3	0.1
EC	300	482	0.003	0.76	0.002	0.0	1.6	160.7	0.3
TDS	500	308.48	0.002	0.76	0.001	0.0	0.6	61.7	0.1
As	10	7	0.1	0.76	0.076	0.0	0.7	70.0	5.3
Sum			∑1/Sn = 1.319		∑Wn = 1			∑WnQn/∑Wn = WQI = 36.4	

To calculate Vn/Sn for pH $= \frac{(Vn\,pH - V0\,pH)}{(Sn\,pH - V0\,pH)} = \frac{7.9-7.0}{7.5-7.0} = 1.8$.

Table 3
WQI rating scale.

WQI	Category
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
>100	Unfit for consumption

2.5. Outcome variables

Stunting, underweight, and wasting were considered as the primary outcome variables in this study, as they are the main indicators used to measure child undernutrition. According to the WHO definition, children with a height/age standard deviation less than −200 are classified as 'stunted'; weight/age standard deviation of less than −200 as 'underweight'; and weight/height standard deviation of less than −200 as 'wasted' (Porwal et al., 2021). The final sample of the study population was 177,506 children.

2.6. Independent variables

The study considers groundwater quality as the primary independent variable and is classified into five categories: excellent (0–25), good (25–50), poor (50–75), very poor (75–100), and unfit for consumption (above 100) (Chakraborty et al., 2021). Various groundwater contaminants are considered as additional independent variables. The Chi-Square test (Pandis, 2016) is employed to determine significant associations between these contaminants and child undernutrition. Subsequently, based on the Chi-Square test results, pH, Ca, Mg, SO_4, Cl^-, NO_3^-, TDS, and As are selected as other independent variables for analysis. All contaminants were categorized based on the BIS standard.

2.7. Other predictor variables

Based on previous literature, we included certain predictor variables because they showed significant connections with stunting, underweight, and wasting (BS and Guddattu, 2022; Corsi et al., 2016). These variables include information on the sources of drinking water (piped water, groundwater and other sources of water); toilet facilities (improved and unimproved); sex of the children (male, female); mother's educational attainment (no education, primary, secondary, and higher); and wealth status (poorest, poor, middle, richer, richest quintile); consume dairy products, pulses/beans, vegetables, fruits, egg, meat (never, daily, weekly, occasionally); place of residence (urban and rural); and geographic region (north, central, east, northeast, west, south). The local environmental factors: maximum temperature (≤15 °C, 15–20 °C, 20°-25 °C, >25 °C), minimum temperature (≤15 °C, 15–20 °C, 20°-25 °C, >25 °C), precipitation (≤100 cm, 100–200 cm, >200 cm) elevation (≤100 m, 100–200 m, 200–300 m, 300–1000 m and > 1000 m), landcover & landuse (vegetation cover, shrub cover, herbaceous cover, cultivated and managed areas, bare land, water bodies), soil (forest and mountain, alluvial, black, red and yellow, laterite, arid), and industrial locations (yes, no) were included as other predictor variables.

2.8. Statistical analysis

Descriptive analyses were carried out, and the findings were presented in unweighted frequencies and weighted percentages. Then, bivariate analyses were carried out to analyze the relationships. In this study, we employed ordered logistic regression (Fullerton, 2009) to analyze the relationship between groundwater quality and various environmental factors. Groundwater quality was treated as the outcome variable and categorized into ordered levels representing different degrees of quality. The independent variables included maximum temperature, minimum temperature, precipitation, elevation, landcover and landuse, soil characteristics, geology, and industrial locations. The ordered logistic regression model was structured as follows:

$$\text{Logit}\left(P\left(Y\left(\leq j\right)\right)\right) = \beta^{j}{}_{0} + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p + e$$

Where:

Y: represent groundwater quality (outcome variable); P (Y (≤ j): represents the cumulative probability of the groundwater quality falling into the jth or lower category; Logit (): is the natural logarithm of the odds ratio; β_0^j: is the threshold parameter for the jth category of groundwater quality; X_1, X2,…,X_p: Independent variables; β_1, β_2,…,β_p: are the coefficients associated with each independent variable; ϵ: represents the error term capturing unexplained variation in groundwater quality not accounted for by the independent variables.

In order to determine the association between groundwater quality and child undernutrition (stunting, underweight and wasting), the logistic regression model (Nick and Campbell, 2007) was used. The logistic regression equation models help to identify the relationship between one or more independent variables X_1, X_2, X_3, …, X_n (groundwater quality, local environmental conditions, socio-demographic factors, and dietary habits) and a binary dependent variable Y (Stunting, Underweight and Wasting). The equation is formulated as follows:

$$\text{logit}\left(P(Y=1)\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots + \beta_n X_n$$

Where:

P(Y = 1) is the probability of child undernutrition (Stunting, Underweight, Wasting); logit(P(Y = 1)) is the log odds of child undernutrition; β_0 is the intercept term; $\beta_1, \beta_2, \beta_3, \ldots, \beta_n$ are the coefficients associated with each independent variable; $X_1, X_2, X_3, \ldots, X_n$ are the independent variables representing groundwater quality, local environmental conditions, socio-demographic factors, and dietary habits. All statistical analyses were conducted using StataSE 16 software; groundwater quality calculation was performed using RStudio software, and spatial analysis and mapping were performed using ArcMap 10.8 software. Fig. 1 illustrates the methodological framework of the study, providing a visual overview of the research approach.

3. Results

3.1. Assessment and mapping of groundwater quality in India

In this study, we present a comprehensive analysis of the spatial distribution of eleven crucial parameters in groundwater across different regions of India, as depicted in Fig. 2(a-k). Our study found that most areas in the west and south of India have high pH levels and higher concentrations of Ca, Mg, SO_4, Cl^-, NO_3^- and F^- in the water. However, in the north and east, there is more As. Also, we noticed that the west and south regions have harder water, meaning more stuff is dissolved, and it conducts electricity better. Fig. 3(a, b) shows all this information on one map. Fig. 3(a) provides an overview of the spatial distribution of groundwater quality in India based on the water quality index. Fig. 3(b) shows the district-wise distribution of groundwater quality, calculated using zonal statistics for mean value calculation, providing a detailed insight into local variations across the country. The water quality index values below 25 indicate excellent groundwater quality, and values above 100 indicate groundwater unfit for consumption. The results demonstrate that the majority of western, central, and southern districts of India exhibit good to excellent groundwater quality. Conversely, the northern, south-eastern, and some eastern districts display poor to very poor groundwater quality. These findings shed light on the regional disparities in groundwater quality across India.

Table 4 presents the groundwater quality situation in each State and Union Territory (UT) of India, presented as a percentage of the total area of the respective states and UTs. The results reveal that >40 % of the area in Rajasthan (71.71 %), Andaman & Nicobar Islands (63.35 %), Assam (46.09 %), Uttar Pradesh (44.56 %) and West Bengal (41.83 %) is characterized by groundwater that is unfit for consumption. In contrast, most areas of Goa, Uttarakhand, Kerala, Chhattisgarh, Dadra & Nagar Haveli, Puducherry, Maharashtra and Madhya Pradesh have good to excellent groundwater quality.

Appendix 1 presents an overview of drinking water sources across Indian states and UTs, showing that in states like Bihar, Uttar Pradesh, Assam, West Bengal, Odisha, Jharkhand, and Chhattisgarh, where nearly half of India's population resides, the majority of people depend on groundwater.

3.2. Association between groundwater quality and geo-environmental determinants

The geographic distribution and magnitude of crucial environmental factors influencing groundwater are depicted in Fig. 4(a-h). These factors include maximum and minimum average temperatures (Fig. 4(a) and (b)), average precipitation (Fig. 4(c)), elevation (Fig. 4(d)), land cover and land use (Fig. 4(e)), soil type (Fig. 4(f)), geological formations (Fig. 4(g)), and industrial areas (Fig. 4(h)). Table 5 presents the association between groundwater quality and these geo-environmental variables, elucidated through ordered logistic regression as odds ratios. As the temperature increases from ≤15 °C to >25 °C, the odds of having poorer groundwater quality increase substantially, with odds ratios of 1.22, 2.23, and 4.18 for temperature ranges of 15–20 °C, 20–25 °C, and > 25 °C, respectively. Similarly, for minimum temperature, higher temperatures (>25 °C) are associated with significantly higher odds of poorer groundwater quality. Regarding precipitation, as the amount of precipitation increases from ≤100 cm to >200 cm, the odds of having poorer groundwater quality decrease significantly, with odds ratios of 0.23 and 0.05 for precipitation ranges of 100–200 cm and >200 cm, respectively. Regarding elevation, areas at 100–200 m and 200–300 m exhibit significantly higher odds ratios of 2.32 and 3.57, respectively, compared to areas at ≤100 m, suggesting a correlation between higher elevation and poorer groundwater quality. Conversely, areas at elevations >1000 m show a lower odds ratio of 0.45, indicating a strong association with excellent groundwater quality. Regarding land cover/land use, cultivated and managed areas display the highest odds ratio of 3.14, followed by herbaceous cover with an odds ratio of 1.53. This suggests that cultivated & managed areas are strongly associated with poorer groundwater quality, while herbaceous cover also shows a significant association. Conversely, water bodies exhibit a lower odds

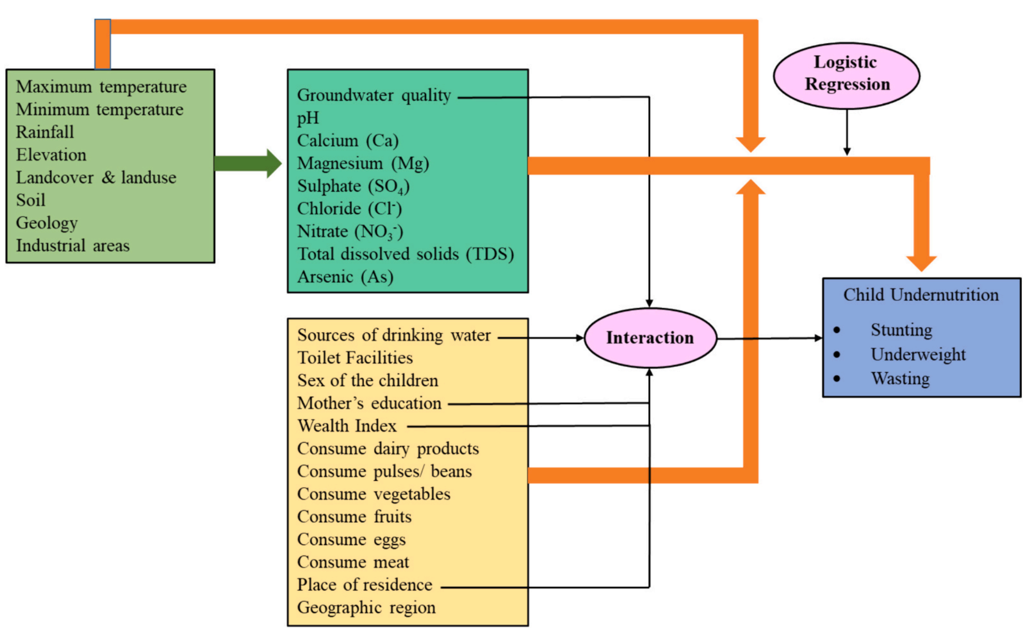


Fig. 1. Methodological framework of the study.

ratio of 0.65, indicating a strong association with excellent groundwater quality. Tertiary sedimentary and igneous rocks exhibit a significantly lower odds ratio of 0.46, indicating a strong association with better groundwater quality than Quaternary sediments and rocks. Conversely, Mesozoic rocks and Carboniferous and Ordovician rocks show higher odds ratios of 1.64 and 1.30, respectively, suggesting associations with poorer groundwater quality. Paleozoic rocks exhibit a slightly lower odds ratio of 0.80, indicating a relatively strong association with excellent groundwater quality. Industrial areas are associated with a higher odds ratio of 1.71, indicating a significant association with poorer groundwater quality compared to areas without industrial activity.

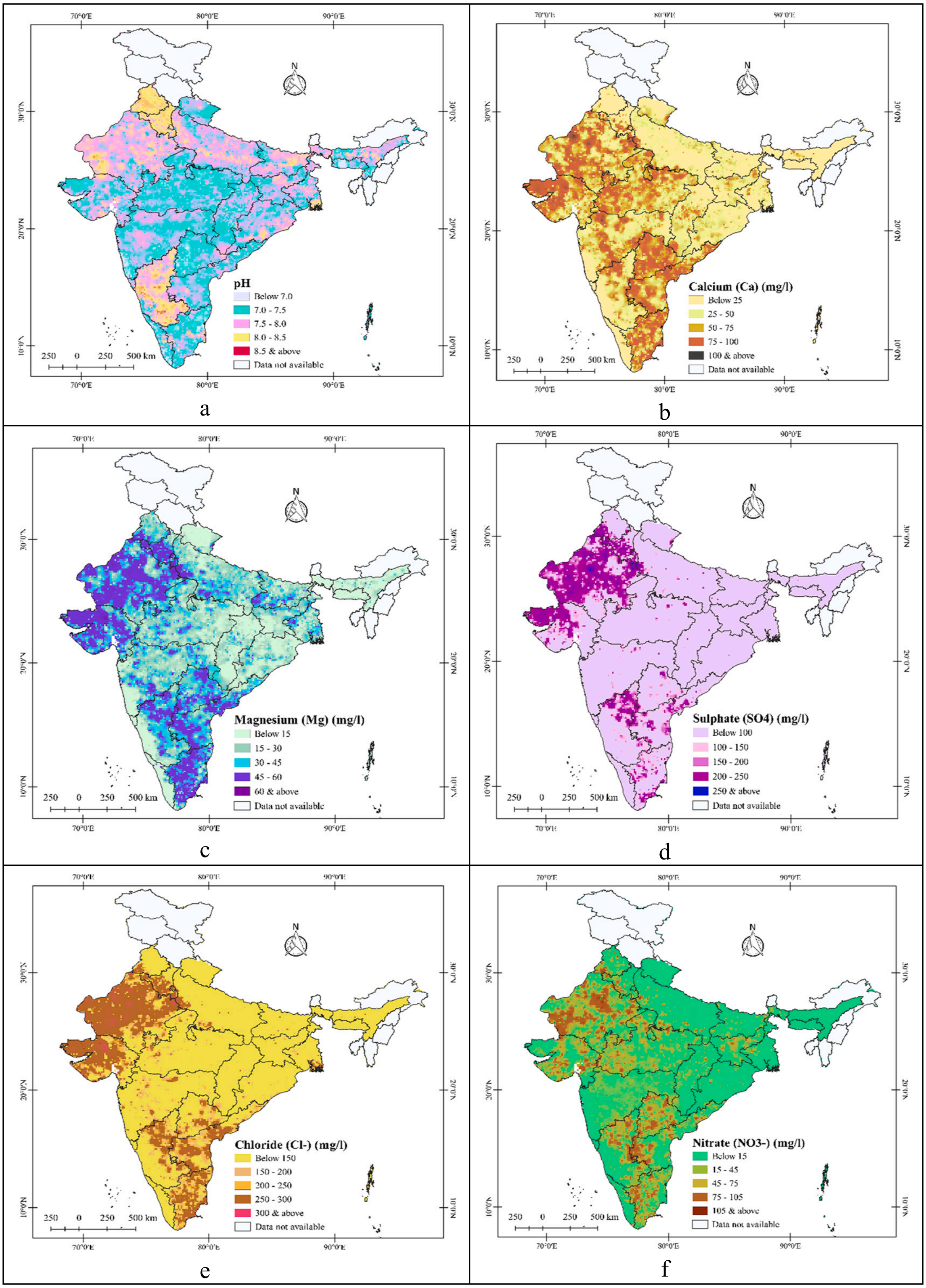


Fig. 2. (a-j) Spatial distribution of various water contaminants (a) pH; (b) Ca; (c) Mg; (d) SO_4; (e) Cl^-; (f) NO_3^-; (g) F^-; (h) TH; (i) TDS; (j) EC; and (k) As across India, 2019–21.

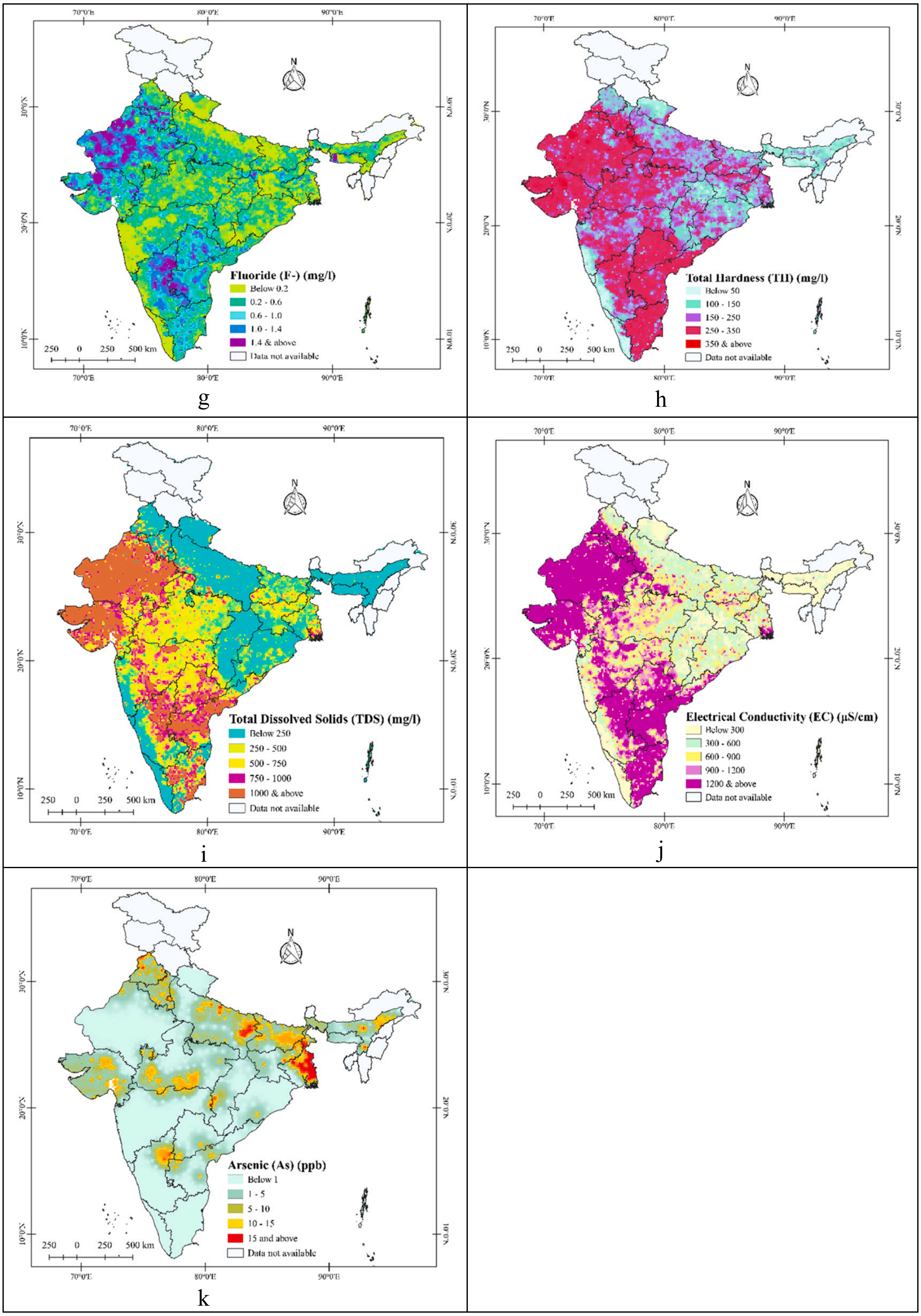
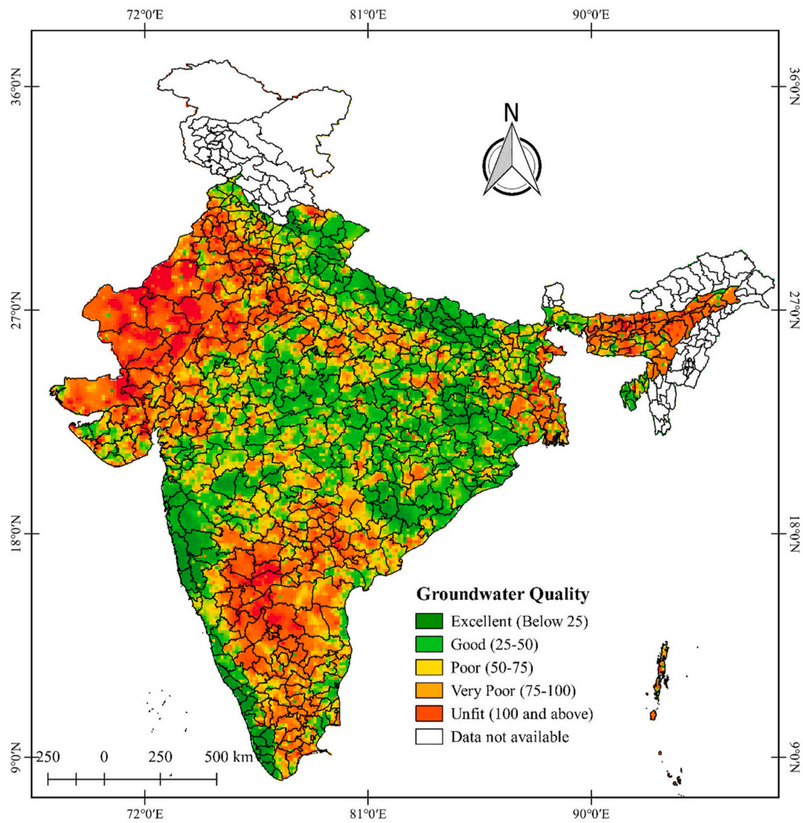


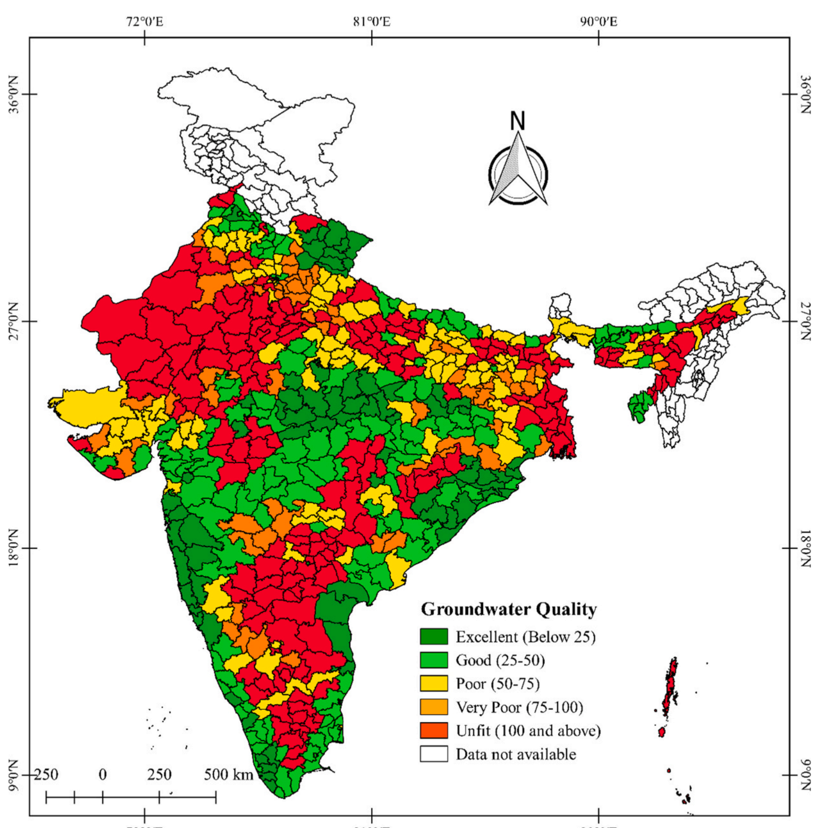
Fig. 2. (*continued*).

3.3. Relationship between groundwater quality and child undernutrition in India

Fig. 5 presents the percentage distribution of stunted, underweight, and wasted children in Indian States and Union Territories (UTs), revealing major challenges in child nutrition in the country. In India, 35.5 % of children are stunted, 32.1 % are underweight, and 19.3 % are wasted. Meghalaya, Bihar, Jharkhand, Uttar Pradesh, and Dadra & Nagar Haveli emerged as the top five States/UTs with the highest percentage of stunted children, with values ranging from 47.0 % to 40.1 %. Conversely, Puducherry, Sikkim, Andaman & Nicobar Islands, Kerala, and Punjab exhibited the lowest proportion of stunted children, with



a



b

Fig. 3. (a, b) Spatial distribution of groundwater quality in India, with (a) overall distribution based on Water Quality Index, and (b) district-wise distribution of groundwater quality.

Table 4
Distribution of groundwater quality in India (areas in %).

States and Uts	Excellent	Good	Poor	Very poor	Unfit
Andaman & Nicobar Islands	2.34	2.43	4.86	29.12	63.35
Andhra Pradesh	28.78	38.96	14.22	4.23	13.81
Assam	5.42	31.32	12.91	4.26	46.09
Bihar	4.48	26.58	19.84	17.18	31.92
Chandigarh	17.88	54.28	7.84	11.60	8.40
Chhattisgarh	34.28	35.56	8.55	5.93	15.68
Dadra & Nagar Haveli	33.32	66.68	0.00	0.00	0.00
Daman & Diu	0.00	0.00	100.00	0.00	0.00
Goa	96.23	3.77	0.00	0.00	0.00
Gujarat	6.51	28.23	41.20	9.04	15.02
Haryana	2.32	44.07	26.03	11.85	15.73
Jharkhand	2.58	8.38	26.87	41.49	20.68
Karnataka	7.26	19.52	25.83	23.10	24.30
Kerala	59.00	28.61	7.26	2.14	2.99
Madhya Pradesh	32.56	29.14	17.70	8.32	12.28
Maharashtra	33.08	38.02	8.97	5.37	14.56
Meghalaya	12.08	20.23	21.43	14.24	32.02
NCT of Delhi	2.46	20.04	30.85	23.01	23.64
Odisha	30.31	20.03	10.06	8.40	31.20
Puducherry	33.29	33.29	33.41	0.00	0.00
Punjab	18.66	44.06	16.25	8.28	12.76
Rajasthan	0.93	4.11	9.01	14.24	71.71
Tamil Nadu	15.79	30.21	17.27	8.44	28.29
Telangana	9.86	24.63	23.18	15.02	27.31
Tripura	8.13	78.26	6.08	5.14	2.39
Uttar Pradesh	5.74	22.80	15.09	11.81	44.56
Uttarakhand	70.82	4.26	7.24	5.36	12.32
West Bengal	9.09	16.61	15.14	17.33	9.09
India	16.15	27.81	17.91	11.60	26.53

percentages ranging from 19.8 % to 24.3 %. When considering underweight children Bihar, Dadra & Nagar Haveli, Gujarat, Jharkhand, and Maharashtra recorded the highest shares, ranging from 35.2 % to 43.5 %. In contrast, Sikkim, Puducherry, Punjab, Kerala, and Uttarakhand displayed the lowest proportions of underweight children, with percentages ranging from 8.8 % to 19.9 %. Regarding wasting, eight states reported a share of wasted children exceeding 20 %, including Maharashtra, Gujarat, Bihar, Jharkhand, Telangana, Assam, Dadra & Nagar Haveli, and West Bengal. Chandigarh stood out as the only UT with <10 % (8.5 %) of wasted children. Bihar, Gujarat, and Jharkhand exhibited high percentages across all three indicators. Conversely, Puducherry and Punjab demonstrated low proportions across all three indicators.

Table 6 provides an overview of the background characteristics of children and the percentage distribution of stunting, underweight, and wasting in India. Our findings reveal a clear and significant association between groundwater quality and the prevalence of stunting, underweight, and wasting among children.

In areas with excellent groundwater quality, the rates of stunting, underweight, and wasting were 29.95 %, 25.25 %, and 16.20 %, respectively. In regions with good groundwater quality, these rates were slightly higher at 32.68 %, 28.79 %, and 17.38 %. In zones with poor groundwater quality, the rates of stunting, underweight, and wasting further increased to 34.83 %, 32.07 %, and 20.06 %. The very poor groundwater quality areas had even higher rates of 36.71 %, 33.80 %, and 20.59 %. Notably, in regions where groundwater was unfit for consumption, the rates of stunting and underweight were the highest at 37.61 % and 35.48 %.

Furthermore, children who consumed groundwater had higher percentages of stunting, underweight, and wasting, with rates of 39.72 %, 33.79 %, and 19.61 %, respectively, compared to those who consumed piped water (33.73 %, 28.68 %, and 18.81 %). Similarly, unimproved sanitation facilities were associated with higher percentages of stunting, underweight, and wasting (43.20 %, 38.02 %, and 21.22 %, respectively) compared to those with improved sanitation facilities (33.12 %, 27.87 %, and 18.38 %, respectively).

Male children displayed higher rates of stunting, underweight, and wasting (36.86 %, 31.31 %, and 19.96 %) than female children (35.17 %, 30.29 %, and 18.41 %). Children of mothers with no education had significantly higher percentages of stunting, underweight, and wasting (47.22 %, 40.90 %, and 21.60 %) compared to those with highly educated mothers (23.02 %, 19.09 %, and 16.65 %). Similarly, children from the poorest wealth families had higher rates of stunting, underweight, and wasting (46.27 %, 41.12 %, and 22.40 %) than those from the wealthiest families (23.72 %, 19.05 %, and 15.60 %).

Children who never consume certain food items tend to have higher percentages of stunting, underweight, and wasting compared to those who consume them daily or occasionally. For instance, children who never consume fruits, eggs, or meat show higher percentages of these health indicators.

Geographical factors also played an important role in determining child nutrition. Children residing in rural areas exhibited higher percentages of stunting, underweight, and wasting (37.97 %, 32.59 %, and 19.47 %, respectively) than their urban counterparts (30.57 %, 25.79 %, and 18.47 %). Regions such as the East (39.08 % stunting, 35.78 % underweight, and 21.60 % wasting), West (37.39 %, 36.16 %, and 25.21 %), Central (38.78 %, 30.62 %, and 17.67 %), and Northeast (36.88 %, 29.51 %, and 20.08 %) exhibited the highest rates of stunting, underweight, and wasting.

3.4. Effect of groundwater quality on child undernutrition

To gain insights into the relationship between groundwater quality and child undernutrition, the study employed logistic regression models to examine the odds of stunting, underweight and wasting (Table 7) in children in relation to groundwater quality and other factors. Following chi-square testing, variables such as F, TH, EC, and Geology were excluded from further analysis due to their lack of significant association with child undernutrition. Our analysis comprised three distinct models for each undernutrition parameter, with the third model revealing adjusted odds. Through Model 3, we were able to illuminate the primary determinants of child undernutrition, offering valuable insights into its underlying factors. By scrutinizing unadjusted and adjusted odds, we uncovered nuanced relationships between various factors and child undernutrition, enhancing our understanding of its multifaceted nature. Our study reveals a significant association between groundwater quality and child undernutrition. Children residing in areas with good, poor, very poor, and unfit-for-consumption groundwater quality have a 19 %, 22 %, 25 %, and 35 % higher likelihood of being stunted, and a 10 %, 24 %, 30 %, and 38 % higher likelihood of being underweight, and a 5 %, 8 %, 9 %, and 11 % higher likelihood of being wasted compared to those residing in areas with excellent groundwater quality. Specifically, groundwater with a pH level > 8.5 is 16 %, 2 %, and 4 % more likely to result in stunting, underweight, and wasting, whereas pH levels between 6.5 and 8.5 are 17 %, 4 %, and 8 % less likely to cause these conditions compared to pH levels ≤6.5. Groundwater with Mg levels >30 mg/l is 3 %, 1 %, and 1 % more likely to lead to stunting, underweight, and wasting than levels ≤30 mg/l. Additionally, elevated SO_4 levels (>200 mg/l) are associated with a 4 % and 1 % increased likelihood of stunting and underweight compared to levels ≤200 mg/l. Moreover, NO_3^- levels >45 mg/l are 1 % more likely to result in underweight and wasting than levels ≤45 mg/l. TDS levels >500 mg/l are associated with a 1 %, 1 %, and 1 % higher likelihood of stunting, underweight, and wasting than levels ≤500 mg/l. Furthermore, groundwater with As levels >0.01 mg/l is 6 %, 6 %, and 4 % more likely to result in stunting, underweight, and wasting than levels ≤0.01 mg/l. Local environmental factors also play a role in child undernutrition, with increasing temperatures associated with higher odds of undernutrition outcomes. Maximum and minimum temperatures >25 °C are 7 %, 4 %, 13 % and 3 %, 5 %, and 4 % more likely to result in stunting, underweight, and wasting compared to temperatures ≤15 °C. Conversely, maximum and minimum temperatures between 15 °C and 20 °C are 1 %, 5 %, 2 % and 2 %, 1 %, 2 % less

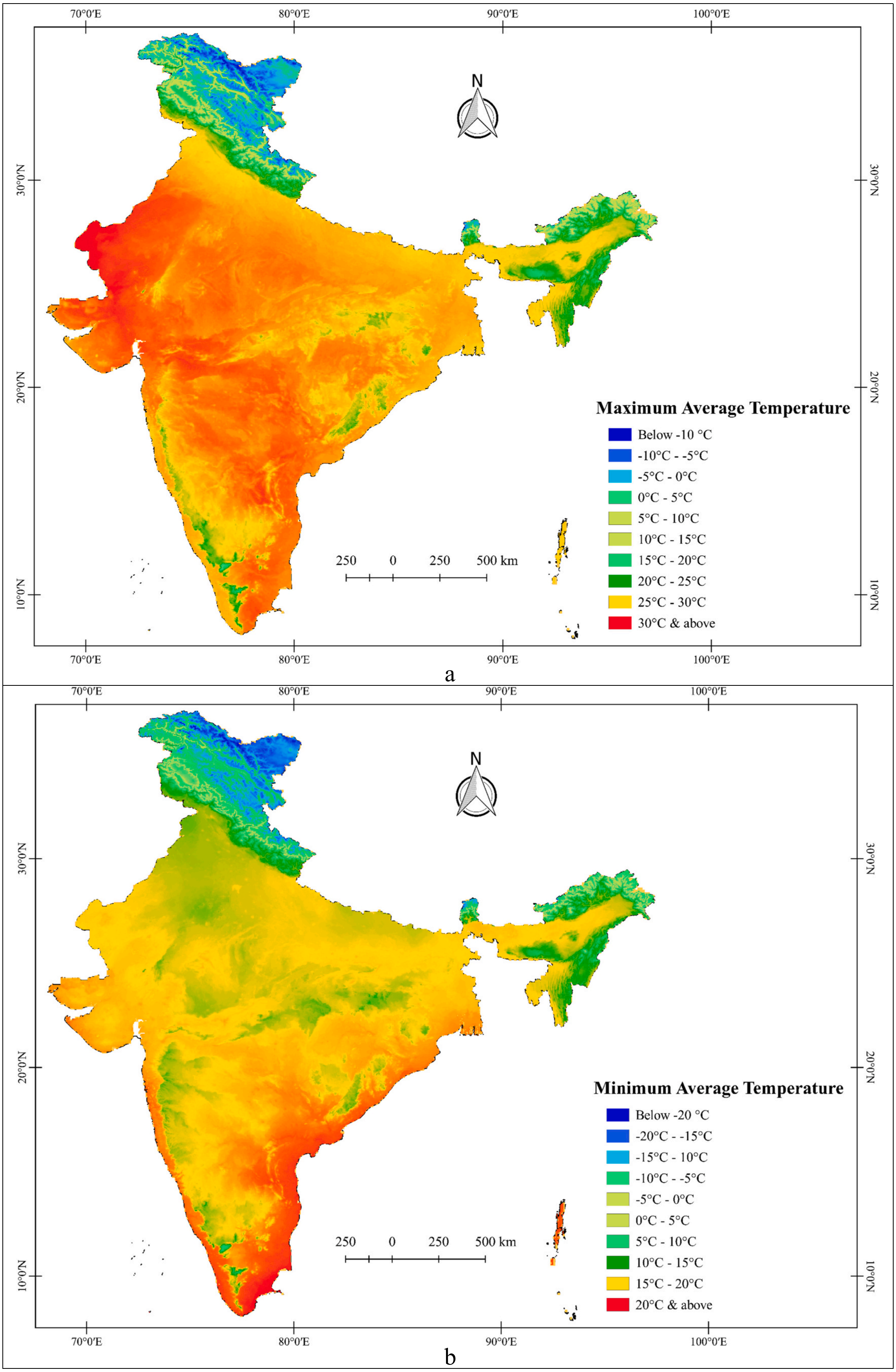


Fig. 4. (a-h) Spatial distribution of (a) maximum average temperature; (b) minimum average temperature; (c) average precipitation; (d) elevation; (e) landcover and landuse; (f) soil; (g) geology; (h) industrial belts across India.

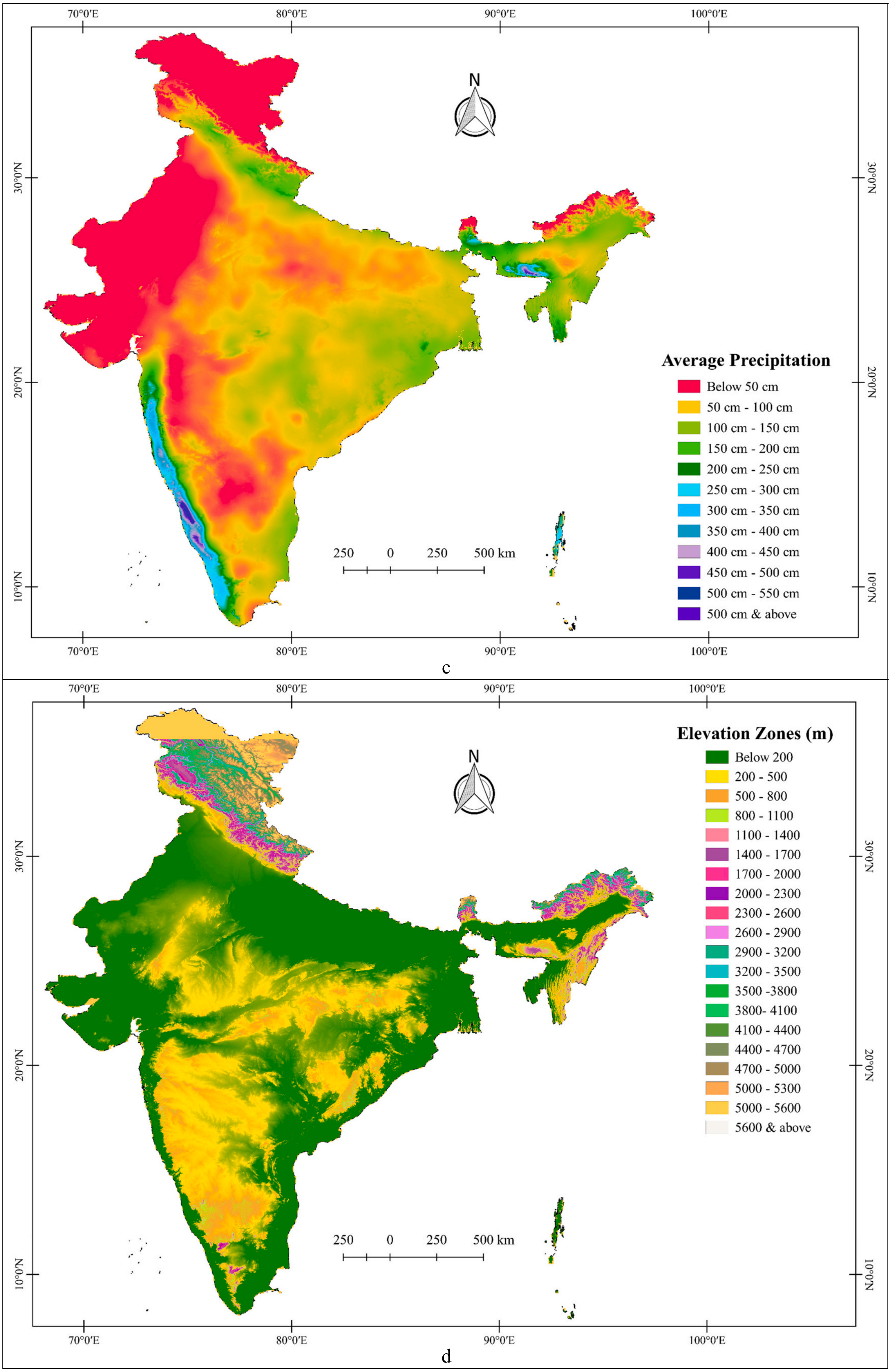
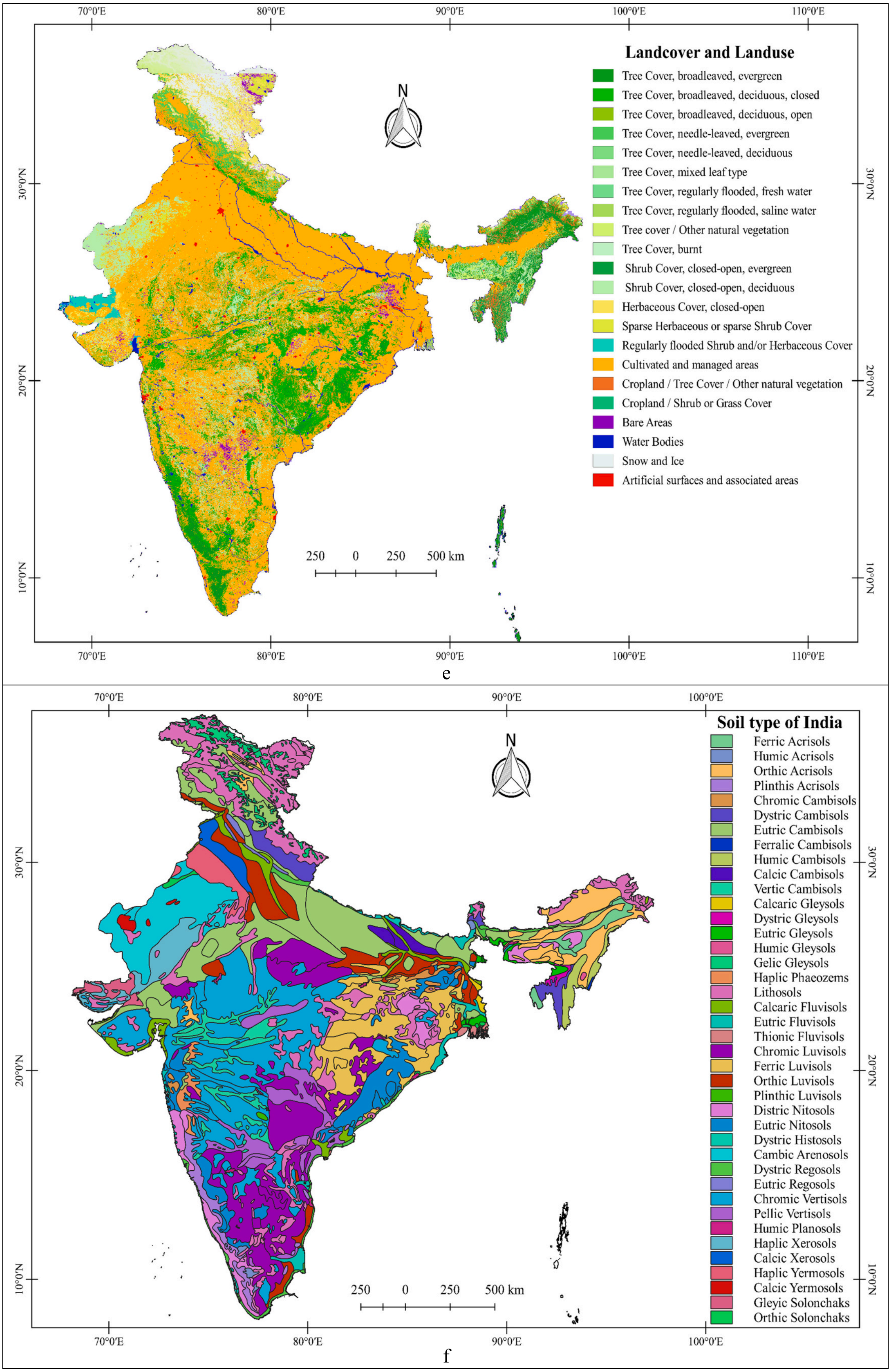


Fig. 4. (*continued*).



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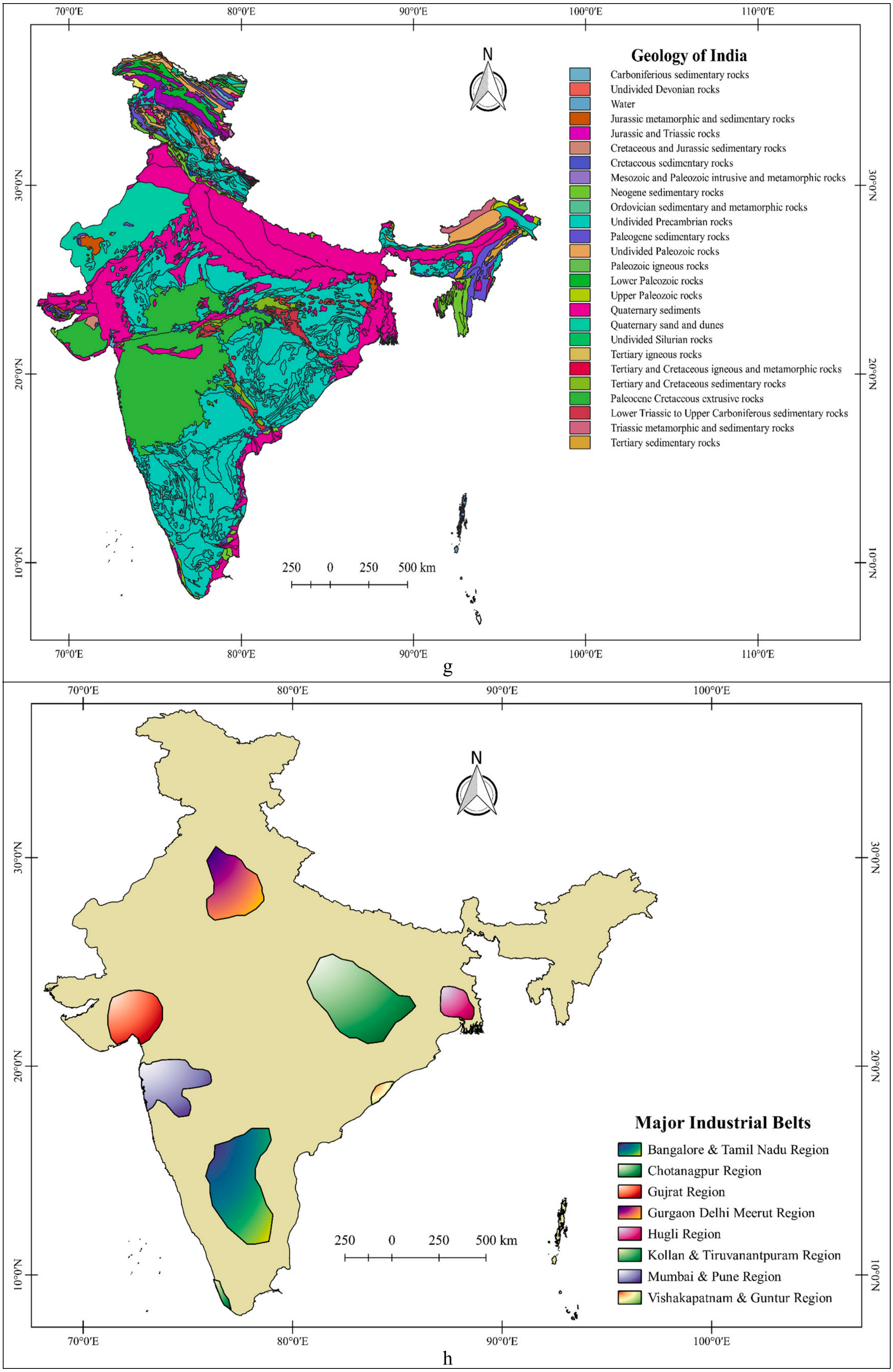

Fig. 4. (*continued*).

Table 5
The results of the ordered logistic regression model represent odds ratio estimates of the association between environmental determinants and groundwater quality in India.

Background characteristics	Groundwater quality (Odds ratio) [95 % CI]
Maximum temperature	
≤15 °C[a]	1[1.00,1.00]
15–20 °C	1.22**[1.05,1.41]
20–25 °C	2.23***[1.92,2.59]
>25 °C	4.18***[3.38,5.17]
Minimum temperature	
≤15 °C[a]	1[1.00,1.00]
15–20 °C	1.13*[0.97,1.32]
20–25 °C	2.08***[1.78,2.43]
>25 °C	3.89***[3.13,4.85]
Precipitation	
≤100 cm[a]	1[1.00,1.00]
100–200 cm	0.23***[0.23,0.24]
>200 cm	0.05***[0.05,0.05]
Elevation	
≤100 m[a]	1[1.00,1.00]
100–200 m	2.32***[2.26,2.38]
200–300 m	3.57***[3.48,3.66]
300–1000 m	1.05***[1.01,1.12]
>1000 m	0.45***[0.43,0.48]
Landcover & landuse	
Vegetation cover[a]	1[1.00,1.00]
Shrub cover	1.13***[1.10,1.17]
Herbaceous cover	1.53***[1.47,1.59]
Cultivated & managed areas	3.14***[3.08,3.20]
Bare land	1.45***[1.38,1.51]
Water bodies	0.65***[0.60,0.71]
Soil	
Forest and mountain[a]	1[1.00,1.00]
Alluvial	3.11***[2.82,3.44]
Black	1.06***[1.01,1.10]
Red and yellow	1.14***[1.10,1.17]
Laterite	1.46***[1.39,1.52]
Arid	5.25***[4.92,5.60]
Geology	
Quaternary sediments & rocks[a]	1[1.00,1.00]
Tertiary sedimentary & igneous rocks	0.46***[0.45,0.48]
Mesozoic rocks	1.64***[1.44,1.86]
Paleozoic rocks	0.80***[0.75,0.85]
Carboniferous & ordovician rocks	1.30***[1.26,1.33]
Industrial areas	
No[a]	1[1.00,1.00]
Yes	1.71***[1.67,1.75]

[a] Reference Category.
*** Significant at 1 %.
** Significant at 5 %.
* Significant at 10 %.

likely to lead to stunting, underweight, and wasting compared to temperatures ≤15 °C. Areas with rainfall levels between 100 and 200 cm are 4 %, 8 %, and 2 % less likely to result in stunting, underweight, and wasting than areas with rainfall ≤100 cm. Similarly, areas with elevations between 300 and 1000 m are 9 %, 4 %, and 7 % less likely to result in stunting, underweight, and wasting, while areas with elevations between 1000 and 2000 m are 5 %, 6 % and 13 % more likely compared to areas with elevations ≤300 m. Children residing near water bodies are less likely to experience undernutrition, while those near cultivated and managed areas or bare land are more likely to be affected than those in vegetation-covered areas. Additionally, children in arid and laterite soil areas are more likely to be affected, whereas those in alluvial and black soil areas are less likely to be affected than those in forest and mountain soil areas. Moreover, children in industrial belt areas are 2 %, 3 %, and 6 % more likely to experience stunting, underweight, and wasting compared to those in non-industrial areas. Children who drink groundwater are 3 %, 4 %, and 1 % more likely to be stunted, underweight, and wasted than those who drink piped water. Those without access to improved toilet facilities are 10 %, 9 % and 3 % more likely to be stunted, underweight, and wasted than those with access to such facilities. Female children are 8 %, 5 %, and 9 % less likely to be stunted, underweight, and wasted than male children. As wealth status increases, the likelihood of being stunted, underweight, and wasted decreases. Children who consume dairy products, vegetables, and fruits daily are less likely to be stunted, underweight, and wasted than those who never consume these foods. Children in rural areas are 29 %, 31 %, and 9 % more likely to be stunted, underweight, and wasted than those in urban areas. In the Western region, children are 46 %, 92 %, and 82 % more likely to be stunted, underweight, and wasted; in the Central region, 14 %, 19 %, and 15 %; in the Eastern region, 11 %, 32 %, and 38 %; in the Northeast region, 4 %, 9 %, and 33 %; and in the Southern region, 24 %, 32 %, and 8 % more likely to be stunted, underweight, and wasted respectively, compared to children in the Northern region.

Through the use of hotspot mapping in Appendix 2 (a-c), it becomes clear that areas with high prevalence of nutritional deficits among children overlap with regions with unfit groundwater for consumption. The study has revealed that most areas of Western, Eastern, Northeastern, South-eastern, and South-central India exhibit poor groundwater quality, which is strongly associated with the high prevalence of stunting, underweight, and wasting among children in these regions. The hotspot mapping analysis has played a crucial role in visualizing this correlation, making it easier to identify the areas most affected by the issue of child undernutrition.

3.5. Heterogeneity in groundwater quality impacts

Table 8 illustrates the combined impact of place of residence, mothers' education, wealth status, sources of drinking water, and groundwater quality on child undernutrition outcomes. The findings reveal significant disparities in the effects of poor groundwater quality across different subgroups. Children from rural areas, with mothers who have primary school education, belonging to poor households, consuming groundwater, and living in areas with poor groundwater quality have a 64 %, 61 %, and 49 % higher chance of stunting, underweight, and wasting compared to children from urban areas, with mothers who have primary school education, belonging to poor households, consuming piped water, and living in areas with excellent groundwater quality. In similar conditions but in urban areas and consuming piped water, children are found to be 36 %, 44 %, and 36 % more likely to experience stunting, underweight, and wasting, respectively, compared to children from urban areas with mothers who have primary school education, belonging to poor households, consuming piped water, and living in areas with excellent groundwater quality. Conversely, children from urban areas, with mothers who are highly educated, belong to rich households, consume piped water, and live in areas with excellent groundwater quality, are 88 %, 67 %, and 71 % less likely to experience stunting, underweight, and wasting compared to children from urban areas, with mothers who have primary school education, belonging to poor households, consuming piped water, and living in areas with excellent groundwater quality. In similar conditions but consuming groundwater, children are 67 %, 62 %, and 64 % less likely to experience stunting, underweight, and wasting compared to children from urban areas, with mothers who have primary school education, belonging to poor households, consuming piped water, and living in areas with excellent groundwater quality. In similar conditions

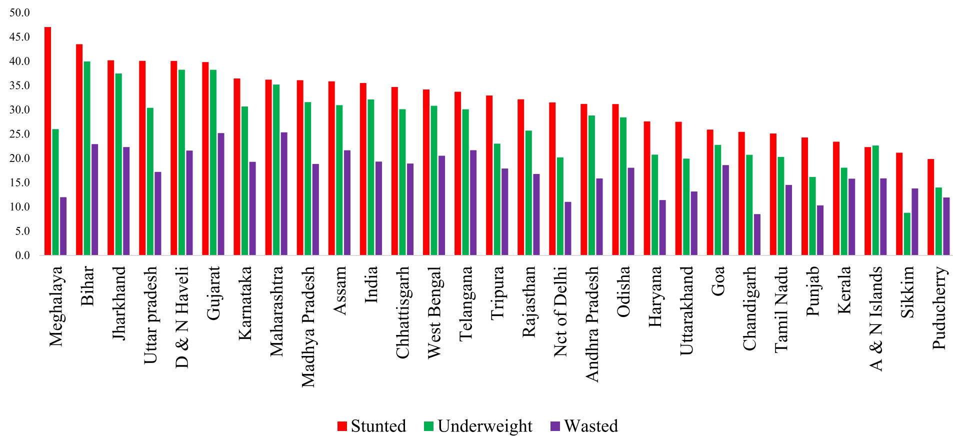

Fig. 5. Percentage distribution of stunting, underweight, and wasting children in Indian States and Union Territories.

but in rural areas and consuming piped water, children are 70 %, 63 %, and 69 % less likely, and in similar conditions but in rural areas and consuming groundwater, children are 63 %, 59 %, and 62 % less likely to experience stunting, underweight, and wasting compared to children from urban areas, with mothers who have primary school education, belonging to poor households, consuming piped water, and living in areas with excellent groundwater quality. Table 8 clarifies how the interplay of socio-economic factors along with groundwater significantly influences child stunting, wasting, and underweight. When children consume the same type of water, the probability of undernutrition is much higher among children from poor households with mothers who have primary education and belong to rural areas, compared to those from affluent families with highly educated mothers living in urban areas. Furthermore, children who drink piped water sources have a lower likelihood of undernutrition than those who consume groundwater. Nonetheless, wealth status, mother's education, and place of residence also play important roles, as children from affluent households, with highly educated mothers living in urban areas and drinking piped water, have a lower probability of undernutrition.

4. Discussion

Groundwater is a vital resource for several activities, including irrigation, domestic use, and industrial purposes. To our knowledge this is the first study revelling the spatial distribution of groundwater quality and highlighting the association between groundwater quality and child nutrition in India. The study highlights some important findings with relevant policy implications. Firstly, there is a significant variation in groundwater quality across different parts of India with many regions performing poorly. Secondly, higher temperatures and elevations, cultivated and managed land cover, and proximity to industrial areas are associated with poorer groundwater quality, while higher precipitation, water bodies, and certain geological formations are associated with better groundwater quality. Thirdly, there is significant association between groundwater quality, environmental factors, and child undernutrition. Specifically, children residing in areas with poor groundwater quality, including elevated pH levels (>8.5), high Mg levels (>30 mg/l), and elevated SO_4 levels (>200 mg/l), exhibit higher likelihoods of stunting, underweight, and wasting. Additionally, adverse environmental conditions such as higher temperatures (>25 °C), lower elevations (<300 m), and proximity to cultivated or industrial areas are also associated with increased risks of child undernutrition. Fourthly, the study underscores the crucial effect of wealth disparities in accessing clean water, leading to significant variations in child undernutrition, even in regions with poor groundwater quality.

The variation in groundwater quality observed in different regions of India can be attributed to geological and anthropogenic factors. The temperature variations (T) and rainfall (R) significantly influence the chemical dynamics within soil geology, ultimately impacting groundwater quality. The Clausius-Clapeyron equation elucidates how temperature changes affect precipitation patterns, potentially altering the rate of chemical reactions within the soil.

Clausius-Clapeyron equation: $\frac{\partial\, ln(R)}{\partial T} = \frac{L}{R \cdot T \cdot \beta}$

This equation describes how temperature (T) changes affect the rate of evaporation and, consequently, the amount of precipitation (R). L represents the latent heat of vaporization, R is the gas constant, and β is the Clausius-Clapeyron coefficient (Paraíba et al., 2003). A temperature rise can lead to increased evaporation and reduced rainfall, impacting groundwater reservoirs' recharge and affecting groundwater quality. In conjunction with soil type and composition, represented by equilibrium equations, this leads to the mobilization of contaminants (C) into groundwater. The chemical equilibrium between water and minerals in the soil. For example, dissolved minerals like carbonate minerals or sulfide ores can release ions into the groundwater. This process can be represented by equations such as:

$$CaCO_3\ (s) \rightleftharpoons Ca^{2+}\ (aq) + {CO_3}^{2-} (aq)$$

Where $CaCO_3$ represents calcium carbonate, and Ca^{2+} and CO_3^{2-} represent dissolved calcium and carbonate ions, respectively. This equation illustrates how mineral dissolution contributes to the chemical composition of groundwater (Sand et al., 2016; Zachara et al., 2020). Moreover, the presence of specific geological formations like Mesozoic and Carboniferous & Ordovician rocks (G) can further exacerbate chemical interactions, as illustrated by reaction kinetics.

$\text{rate} = k[A][B]$

This equation describes the rate of a chemical reaction between species A and B, where *k* is the rate constant, and [A] and [B] represent the concentrations of the reactants. In groundwater contamination, this equation can be applied to reactions involving contaminants and minerals in the soil (Wilkin and DiGiulio, 2010; Zhang et al., 2007). For instance, the oxidation of sulfide minerals can lead to the release of sulfate ions into groundwater, contributing to contamination. Introducing contaminants from anthropogenic sources, including industrial activities and agricultural practices in cultivated and managed areas, further compounds the issue, highlighting the interconnected nature of environmental and human-induced factors in groundwater quality degradation. Previous studies (Das et al., 2003; Ji et al., 2020; Nizam et al., 2022) have shown that geological composition, environmental processes, and human activities, such as industrialization, agriculture, and urbanization, play crucial roles in contaminating and depleting groundwater resources. For instance, regions like Rajasthan with diverse rock types and limited recharge due to arid climate exhibit poor groundwater quality, while areas with appropriate geological conditions

Table 6
Percentage distribution of stunting, underweight, and wasting children by background characteristics.

Background characteristics	Stunted (%)	Not stunted (%)	p	Underweight (%)	Not underweight (%)	p	Wasted (%)	Not wasted (%)	p
	(*n* = 65,211)	(*n* = 112,295)		(*n* = 54,605)	(*n* = 122,901)		(*n* = 33,738)	(*n* = 143,768)	
Groundwater quality									
Excellent	29.95	70.05	0.000	25.25	74.75	0.000	16.20	83.80	0.000
Good	32.68	67.32		28.79	71.21		17.38	82.62	
Poor	34.83	65.17		32.07	67.93		20.06	79.94	
Very poor	36.71	63.29		34.80	65.20		20.59	79.41	
Unfit for consumption	37.61	62.39		35.48	64.52		20.74	79.26	
Sources of drinking water									
Piped water	33.73	66.27	0.000	28.68	71.32	0.000	18.81	81.19	0.000
Groundwater	39.72	60.28		33.79	66.21		19.61	80.39	
Other sources of water	32.42	67.58		28.43	71.57		19.08	80.92	
Toilet facilities									
Improved	33.12	66.88	0.000	27.87	72.13	0.000	18.38	81.62	0.000
Unimproved	43.20	56.80		38.02	61.98		21.22	78.78	
Sex									
Male	36.86	63.14	0.000	31.31	68.69	0.000	19.96	80.04	0.000
Female	35.17	64.83		30.29	69.71		18.41	81.59	
Mothers' education									
No education	47.22	52.78	0.000	40.90	59.10	0.000	21.60	78.40	0.000
Primary	42.40	57.60		35.96	64.04		19.95	80.05	
Secondary	33.83	66.17		28.96	71.04		18.82	81.18	
Higher	23.02	76.98		19.09	80.91		16.65	83.35	
Wealth index									
Poorest	46.27	53.73	0.000	41.12	58.88	0.000	22.40	77.60	0.000
Poorer	39.78	60.22		34.20	65.80		20.09	79.91	
Middle	35.21	64.79		29.73	70.27		18.61	81.39	
Richer	30.89	69.11		25.71	74.29		18.05	81.95	
Richest	23.72	76.28		19.05	80.95		15.60	84.40	
Consume dairy products									
Never	40.80	59.20	0.000	36.13	63.87	0.000	20.59	79.41	0.000
Daily	32.66	67.34		27.01	72.99		17.90	82.10	
Weekly	37.57	62.43		32.92	67.08		20.31	79.69	
Occasionally	40.19	59.81		35.06	64.94		20.42	79.58	
Consume pulses/beans									
Never	38.82	61.18	0.000	30.30	69.70	0.000	19.09	80.91	0.000
Daily	35.70	64.30		30.51	69.49		17.52	82.48	
Weekly	36.29	63.71		30.94	69.06		19.11	80.89	
Occasionally	36.93	63.07		32.22	67.78		20.94	79.06	
Consume vegetables									
Never	62.77	37.23	0.000	30.59	69.41	0.000	20.48	79.52	0.000
Daily	64.39	35.61		29.98	70.02		18.93	81.07	
Weekly	63.75	36.25		30.72	69.28		19.31	80.69	
Occasionally	63.48	36.52		32.21	67.79		20.48	79.52	
Consume fruits									
Never	41.21	58.79	0.000	37.39	62.61	0.000	23.25	76.75	0.000
Daily	28.10	71.90		22.85	77.15		16.69	83.31	
Weekly	33.75	66.25		28.59	71.41		18.70	81.30	
Occasionally	39.22	60.78		33.89	66.11		20.00	80.00	
Consume eggs									
Never	33.61	66.39	0.000	27.38	72.62	0.000	17.00	83.00	0.000
Daily	32.48	67.52		27.28	72.72		17.62	82.38	
Weekly	35.35	64.65		30.67	69.33		19.80	80.20	
Occasionally	39.82	60.18		34.70	65.30		20.67	79.33	
Consume meat									
Never	33.53	66.47	0.000	27.37	72.63	0.000	16.96	83.04	0.000
Daily	36.92	63.08		29.96	70.04		17.13	82.87	

(*continued on next page*)

Table 6 (*continued*)

Background characteristics	Stunted (%)	Not stunted (%)	p	Underweight (%)	Not underweight (%)	p	Wasted (%)	Not wasted (%)	p
	(n = 65,211)	(n = 112,295)		(n = 54,605)	(n = 122,901)		(n = 33,738)	(n = 143,768)	
Weekly	35.13	64.87		30.60	69.40		19.98	80.02	
Occasionally	39.02	60.98		33.94	66.06		20.43	79.57	
Place of residence									
Urban	30.57	69.43	0.000	25.79	74.21	0.000	18.47	81.53	0.000
Rural	37.97	62.03		32.59	67.41		19.47	80.53	
Geographic region									
North	29.91	70.09	0.000	22.64	77.36	0.000	14.17	85.83	0.000
Central	38.78	61.22		30.62	69.38		17.67	82.33	
East	39.08	60.92		35.78	64.22		21.60	78.40	
Northeast	36.88	63.12		29.51	70.49		20.08	79.92	
West	37.39	62.61		36.16	63.84		25.21	74.79	
South	30.00	70.00		25.50	74.50		17.01	82.99	
India	35.50	64.50		32.10	67.90		19.03	80.97	

and better recharge, such as Madhya Pradesh and Chhattisgarh, maintain good groundwater quality. Effective management and conservation strategies are necessary to address the issue of poor groundwater quality in the West, East, Northeast, and South-central regions of India. These strategies should include the implementation of sustainable agricultural practices, the promotion of efficient water use, the development of appropriate waste management systems, and the enforcement of regulations to control industrial pollution. Furthermore, public awareness campaigns should be conducted to educate people about the importance of groundwater and the consequences of over-exploitation and contamination.

The study found a significant relationship between water quality and child undernutrition, indicating that poor groundwater quality is associated with increased odds of stunting, underweight, and wasting in children. Furthermore, the odds of child undernutrition further escalate with the introduction of environmental factors alongside groundwater quality. Poor groundwater quality, characterized by high levels of contaminants like As, NO_3^-, SO_4^{2-}, Mg, TDS and other heavy metals, can directly or indirectly affect children's health through drinking water, irrigation, and food chain pathways. High concentrations of such contaminants have been linked to adverse health outcomes, including stunting, underweight, and wasting, as they can interfere with nutrient absorption and disrupt metabolic processes in growing children. Socioeconomic and dietary habits play a significant role in reducing child undernutrition in India. According to the Groundwater Management and Regulation report, GOI 2021, groundwater extraction in India has increased from 58 % in 2004 to 63 % in 2017 (The Comptroller and Auditor General of India, 2021). In India, millions of people staying in rural and peri urban areas with low-income are most vulnerable to waterborne diseases. Previous outbreaks of waterborne diseases in India revealed that 70 %–80 % were due to contaminated wells (Schmoll, 2006). The School of Environmental Studies (SOES), Jadavpur University, 2004 identified arsenic-affected zones to restrict groundwater drinking as arsenic is an important contaminant for public health and concern (Chakraborti et al., 2018). As the low socioeconomic status and malnourishment are highly correlated poor people have no other option but to drink arsenic-contaminated water and experience poor health effects (Acharyya et al., 2015). In order to reduce the effect of arsenic toxicity, SOES research has suggested that better nutrition may help people specially in the Ganga River Basin (Chakraborti et al., 2004). Epidemiological studies have demonstrated that deficiency of beta-carotene, methionine, zinc and selenium increases the risk of arsenical skin lesions. Intake of food rich in vitamins, protein, antioxidants help in arsenic detoxification (Hsueh et al., 1997; Roychowdhury et al., 2003; Sharma and Flora, 2018). Several other human studies demonstrated the significant role of nutritional alleviation in combating arsenic-caused skin lesions, skin cancer and cardiovascular diseases (Bjørklund et al., 2022; Sharma and Flora, 2018). Over time, the Indian government implemented programs like promoting and ensuring access to nutritious food in combating arsenic toxicity and other stringent methods to ensure that people have safe drinking water. Our study found a concerning prevalence of stunting and underweight children in several Indian states, namely Meghalaya, Bihar, Jharkhand, Uttar Pradesh, Assam, Madhya Pradesh, Chhattisgarh, West Bengal, Telangana, Odisha, and Tripura. Of note, groundwater quality was found to be poor to unfit for consumption in most of the areas of these states. This coexistence of poor groundwater quality and a high prevalence of stunted, underweight and wasted children in these states strongly suggests that groundwater is a significant risk factor for these health issues. Although the groundwater quality in Madhya Pradesh and Chhattisgarh is comparatively better, most individuals in these states still rely on non-piped water sources. This could be due to a combination of factors such as high poverty levels, limited access to healthcare facilities, poor sanitation and hygiene practices, and cultural norms that promote early marriage and early weaning of infants, all of which can contribute to stunting and underweight (Dasgupta et al., 2016; Karlsson et al., 2021; Kohli et al., 2020). A study by Yujie and colleague aligns with our finding that children face almost twice higher the carcinogenic risks than the adults (Ji et al., 2020).

Finally, the study underscores the crucial effect of wealth disparities in accessing clean water, leading to significant variations in child undernutrition, even in regions with poor groundwater quality. It highlights the diverse impact of groundwater quality on child nutrition outcomes, emphasizing substantial disparities across different socioeconomic backgrounds. Specifically, when considering the combined effects of place of residence, mothers' education, wealth status, sources of drinking water, and groundwater quality, it is evident that children from poor rural households with less educated mothers, economically disadvantaged families who consume poor-quality groundwater face significantly higher risks of being stunting, underweight and wasting compared to their peers with the same background but have access to good-quality piped water. Conversely, a noteworthy contrast emerges among children from the wealthiest families who consume poor-quality groundwater, as they exhibit significantly lower risks of stunting, underweight, and wasting compared to those from the poorest families who consume good-quality piped water. This suggests that wealthier families have greater access to water purification facilities, allowing them to mitigate the negative effects of poor groundwater quality on child nutrition outcomes. Furthermore, the analysis demonstrates a decreasing likelihood of stunting, underweight, and wasting among children from the poorest to the richest wealth families when consuming the same type of water. This finding underscores the role of wealth difference in accessing clean and safe drinking water. Despite utilizing the same water source, wealthier families can effectively protect their

Table 7
The results of the logistic regression model represent in odds ratio estimates the association between groundwater quality, environmental factors and socio-demographic determinants with child undernutrition in India.

Background characteristics	Stunting			Underweight			Wasting		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Groundwater quality									
Excellent[a]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]
Good	1.14***[1.09,1.20]		1.19***[1.10,1.29]	1.17***[1.08,1.23]		1.10***[1.07,1.16]	1.07***[1.05,1.21]		1.05***[1.04,1.06]
Poor	1.26***[1.18,1.32]		1.22***[1.12,1.32]	1.25***[1.19,1.31]		1.24***[1.20,1.26]	1.13***[1.07,1.18]		1.08***[1.06,1.09]
Very poor	1.30***[1.24,1.36]		1.25***[1.15,1.36]	1.29***[1.22,1.34]		1.30***[1.27,1.36]	1.14*[1.07,1.18]		1.09*[1.07,1.10]
Unfit for consumption	1.33***[1.25,1.37]		1.35***[1.22,1.46]	1.31***[1.23,1.36]		1.38***[1.34,1.42]	1.16*[1.10,1.21]		1.11*[1.09,1.12]
pH									
≤6.5[a]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]
6.5–8.5		0.86**[0.84,0.90]	0.83**[0.78,0.90]		0.95*[0.92,0.99]	0.96*[0.93,0.99]		0.97*[0.95,0.99]	0.92*[0.85,0.95]
>8.5		1.10** [1.08,1.13]	1.16**[1.04,1.28]		1.03*[1.01,1.07]	1.02*[1.01,1.04]		1.03*[1.02,1.03]	1.04*[1.02,1.06]
Calcium (Ca)									
≤75 mg/l[a]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]
>75 mg/l		0.99[0.98,1.00]	0.99[0.98,1.00]		1[0.99,1.01]	1[1.00,1.01]		1[0.99,1.00]	1[0.99,1.00]
Magnesium (Mg)									
≤30 mg/l[a]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]
>30 mg/l		1.02***[1.01,1.03]	1.03***[1.01,1.06]		1.02*[1.00,1.04]	1.01*[1.01,1.02]		1.01*[1.00,1.01]	1.01*[1.00,1.01]
Sulphate (SO_4)									
≤200 mg/l[a]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]
>200 mg/l		1.02**[1.00,1.03]	1.04***[1.02,1.06]		1.01**[1.00,1.02]	1.01**[1.00,1.02]		1[0.99,1.00]	0.99[0.97,1.00]
Chloride (Cl^-)									
≤250 mg/l[a]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]
>250 mg/l		0.99[0.98,1.00]	0.99[0.98,1.00]		0.99[0.98,1.00]	0.98[0.97,0.99]		0.99[0.98,1.00]	0.99[0.98,1.00]
Nitrate (NO_3^-)									
≤45 mg/l[a]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]
>45 mg/l		1.01[1.00,1.04]	1.01[0.99,1.02]		1.01**[1.00,1.02]	1.02**[1.01,1.03]		1.01**[1.00,1.01]	1.01*[1.00,1.01]
Total dissolved solids (TDS)									
≤500 mg/l[a]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]
>500 mg/l		1.03*[1.02,1.06]	1.01*[1.00,1.02]		1.03**[1.01,1.04]	1.01**[1.00,1.02]		1.02***[1.01,1.02]	1.01**[1.00,1.01]
Arsenic (As)									
≤0.01 mg/l[a]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]		1[1.00,1.00]	1[1.00,1.00]
>0.01 mg/l		1.04**[1.02,1.06]	1.06**[1.02,1.10]		1.05**[1.03,1.07]	1.06***[1.04,1.08]		1.02**[1.01,1.04]	1.04***[1.02,1.06]
Maximum temperature									
≤15 °C[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
15–20 °C			0.99*[0.98,1.00]			0.95*[0.93,0.98]			0.98*[0.96,0.99]
20–25 °C			1.03*[1.02,1.05]			1.01*[1.00,1.04]			1.04*[1.01,1.08]
>25 °C			1.07*[1.04,1.10]			1.04*[1.02,1.06]			1.13**[1.09,1.18]
Minimum temperature									

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Table 7 (*continued*)

Background characteristics	Stunting			Underweight			Wasting		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
≤15 °C[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
15–20 °C			0.98*[0.98,0.99]			0.99*[0.98,1.02]			0.98*[0.96,0.98]
20–25 °C			1.01*[1.00,1.02]			1.02*[1.01,1.04]			1.02*[1.01,1.03]
>25 °C			1.03*[1.02,1.04]			1.05*[1.02,1.07]			1.04*[1.02,1.06]
Rainfall									
≤100 cm[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
100–200 cm			0.96***[0.92,0.98]			0.92***[0.90,0.94]			0.98*[0.95,1.01]
>200 cm			0.95[0.93,0.98]			0.85***[0.80,0.91]			0.89**[0.86,0.92]
Elevation									
≤300 m[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
300–1000 m			0.91***[0.89,0.93]			0.96*[0.92,0.98]			0.93*[0.89,0.94]
1000–2000 m			1.05*[1.02,1.09]			1.06*[1.04,1.10]			1.13***[1.09,1.17]
>2000 m			1.06[1.01,1.10]			1.09*[1.05,1.13]			1.17*[1.12,1.24]
Landcover & landuse									
Vegetation cover[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Shrub cover			1.04[0.98,1.10]			1.02[1.00,1.06]			1.02[1.00,1.05]
Herbaceous cover			1.03[0.92,1.17]			1.01[0.98,1.07]			1.03[0.97,1.14]
Cultivated & managed areas			1.03*[1.02,1.05]			1.01*[1.98,1.04]			1.03*[1.03,1.08]
Bare land			1.07*[1.02,1.13]			1.06*[1.03,1.09]			1.06**[1.02,1.11]
Water bodies			0.97*[0.88,1.06]			0.96*[0.95,0.98]			0.95*[0.91,1.00]
Soil									
Forest and mountain[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Alluvial			0.97*[0.95,0.98]			0.98*[0.96,0.99]			0.95*[0.89,0.99]
Black			0.96*[0.95,0.97]			0.96*[0.94,0.98]			0.92*[0.86,0.97]
Red and Yellow			1.01 [0.95,1.06]			0.99 [0.96,1.02]			0.99 [0.87,1.05]
Laterite			1.02**[1.01,1.04]			1.01*[1.00,1.03]			1.03*[0.98,1.09]
Arid			1.11**[1.09,1.13]			1.08*[1.05,1.14]			1.07*[1.02,1.12]
Industrial areas									
No[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Yes			1.02*[1.01,1.03]			1.03*[1.01,1.05]			1.06***[1.03,1.10]
Sources of drinking water									
Piped water[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Groundwater			1.03***1.02,1.06]			1.04**[1.01,1.08]			1.01**[1.00,1.01]
Other sources of water			0.98***[0.97,0.99]			0.94***[0.91,0.97]			1[0.99,1.01]
Toilet facilities									
Improved[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Unimproved			1.10***[1.07,1.13]			1.09***[1.06,1.12]			1.03*[1.00,1.06]
Sex									
Male[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Female			0.92***[0.90,0.94]			0.95***[0.93,0.97]			0.91***[0.89,0.93]

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Table 7 (*continued*)

Background characteristics	Stunting			Underweight			Wasting		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Mothers' education									
No education[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Primary			0.91***[0.88,0.94]			0.88***[0.85,0.92]			0.94**[0.90,0.98]
Secondary			0.73***[0.71,0.75]			0.74***[0.72,0.76]			0.91***[0.88,0.93]
Higher			0.54***[0.52,0.57]			0.57***[0.55,0.60]			0.90***[0.86,0.94]
Wealth index									
Poorest[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Poorer			0.84***[0.81,0.86]			0.82***[0.79,0.84]			0.91***[0.87,0.94]
Middle			0.73***[0.71,0.76]			0.71***[0.69,0.74]			0.85***[0.82,0.89]
Richer			0.65***[0.62,0.67]			0.63***[0.60,0.65]			0.85***[0.82,0.89]
Richest			0.50***[0.48,0.52]			0.48***[0.46,0.51]			0.77***[0.73,0.81]
Consume dairy products									
Never[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Daily			0.96***[0.93,0.98]			0.97***[0.96,0.98]			0.98*[0.97,0.99]
Weekly			0.97***[0.96,0.99]			0.99[0.98,1.00]			0.99**[0.98,1.00]
Occasionally			0.98***[0.97,1.01]			0.99[0.98,1.00]			1.01[1.00,1.01]
Consume pulses/beans									
Never			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Daily			1.01[0.97,1.05]			0.99[0.98,1.01]			0.99[0.99,1.01]
Weekly			1.02[0.97,1.06]			1.02[1.00,1.06]			1.02[0.99,1.04]
Occasionally			1.02[0.97,1.06]			1.02[0.99,1.06]			1.02[0.99,1.05]
Consume vegetables									
Never[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Daily			0.92*[0.86,0.98]			0.96*[0.94,0.99]			0.98*[0.93,1.03]
Weekly			0.98[0.92,1.04]			0.97[0.95,1.02]			0.99[0.94,1.04]
Occasionally			0.99[0.92,1.05]			0.98[0.96,1.03]			0.99[0.94,1.04]
Consume fruits									
Never[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Daily			0.96**[0.92,0.99]			0.97*[0.96,0.98]			0.97**[0.96,0.99]
Weekly			0.98**[0.97,1.00]			0.99[0.98,1.01]			0.98*[0.96,1.00]
Occasionally			1.01[0.99,1.03]			1[0.98,1.02]			0.98*[0.97,1.00]
Consume eggs									
Never[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Daily			0.99[0.97,1.02]			0.98*[0.97,0.99]			0.99[0.99,1.00]
Weekly			1.01[1.00,1.02]			1.01[1.00,1.02]			1.01[1.00,1.02]
Occasionally			1.02[1.01,1.03]			1.02[1.01,1.03]			1.01[1.00,1.02]
Consume meat									
Never[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Daily			1.02[1.00,1.04]			1[0.98,1.02]			1[0.98,1.02]
Weekly			1.01[1.00,1.02]			1.01[1.00,1.02]			1.01[1.00,1.02]
Occasionally			1.01[1.00,1.02]			1.01[1.00,1.02]			1.01[1.00,1.02]

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Table 7 (*continued*)

Background characteristics	Stunting			Underweight			Wasting		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Place of residence									
Urban[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Rural			1.29***[1.25,1.33]			1.31***[1.27,1.35]			1.09***[1.05,1.13]
Geographic region									
North[a]			1[1.00,1.00]			1[1.00,1.00]			1[1.00,1.00]
Central			1.24***[1.18,1.29]			1.19***[1.14,1.25]			1.15***[1.08,1.21]
East			1.11***[1.05,1.16]			1.32***[1.25,1.39]			1.38***[1.30,1.47]
Northeast			1.04*[0.96,1.12]			1.09*[1.01,1.19]			1.33***[1.21,1.47]
West			1.46***[1.38,1.53]			1.92***[1.82,2.03]			1.82***[1.71,1.94]
South			1.24***[1.17,1.30]			1.32***[1.24,1.39]			1.08*[1.01,1.15]

[a] Reference Category.
*** Significant at 1 %.
** Significant at 5 %.
* Significant at 10 %.

children from the adverse impacts of poor groundwater quality through better water purification facilities. In contrast, children from poorer families, who lack such resources, face a higher risk of experiencing nutrition-related issues due to inadequate water quality (Dasgupta et al., 2016; Karlsson et al., 2021; Kohli et al., 2020). Region-specific strategies, integrated water management, awareness campaigns, and targeted nutrition programs are essential to address these issues. Collaboration across sectors is vital for comprehensive solutions that enhance child health and equitable access to safe drinking water in areas with poor groundwater quality. Previous research from Sub-Saharan Africa has identified links between child mortality and a lack of access to quality drinking water (Fotso et al., 2007). Since 2015, Sustainable Development Goals (SDGs 6.1)- "to achieve universal and equitable access to safe and affordable drinking water for all" have been one of the highlights. In India, accessibility and affordability of clean water are far from the achievement. A study conducted across Chennai city has revealed that the affordability of clean piped water is 15 % higher for low-income households (Amit and Sasidharan, 2019). Another study has found that 49 % of the districts in India face social inequality (SC/ST) in accessing improved drinking water in India (Ghosh et al., 2023). This lack of access to safe drinking water exacerbates health issues, particularly for marginalized communities. Contaminated water sources increase the risk of waterborne diseases, such as diarrhea and cholera, which may aggravate child malnutrition among the most vulnerable populations. These findings outline an urgent need for policy intervention to meet the SDG 6.1 target by ensuring clean water accessibility and combatting child undernutrition.

5. Limitation of the study

The current study had some limitations, and thus, it is necessary to exercise caution while interpreting the findings. The cross-sectional design of the NFHS-5 introduces several challenges. NFHS-5, being a sample survey, does not provide data for the entire population; it surveyed 636,669 households. Furthermore, the survey primarily focuses on socio-demographic data, and due to confidentiality measures, the latitude and longitude information provided is within a 5 km radius, potentially leading to inaccuracies when merging with environmental data. The cluster points did not accurately locate the Primary Sampling Units (PSU). Additionally, groundwater data is only available for some states in India, further complicating our analysis. The environmental data used in our study, obtained from different sources, may introduce inconsistencies and uncertainties. Moreover, considering the validity of the information on the outcome variable, we could not validate externally; however, trends were found in various rounds of the NFHS surveys, ensuring consistency. Owing to the cross-sectional data, causal inference was not possible, and a cohort study would be appropriate for validating our results.

6. Conclusion

The research is the first of its kind that shed light on the critical issue of groundwater quality and its potential impact on child undernutrition in India. The study reveals a substantial spatial variation in groundwater quality across different regions, with many areas performing poorly in water quality. This variation can be attributed to geological factors, weathering processes, and human activities such as industrialization and agriculture. Additionally, the study establishes a clear and marked relationship between water quality and child nutrition, highlighting the higher risks of stunting, underweight, and wasting faced by children in areas with poor groundwater quality. Contaminants like As, NO_3^-, SO_4, Mg, TDS and other heavy metals present in the groundwater can directly or indirectly impact children's health through various pathways. Moreover, the research emphasizes the role of wealth disparities in accessing clean water, leading to distinct variations in child undernutrition outcomes between wealthy and poorer households, even in areas

Table 8
The combined effects of place of residence, mothers' education, wealth status, sources of drinking water, and groundwater quality on child undernutrition outcomes.

Place of residence, mothers' education, wealth status, sources of drinking water, and groundwater quality interaction with child undernutrition

Place of residence	Mothers' education	Wealth status	Sources of drinking water	Groundwater quality	Stunting	Underweight	Wasting
Urban	Primary	Poor	Piped water	Excellent[a]	1[1.00,1.00]	1[1.00,1.00]	1[1.00,1.00]
Urban	Primary	Poor	Piped water	Good	1.17**[1.08,1.21]	1.26**[1.18,1.28]	1.18*[1.12,1.24]
Urban	Primary	Poor	Piped water	Poor	1.36**[1.29,1.41]	1.44*[1.40,1.48]	1.36*[1.32,1.43]
Urban	Primary	Poor	Groundwater	Excellent	1.13*[1.08,1.17]	1.12*[1.07,1.15]	1.09*[1.06,1.14]
Urban	Primary	Poor	Groundwater	Good	1.38**[1.32,1.45]	1.43**[1.38,1.46]	1.19*[1.13,1.23]
Urban	Primary	Poor	Groundwater	Poor	1.53**[0.70,3.32]	1.55**[1.52,1.59]	1.46*[1.40,1.50]
Urban	Primary	Middle	Piped water	Excellent	0.96*[0.92,1.04]	0.96**[0.92,1.00]	0.82**[0.78, 0.86]
Urban	Primary	Middle	Piped water	Good	1.09*[1.02,1.15]	1.09**[1.06,1.12]	1.02**[0.98,1.06]
Urban	Primary	Middle	Piped water	Poor	1.14**[1.10,1.18]	1.14*[1.11,1.20]	1.03**[0.97,1.06]
Urban	Primary	Middle	Groundwater	Excellent	1.08*[1.02,1.14]	0.99[0.92,1.05]	0.85*[0.81,0.91]
Urban	Primary	Middle	Groundwater	Good	1.13*[1.05,1.19]	1.11**[1.08,1.14]	1.04**[0.99,1.07]
Urban	Primary	Middle	Groundwater	Poor	1.18**[1.12,1.23]	1.17***[1.11,1.20]	1.05***[1.01,1.10]
Urban	Primary	Rich	Piped water	Excellent	0.69*[0.62,0.76]	0.42**[0.38,0.46]	0.43**[0.39,0.46]
Urban	Primary	Rich	Piped water	Good	0.73**[0.70,0.77]	0.74**[0.71,0.76]	0.64**[0.59,0.66]
Urban	Primary	Rich	Piped water	Poor	0.79*[0.74,0.82]	0.89*[0.85,0.93]	0.78***[0.75,0.80]
Urban	Primary	Rich	Groundwater	Excellent	0.74[0.67,0.80]	0.46**[0.42,0.48]	0.47*[0.43,0.50]
Urban	Primary	Rich	Groundwater	Good	0.75*[0.71,0.79]	0.75*[0.73,0.79]	0.67**[0.63,0.70]
Urban	Primary	Rich	Groundwater	Poor	0.87*[0.84,0.92]	0.91*[0.86,0.95]	0.81*[0.76,0.85]
Urban	Secondary	Poor	Piped water	Excellent	0.74*[0.71,0.81]	1.07*[1.04,1.11]	1.06**[1.01,1.09]
Urban	Secondary	Poor	Piped water	Good	0.78*[0.73,0.86]	1.31*[1.29,1.37]	1.12[1.10,1.21]
Urban	Secondary	Poor	Piped water	Poor	0.87**[0.82,0.93]	1.37**[1.33,1.42]	1.31**[1.27,1.34]
Urban	Secondary	Poor	Groundwater	Excellent	0.76*[0.72,0.81]	1.11*[1.03,1.15]	1.08**[1.03,1.12]
Urban	Secondary	Poor	Groundwater	Good	0.82[0.76,0.90]	1.35*[1.31,1.40]	1.14*[1.10,1.17]
Urban	Secondary	Poor	Groundwater	Poor	0.96*[0.90,1.01]	1.45*[1.34,1.49]	1.34**[1.30,1.39]
Urban	Secondary	Middle	Piped water	Excellent	0.73*[0.70,0.78]	0.94*[0.90,1.01]	0.84[0.80,0.91]
Urban	Secondary	Middle	Piped water	Good	0.74*[0.71,0.79]	1.06*[1.02,1.11]	1.01***[0.97,1.03]
Urban	Secondary	Middle	Piped water	Poor	0.84**[0.76,0.88]	1.09**[1.06,1.14]	1.03**[0.98,1.04]
Urban	Secondary	Middle	Groundwater	Excellent	0.75*[0.71,0.79]	0.97*[0.93,1.02]	0.87**[0.83,0.90]
Urban	Secondary	Middle	Groundwater	Good	0.80[0.72,0.90]	1.07*[1.03,1.11]	1.02*[0.99,1.08]
Urban	Secondary	Middle	Groundwater	Poor	0.93[0.86,0.97]	1.14**[1.10,1.17]	1.04***[0.99,1.05]
Urban	Secondary	Rich	Piped water	Excellent	0.44**[0.42,0.46]	0.36**[0.32,0.41]	0.38**[0.35,0.42]
Urban	Secondary	Rich	Piped water	Good	0.54*[0.51,0.57]	0.70*[0.67,0.75]	0.56**[0.51,0.59]
Urban	Secondary	Rich	Piped water	Poor	0.60*[0.57,0.65]	0.82*[0.77,0.85]	0.73**[0.70,0.78]
Urban	Secondary	Rich	Groundwater	Excellent	0.38**[0.34,0.43]	0.40**[0.36,0.45]	0.42**[0.38,0.47]
Urban	Secondary	Rich	Groundwater	Good	0.42*[0.36,0.47]	0.72*[0.68,0.77]	0.60***[0.58,0.62]
Urban	Secondary	Rich	Groundwater	Poor	0.57*[0.51,0.62]	0.87*[0.83,0.91]	0.76[0.73,0.81]
Urban	Higher	Poor	Piped water	Excellent	0.72*[0.64,0.78]	1.03***[1.01,1.06]	1.02*[0.97,1.08]
Urban	Higher	Poor	Piped water	Good	0.76**[0.73,0.80]	1.21**[1.18,1.26]	1.16***[1.14,1.18]
Urban	Higher	Poor	Piped Water	Poor	0.82*[0.78,0.84]	1.21**[1.17,1.26]	1.28*[1.24,1.32]
Urban	Higher	Poor	Groundwater	Excellent	0.74*[0.71,0.78]	1.06**[1.02,1.10]	1.04*[1.00,1.10]
Urban	Higher	Poor	Groundwater	Good	0.78[0.71,0.84]	1.23[1.18,1.30]	1.17[1.14,1.21]
Urban	Higher	Poor	Groundwater	Poor	0.88[0.84,0.98]	1.26**[1.22,1.31]	1.18*[1.12,1.24]
Urban	Higher	Middle	Piped water	Excellent	0.59*[0.52,0.68]	0.89**[0.85,0.92]	0.86**[0.82,0.90]
Urban	Higher	Middle	Piped water	Good	0.61**[0.63,0.68]	1.01[0.98,1.07]	0.98*[0.95,1.01]
Urban	Higher	Middle	Piped water	Poor	0.80**[0.74,0.86]	1.06*[1.02,1.10]	1.02*[0.99,1.06]
Urban	Higher	Middle	Groundwater	Excellent	0.69*[0.64,0.76]	0.91*[0.86,0.96]	0.88**[0.82,0.94]
Urban	Higher	Middle	Groundwater	Good	0.71*[0.68,0.77]	1.04[1.01,1.14]	1.01**[0.98,1.05]
Urban	Higher	Middle	Groundwater	Poor	0.81*[0.76,0.86]	1.11**[1.07,1.16]	1.04**[1.00,1.08]
Urban	Higher	Rich	Piped water	Excellent	0.22***[0.18,0.25]	0.33***[0.31,0.36]	0.29***[0.26,0.31]
Urban	Higher	Rich	Piped water	Good	0.38***[0.36,0.42]	0.65***[0.63,0.68]	0.49***[0.46,0.52]
Urban	Higher	Rich	Piped water	Poor	0.49***[0.44,0.52]	0.77***[0.74,0.81]	0.67*[0.61,0.72]
Urban	Higher	Rich	Groundwater	Excellent	0.33***[0.31,0.36]	0.38***[0.34,0.41]	0.36*[0.32,0.40]
Urban	Higher	Rich	Groundwater	Good	0.34**[0.30,0.40]	0.68**[0.65,0.71]	0.53***[0.49,0.54]
Urban	Higher	Rich	Groundwater	Poor	0.42***[0.35,0.43]	0.79***[0.75,0.81]	0.69*[0.65,0.76]
Rural	Primary	Poor	Piped water	Excellent	1.05*[1.01,1.10]	1.10**[1.06,1.16]	1.08**[1.04,1.16]
Rural	Primary	Poor	Piped water	Good	1.22*[1.08,1.28]	1.29*[1.24,1.34]	1.21***[1.18, 1.25]
Rural	Primary	Poor	Piped water	Poor	1.39**[1.32,1.46]	1.49*[1.43,1.53]	1.39*[1.32,1.44]
Rural	Primary	Poor	Groundwater	Excellent	1.18*[1.12,1.23]	1.16**[1.14,1.18]	1.11**[1.08,1.15]
Rural	Primary	Poor	Groundwater	Good	1.43*[1.37,1.50]	1.47**[1.44,1.50]	1.22***[1.18, 1.24]
Rural	Primary	Poor	Groundwater	Poor	1.64**[1.59,1.72]	1.61**[1.58,1.64]	1.49*[1.44,1.52]
Rural	Primary	Middle	Piped water	Excellent	0.74[0.67,0.78]	1.02*[0.98,1.07]	0.84**[0.80,0.86]
Rural	Primary	Middle	Piped water	Good	0.78*[0.74,0.85]	1.12**[1.08,1.14]	1.06**[1.01,1.09]
Rural	Primary	Middle	Piped water	Poor	0.89*[0.83,0.95]	1.18*[1.12,1.23]	1.08*[1.02,1.12]
Rural	Primary	Middle	Groundwater	Excellent	0.82[0.78,0.89]	1.06*[1.03,1.10]	0.90[0.82,0.96]
Rural	Primary	Middle	Groundwater	Good	0.86[0.77,0.94]	1.13**[1.09,1.15]	1.07*[1.01,1.11]
Rural	Primary	Middle	Groundwater	Poor	0.97*[0.94,0.99]	1.22***[1.20,1.25]	1.07***[1.03,1.12]
Rural	Primary	Rich	Piped water	Excellent	0.71*[0.66,0.76]	0.45**[0.43,0.49]	0.47*[0.43,0.51]
Rural	Primary	Rich	Piped water	Good	0.74*[0.69,0.79]	0.76*[0.71,0.81]	0.66*[0.61,0.71]
Rural	Primary	Rich	Piped water	Poor	0.80**[0.77,0.83]	0.92**[0.88,0.96]	0.80**[0.78,0.86]
Rural	Primary	Rich	Groundwater	Excellent	0.75*[0.70,0.81]	0.50**[0.47,0.52]	0.51*[0.46,0.54]
Rural	Primary	Rich	Groundwater	Good	0.76*[0.73,0.79]	0.78*[0.74,0.81]	0.68**[0.64,0.71]
Rural	Primary	Rich	Groundwater	Poor	0.92*[0.86,0.96]	0.94*[0.89,0.97]	0.84**[0.80,0.87]

(continued on next page)

Table 8 (*continued*)

Place of residence, mothers' education, wealth status, sources of drinking water, and groundwater quality interaction with child undernutrition

Place of residence	Mothers' education	Wealth status	Sources of drinking water	Groundwater quality	Stunting	Underweight	Wasting
Rural	Secondary	Poor	Piped water	Excellent	1.02*[0.96,1.10]	1.09[1.02,1.18]	1.10**[1.07,1.12]
Rural	Secondary	Poor	Piped water	Good	1.12*[1.06,1.17]	1.36*[1.32,1.39]	1.15*[1.11, 1.20]
Rural	Secondary	Poor	Piped water	Poor	1.19**[1.13,1.24]	1.43***[1.41,1.46]	1.35**[1.30,1.40]
Rural	Secondary	Poor	Groundwater	Excellent	1.11*[1.04,1.16]	1.14*[1.10,1.19]	1.11*[1.07,1.16]
Rural	Secondary	Poor	Groundwater	Good	1.16*[1.07,1.21]	1.39*[1.31,1.48]	1.16*[1.11, 1.18]
Rural	Secondary	Poor	Groundwater	Poor	1.21**[1.14,1.25]	1.47**[1.45,1.53]	1.36**[1.32,1.41]
Rural	Secondary	Middle	Piped water	Excellent	0.76*[0.72,0.85]	0.99[0.95,1.04]	0.89[0.83,0.99]
Rural	Secondary	Middle	Piped water	Good	0.82*[0.77,0.88]	1.10*[1.06,1.14]	1.03**[1.00,1.07]
Rural	Secondary	Middle	Piped water	Poor	0.91**[0.87,0.96]	1.16**[1.13,1.18]	1.06**[1.02,1.09]
Rural	Secondary	Middle	Groundwater	Excellent	0.81*[0.75,0.87]	1.02*[1.00,1.14]	0.91**[0.88,0.93]
Rural	Secondary	Middle	Groundwater	Good	0.88[0.83,0.97]	1.11*[1.07,1.15]	1.04*[1.01,1.09]
Rural	Secondary	Middle	Groundwater	Poor	0.99*[0.92,1.06]	1.17**[1.12,1.21]	1.07**[1.04,1.10]
Rural	Secondary	Rich	Piped water	Excellent	0.48***[0.45,0.52]	0.40***[0.38,0.43]	0.40*[0.37,0.44]
Rural	Secondary	Rich	Piped water	Good	0.57**[0.53,0.66]	0.74**[0.71,0.78]	0.58**[0.54,0.60]
Rural	Secondary	Rich	Piped water	Poor	0.64**[0.61,0.69]	0.84**[0.81,0.89]	0.74**[0.71,0.79]
Rural	Secondary	Rich	Groundwater	Excellent	0.43*[0.47,0.55]	0.46*[0.41,0.50]	0.46*[0.42,0.51]
Rural	Secondary	Rich	Groundwater	Good	0.48*[0.43,0.52]	0.75*[0.71,0.81]	0.65*[0.61,0.71]
Rural	Secondary	Rich	Groundwater	Poor	0.60**[0.55,0.64]	0.90**[0.85,0.94]	0.80*[0.77,0.85]
Rural	Higher	Poor	Piped water	Excellent	0.74*[0.71,0.84]	1.06**[1.02,1.10]	1.06**[1.01,1.10]
Rural	Higher	Poor	Piped water	Good	0.81*[0.78,0.97]	1.24*[1.21,1.30]	1.18**[1.15, 1.22]
Rural	Higher	Poor	Piped water	Poor	0.91**[0.86,0.97]	1.27**[1.24,1.31]	1.33**[1.28,1.38]
Rural	Higher	Poor	Groundwater	Excellent	0.78*[0.72,0.85]	1.08***[1.06,1.10]	1.07[1.03,1.13]
Rural	Higher	Poor	Groundwater	Good	0.84**[0.77,0.86]	1.29*[1.24,1.33]	1.21**[1.16, 1.26]
Rural	Higher	Poor	Groundwater	Poor	0.95[0.87,0.99]	1.31***[1.27,1.34]	1.23***[1.19, 1.26]
Rural	Higher	Middle	Piped water	Excellent	0.61*[0.57,0.68]	0.93**[0.88,0.98]	0.90**[0.86,0.95]
Rural	Higher	Middle	Piped water	Good	0.64***[0.62,0.68]	1.03*[1.00,1.09]	1.01*[0.97,1.05]
Rural	Higher	Middle	Piped water	Poor	0.82*[0.79,0.87]	1.10*[1.06,1.14]	1.04**[1.00,1.08]
Rural	Higher	Middle	Groundwater	Excellent	0.71**[0.68,0.75]	0.96*[0.92,1.01]	0.91**[0.86,0.94]
Rural	Higher	Middle	Groundwater	Good	0.75*[0.72,0.79]	1.08*[1.05,1.11]	1.03*[0.99,1.07]
Rural	Higher	Middle	Groundwater	Poor	0.85*[0.81,0.91]	1.13**[1.10,1.16]	1.06**[1.01,1.10]
Rural	Higher	Rich	Piped water	Excellent	0.30*[0.25,0.38]	0.37***[0.32,0.41]	0.31***[0.28,0.36]
Rural	Higher	Rich	Piped water	Good	0.43***[0.42,0.44]	0.68***[0.63,0.72]	0.51*[0.47,0.59]
Rural	Higher	Rich	Piped water	Poor	0.51***[0.48,0.54]	0.79***[0.76,0.83]	0.70**[0.67,0.73]
Rural	Higher	Rich	Groundwater	Excellent	0.37***[0.32,0.41]	0.41*[0.35,0.44]	0.38**[0.35,0.42]
Rural	Higher	Rich	Groundwater	Good	0.37***[0.36,0.40]	0.71***[0.68,0.73]	0.56***[0.53,0.59]
Rural	Higher	Rich	Groundwater	Poor	0.45***[0.41,0.49]	0.81***[0.78,0.86]	0.72**[0.68,0.76]

[a] Reference Category.
*** Significant at 1 %.
** Significant at 5 %.
* Significant at 10 %.

with poor groundwater quality. Wealthier household's capacity to purify water is a mitigating factor against the adverse effects of poor water quality on child health, underscoring the importance of equitable access to water purification resources for vulnerable populations. Based on these findings, it is evident that addressing the groundwater quality and child undernutrition issues in India necessitates targeted regional management strategies, integrated water resource practices, public awareness campaigns on water purification, and targeted nutrition interventions. Cross-sectoral collaborations are vital for developing comprehensive solutions to improve child health outcomes and promote equitable access to clean and safe drinking water in areas affected by poor groundwater quality. By understanding and addressing these complex issues, policymakers and stakeholders can work towards safeguarding child health and well-being, paving the way for a healthier and more resilient future for India's children.

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CRediT authorship contribution statement

Sourav Biswas: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Aparajita Chattopadhyay:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Subhojit Shaw:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Roman Hoffmann:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The Authors declare the study has no conflicts of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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