Potential health concerns due to elevated nitrate concentrations in groundwater of villages of Vadodara and Chhota Udaipur districts of Gujarat, India

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**ABSTRACT**

In an attempt to assess the groundwater quality of Vadodara and Chhota Udaipur districts and check its suitability for drinking purposes, a total of 162 samples (50 samples during pre-monsoon season and 54 samples during post-monsoon season from Vadodara district and 29 samples during both pre- and post-monsoon seasons from Chhota Udaipur district) were collected from 63 villages of both the districts for pre-monsoon and post-monsoon seasons during 2016–17. The analysis was carried out for physicochemical characteristics and the analytical results have been interpreted by graphical representation, correlation and regression analysis and water quality index so that the quality of groundwater can be easily understood. The analytical results were then compared with the Indian Standards Drinking Water-Specification (Second Revision). From this study, it is concluded that the overall groundwater quality of the region is comparatively good; however, elevated nitrate levels resulted in many of the samples having raised concern and the necessity to make all possible efforts to improve the quality of groundwater wherever deteriorated.

**Key words:** correlation and regression analysis, groundwater, high nitrate levels, total dissolved solids, Vadodara and Chhota Udaipur, water quality index

**HIGHLIGHTS**

- Elevated nitrate and fluoride concentration observed in the samples collected has raised concern about the quality of groundwater.
- Physico-chemical analysis of groundwater quality of samples collected were compared with Indian Drinking Water Quality Standard.
- Correlation and regression as well as water quality index was used to determine overall quality of water.
INTRODUCTION

One of the essential and natural resource for life on Earth is water. The human population has sustained itself for thousands of years because of water’s complex interactions with the rest of the natural environment (Khatri et al. 2016). Also, the sustainable socioeconomic development of every community is dependent on the availability of freshwater resources (Sharma et al. 2016). Around 99.97% of the total freshwater available is groundwater, while the remaining is available as streams, lakes and rivers (Khatri et al. 2020b). Hence, out of other sources of fresh water like rivers, ponds and lakes, groundwater is the broadly used resource for drinking as well as irrigation and industrial purpose due to its quality and quantity considerations (Dohare et al. 2014). A significant fraction of the total supply for domestic, industrial and agricultural sectors is provided by groundwater in many countries. The groundwater is believed to be comparatively much cleaner and free from pollution than surface water; however, it is generally affected by anthropogenic activities. Pollution of groundwater is aggravated due to municipal, industrial, agricultural and other miscellaneous sources and causes. Also, the ever-increasing demand for groundwater due to rapid industrialization and urbanization results in overexploitation of groundwater resources causing depletion of water levels and also the degradation of groundwater (Chourasia 2018). Groundwater contamination results in poor drinking water quality, loss of water supply, high clean-up costs, high costs for alternative water supplies and/or potential health problems. Owing to poor drinking water quality, the world is affected with 80% of diseases, as per the WHO, 1984 (Kalaivanan et al. 2017).

Water quality, measured by assessing the physicochemical and biological properties of water against a set of standards, is used to determine whether water is suitable for consumption or safe for the environment (Khatri & Tyagi 2014). Hence, assessment of groundwater quality and quantity becomes necessary to be acquainted with the sustainability of groundwater resources (Shah & Mistry 2013). In the present study, we have selected Vadodara and Chhota Udaipur districts of Gujarat state as our study area. Vadodara is a well-known district in Gujarat, India and is located on the banks of the Vishwamitri river. It was the capital of Gaekwad state until 1947 and is prominent for Laxmi Vilas Palace, which served as the residence of the Maratha royal Gaekwad dynasty, that ruled over Baroda state (History of Vadodara district 2021). Chhota Udaipur, carved out of the Vadodara district, is a tribal district in the state of Gujarat with a rich indigenous history and culture. Chhota Udaipur district has a rich forest area that forms a part of Jambughoda and Ratanmahal wildlife sanctuaries. The district is also known for the Rathwa tribal community and is home to a large dairy industry (History of Chhota Udaipur district 2021). Both the districts selected for the study has enriched tourist sites explored by numerous visitors across the year amplifying the need for groundwater quality assessment. Groundwater collected from Vadodara and Chhota Udaipur districts was checked by analysing a total of 162 samples during the pre-monsoon (April–May) and post-monsoon (October–November) seasons.
Objective of the study
The primary objectives of this study are as follows: to assess the current status of groundwater quality of Vadodara and Chhota Udaipur districts by examining and evaluating the physicochemical characteristics of groundwater; to assess the overall quality of monitored sources by comparing the analytical results with the Indian Standards Drinking Water-Specification (Second Revision) (IS 10500:2012); to provide the current database with aid in decision-making for policy level change at different levels with respect to the current status of groundwater; to carry out statistical analysis using various data interpretation techniques, namely, seasonal comparison, water quality index and correlation and regression analysis methods.

Study area
Vadodara and Chhota Udaipur districts are located in the central part of mainland Gujarat. Chhota Udaipur district was carved out of the Vadodara district on August 15, 2013 with its headquarters at Chhota Udaipur town (Shah 2016-17). The districts are bounded to the north and northeast by Anand, Panchmahals and Dahod districts, to the east and southeast by Madhya Pradesh and Maharashtra state, to the southeast by Narmada district and to the south and west by Bharuch district (District Groundwater Brochure: Vadodara 2011). A brief district profile of both the districts is presented in Table 1.

Groundwater availability
The taluka-wise details of available groundwater recharge per year, existing gross groundwater draft per year and level of groundwater development along with categorization for future groundwater development for both the districts is given in Table 2. The data were used as a primary source for selection of sampling locations at large.

METHODOLOGY
The hydro-geochemistry study of Vadodara and Chhota Udaipur districts was carried out by monitoring and analysing the groundwater samples from randomly selected villages. The methodology adopted includes site selection, sample collection, analysis, results, discussion and conclusion, followed by correlation and regression analysis and water quality index which were also found for both districts.

Table 1 | Brief profile of Vadodara and Chhota Udaipur districts

| Particulars          | Vadodara district         | Chhota Udaipur district |
|----------------------|---------------------------|-------------------------|
| Geographical area    | 7,548.50 sq. km           | 3,087 sq. km            |
| Latitudes            | 21°49'19“ to 22°48'37“    | 20.49’ to 22.49’        |
| Longitudes           | 72°51’05“ to 74°16’55“    | 72.51’ to 74.17’        |
| Number of villages   | 657                       | 888                     |
| Name of talukas      | Dabhoi, Karjan, Padra, Savli, Shinor, Vadodara and Vaghodiya | Chhota Udaipur, Pavi Jetpur, Kawant, Naswadi, Sankheda and Bodeli |
| Maximum temperature  | 41 °C                     | 45 °C                   |
| Minimum temperature  | 12 °C                     | 8 °C                    |
| Average annual rainfall | 965 mm                  | 1,083 mm               |
| Soil type            | Black soil, alluvial soil and hilly soil | Hard black soil, medium black soil, sandy loam soil and saline soil |
| Hydrogeology         | Groundwater occurs both as unconfined and confined conditions. Saturated zones of unconsolidated shallow alluvium and weathered zones, shallow depth jointed and fractured rocks form unconfined aquifers, whereas multilayered aquifer below impervious clay horizons in alluvium formation and interflow zones of basalts, intertrappean beds, deep seated fracture zones, shear zones in basalts, granites and gneisses give rise to semi-confined to confined conditions |
About 50 sampling locations during the pre-monsoon season and 54 sampling locations during the post-monsoon season of Vadodara district were selected; whereas for Chhota Udaipur district, 29 samples were selected based on the stratified random sampling method and their respective geographical locations for sampling and monitoring. The selected villages represent the groundwater quality of the districts. The taluka-wise list of villages selected for sampling is given in Table 3, also the location map of the villages selected is shown in Figure 1.

### Sampling and monitoring

A total of 162 groundwater samples were collected from the identified villages during pre- and post-monsoon seasons, respectively, and the collection method used was ‘grab sampling’ method. The samples were collected in polyethylene carboys as per Gujarat Environment Management Institute (GEMI)’s sampling protocol for water and wastewater, and samples requiring preservation were preserved on-site using preservatives as prescribed in Standard Methods for the Examination of Water and Waste Water (2012).

The primary information collected by GEMI’s sampling team during sampling includes allotment of unique sample IDs that are further used for representation of analytical data in graphical form for each sample collected from a distinct location along with its latitude and longitude, source type and depth of source and are summarized in Tables 4 and 5. The use of the groundwater sources from where the samples were collected was mostly drinking and domestic use followed by irrigation at a few locations. This implies direct dependency of the resident population in the study area on groundwater.

### Analysis of groundwater

The samples collected were submitted to GEMI’s laboratory with due procedure where analysis was carried out as per Standard Methods for the Examination of Water and Waste Water for the drinking water parameters. GEMI’s laboratory is recognized as a ‘State Water Lab’, ‘Environmental Laboratory’, ‘National Accreditation Board for Testing and Calibration Laboratory (NABL)’, and as a ‘Scientific and Industrial Research Organization (SIRO)’. All the groundwater samples were analysed for the selected relevant physicochemical parameters. The physical parameters include pH and turbidity.
Table 3 | Taluka-wise details of villages selected for sampling in Vadodara and Chhota Udaipur districts

| Sr. No. | Taluka                  | Villages                                                                 |
|--------|-------------------------|--------------------------------------------------------------------------|
|        | Vadodara district       |                                                                          |
| 1.     | Waghodia                | Asoj, Jarod, Waghodia, Sangadol, Timbi                                    |
| 2.     | Savli                   | Manjusar, Savli, Shihora, Vejpur, Mevli, Ghantiyal                       |
| 3.     | Nandod                  | Poicha                                                                    |
| 4.     | Becharaji               | Kanoda                                                                    |
| 5.     | Sankheda                | Kasumbia                                                                  |
| 6.     | Dabhoi                  | Mohammadpura, Tentalav, Chandod, Shirola, Koyavarohan, Meghakui, Borbar  |
| 7.     | Sinor                   | Awakhal, Sinor                                                           |
| 8.     | Vadodara                | Ranoli, Alkapuri, Por, Por Kayavarohan Road, Wadsala                      |
| 9.     | Karjan                  | Choranda, Alampura, Motikoral, Samri, Divi, Sayar                         |
| 10.    | Padra                   | Mobha, Muval, Ranu, Sarasvani, Padra                                      |
|        | Chhota Udaipur district |                                                                          |
| 11.    | Chhota Udaipur          | Puniyavant, Kasara, Kachhel, Gabadiya, Ganthiya, Oliamba                  |
| 12.    | Naswadi                 | Naswadi, Nannupura, Akona, Rampuri, Kukavati, Kandva, Rayasingpura, Piplej, Anandpuri |
| 13.    | Sankheda                | Sankheda, Malu, Gajipur, Talakpur, Akakheda, Handod, Khandupura, Ratanpur, Bahadurpur |

*aVillages monitored in the post-monsoon season only.

Figure 1 | Sampling locations for Vadodara and Chhota Udaipur districts.
### Table 4 | Details collected during sampling and monitoring of Vadodara district

| Sample ID | Village            | Latitude   | Longitude  | Source type | Depth of source (ft) |
|-----------|--------------------|------------|------------|-------------|----------------------|
| 1.        | Ashoj              | 22.422051  | 73.208271  | Borewell    | 160                  |
| 2.        | Manjusar           | 22.445154  | 73.19986   | Borewell    | 150                  |
| 3.        | Savli_1            | 22.56367   | 73.22036   | Borewell    | 160                  |
| 4.        | Savli_2            | 22.56797   | 73.22164   | Borewell    | 160                  |
| 5.        | Poicha_1           | 22.58644   | 73.17814   | Borewell    | 150                  |
| 6.        | Kanoda             | 22.59275   | 73.20281   | Borewell    | 160                  |
| 7.        | Namisora           | 22.501895  | 73.186956  | Borewell    | 170                  |
| 8.        | Poicha_2           | 22.58536   | 73.17581   | Borewell    | 180                  |
| 9.        | Poicha_3           | 22.58097   | 73.19147   | Hand pump   | 180                  |
| 10.       | Shihora            | 22.663892  | 73.280364  | Borewell    | 150                  |
| 11.       | Veipur             | 22.741369  | 73.350238  | Hand pump   | 160                  |
| 12.       | Mevli              | 22.61174   | 73.326656  | Hand pump   | 150                  |
| 13.       | Ghantiya           | 22.519921  | 73.380448  | Hand pump   | 160                  |
| 14.       | Jarod              | 22.43925   | 73.33111   | Borewell    | 170                  |
| 15.       | Kodarvaya          | 22.409305  | 73.37971   | Hand pump   | 160                  |
| 16.       | Nimeta             | 22.351219  | 73.304914  | Hand pump   | 180                  |
| 17.       | Waghadia (near school) | 22.291346 | 73.233778  | Borewell    | 170                  |
| 18.       | Sangadol_1         | 22.31664   | 73.43969   | Borewell    | 160                  |
| 19.       | Sangadol_2         | 22.33378   | 73.43969   | Hand pump   | 150                  |
| 20.       | Kasumbia           | 22.232665  | 73.515238  | Hand pump   | 150                  |
| 21.       | Mohammadpura       | 22.290323  | 72.940151  | Borewell    | 70                   |
| 22.       | Timbi              | 22.31784   | 73.279485  | Borewell    | 40                   |
| 23.       | Dabhoi (Javapura)  | 22.11542   | 73.44839   | Borewell    | 100                  |
| 24.       | Dharmpur           | 22.102905  | 73.444539  | Borewell    | 80                   |
| 25.       | Tentalav           | 22.046044  | 73.423178  | Borewell    | 70                   |
| 26.       | Chandod            | 21.985793  | 73.455587  | Borewell    | 80                   |
| 27.       | Shirola            | 22.057356  | 73.378975  | Borewell    | 180                  |
| 28.       | Awakhal            | 22.00757   | 73.317075  | Borewell    | 120                  |
| 29.       | Koyavarohan        | 22.00757   | 73.317075  | Borewell    | 160                  |
| 30.       | Ranoli             | 22.400377  | 73.13201   | Borewell    | 170                  |
| 31.       | Alkapuri           | 22.313295  | 73.176588  | Borewell    | 180                  |
| 32.       | Por_Taluka         | 22.139507  | 73.189985  | Borewell    | 120                  |
| 33.       | Por-Kayavarohan road | 22.139567 | 73.189995  | Borewell    | 230                  |
| 34.       | Karjan             | 22.05521   | 73.117257  | Borewell    | 250                  |
| 35.       | Choranda           | 21.988927  | 73.173513  | Borewell    | 250                  |
| 36.       | Sinor              | 21.9137    | 73.338729  | Borewell    | 180                  |
| 37.       | Sursamal           | 22.30136   | 73.202022  | Borewell    | 170                  |
| 38.       | Alampura           | 21.849902  | 73.209683  | Borewell    | 80                   |
| 39.       | Motikoral          | 21.836598  | 73.208932  | Borewell    | 110                  |
| 40.       | Samri              | 21.933566  | 73.197066  | Borewell    | 150                  |
| 41.       | Divi               | 21.930128  | 73.108405  | Borewell    | 90                   |
| 42.       | Kanbhu             | 22.061559  | 73.027245  | Borewell    | 160                  |

(Continued.)
chemical parameters include electrical conductivity, total dissolved solids, chloride, total hardness, calcium hardness, magnesium hardness, alkalinity, fluoride, sulfate and nitrate concentration. Further analysis for heavy metals was also performed in a few selected groundwater samples. The parameters analysed were compared with Indian Standards Drinking Water-Specification (Second Revision) (IS 10500: 2012) since the groundwater of the study area is used for drinking and domestic purposes (Khatri et al. 2021).

**ANALYTICAL RESULT AND INTERPRETATION**

The analytical details pertaining to the monitored parameters for both Vadodara and Chhota Udaipur districts including their acceptable and permissible limits, result range of pre-monsoon and post-monsoon seasons, sample IDs exceeding permissible limit and relevant inferences drawn for respective parameters are discussed further along with the graphical representation of the analytical results reported.

pH of solution is taken as the negative logarithm of hydrogen ion concentration for many practical purposes. The value range of pH from 7 to 14 is alkaline, from 0 to 7 is acidic and 7 is neutral. The pH of drinking water lies between 6.5 and 8.5. The overall pH of the pre-monsoon samples ranged between 6.65 and 8.74, whereas post-monsoon samples ranged from 6.72 to 8.22. Overall, the pH of the samples was found to be within the permissible limits of Indian Standards Drinking Water-Specification (Second Revision) except for a few samples. The graphical representation of the analytical results for all the monitored sources is illustrated in Figure 2.

Electrical conductivity is the capacity of water to carry an electrical current and varies both with number and types of ions the solution contains. In contrast, the conductivity of distilled water is less than 1 μmhos/cm. This conductivity depends on the presence of ions, their total concentration, mobility, valence and relative concentration and on the temperature of the liquid. Solutions of most inorganic acids, bases and salts are relatively good conductors. The overall conductivity of the pre-monsoon samples ranged between 406 μS/cm and 3,370 μS/cm and for post-monsoon samples ranged between 294 μS/cm and 6,160 μS/cm.

Total dissolved solids (TDS) is generally not considered as a primary pollutant, but it is rather used as an indication of aesthetic characteristics of drinking water and as an aggregate indicator of the presence of a broad array of chemical contaminants. It indicates the general nature of water quality or salinity. The acceptable and permissible limit of TDS is 500 mg/L to 2,000 mg/L, respectively, according to the specifications of Indian Standards. The overall concentration of TDS was reported between 140 mg/L and 1,956 mg/L in the pre-monsoon samples. Post-monsoon samples showed a TDS range of about 136 mg/L to 3,604 mg/L. Only two samples from Vadodara district and collected during the post-monsoon season exceeded the permissible limit. The high TDS might be due to leaching of various pollutants into the groundwater, industrial effluents, agricultural runoff, etc. The graphical representation of the analytical results for all the monitored sources is shown in Figure 3.
Chloride in excess quantity is usually taken as an index of pollution and considered as a tracer for groundwater contamination. All types of natural and raw water contain chlorides. It comes from activities carried out in agricultural areas, industrial activities and from chloride stones. As per IS 10500: 2012, the desirable limit for chloride is 250 mg/L and the permissible limit is 1,000 mg/L. The concentration of chloride ranged between 21 mg/L and 615 mg/L in the pre-monsoon samples. Post-monsoon samples showed a concentration of 0 mg/L to 1,154 mg/L. The higher concentration of chloride found in one sample of groundwater may be due to pollution sources such as domestic effluents, fertilizers, septic tanks, human waste, livestock waste and due to natural resources. Continuous consumption of higher chloride concentration may cause cardiac and kidney disease. The graphical representation of the analytical results for all the monitored sources is illustrated in Figure 4.

The desirable and permissible limit for total hardness as per IS 10500: 2012 lies between 200 mg/L and 600 mg/L, respectively. The effect of hardness is demonstrated as scaling in utensils, hot water systems in boilers, etc. Soap scum sources are dissolved calcium and magnesium from soil and aquifer minerals containing limestone or dolomite. In the study, pre-monsoon samples showed a hardness range of 100 mg/L to 1,150 mg/L and post-monsoon samples a hardness range of about

### Table 5 | Details collected during sampling and monitoring of Chhota Udaipur district

| Sample ID | Village       | Latitude     | Longitude     | Source type | Depth of source (ft) |
|-----------|---------------|--------------|---------------|-------------|----------------------|
| 55.       | Malu           | 22.25621755  | 73.53268845   | Borewell    | 100                  |
| 56.       | Gaiapur        | 22.25036972  | 73.53278056   | Hand pump   | 80                   |
| 57.       | Talakpur       | 22.19552059  | 73.62199615   | Hand pump   | 90                   |
| 58.       | Akakheda       | 22.18400465  | 73.61262878   | Borewell    | 110                  |
| 59.       | Sankheda       | 22.18518144  | 73.61233771   | Borewell    | 120                  |
| 60.       | Handod         | 22.14591587  | 73.5723729    | Hand pump   | 100                  |
| 61.       | Khandupura     | 22.14591587  | 73.5723729    | Borewell    | 80                   |
| 62.       | Sanodiya       | 22.15318448  | 73.60934488   | Borewell    | 130                  |
| 63.       | Ratnapur       | 22.11464018  | 73.50716918   | Hand pump   | 100                  |
| 64.       | Akona          | 22.03775000  | 73.70936111   | Hand pump   | 40–50                |
| 65.       | Rampuri_1      | 22.04875000  | 73.71150000   | Hand pump   | 50                   |
| 66.       | Rampuri_2      | 22.04841667  | 73.71144444   | Hand pump   | 50                   |
| 67.       | Anandpuri      | 22.05444444  | 73.72875000   | Borewell    | 70–80                |
| 68.       | Kukavati       | 22.05586111  | 73.73641667   | Borewell    | 70–80                |
| 69.       | Kandva_1       | 22.05116667  | 73.75180556   | Borewell    | 70–80                |
| 70.       | Kandva_2       | 22.05027778  | 73.75158333   | Hand pump   | 50                   |
| 71.       | Naswadi        | 22.02808333  | 73.77308333   | Canal       | 100                  |
| 72.       | Nunnupura      | 22.03430556  | 73.74675000   | Hand pump   | 50                   |
| 73.       | Rayansingpura  | 22.02022222  | 73.69836111   | Hand pump   | 50                   |
| 74.       | Puniyavant_1   | 22.33172222  | 73.96441667   | Borewell    | 100                  |
| 75.       | Puniyavant_2   | 22.33161111  | 73.96408333   | Hand pump   | 50                   |
| 76.       | Chhota Udaipur_1| 22.31358333 | 74.01122222   | Hand pump   | 40                   |
| 77.       | Chhota Udaipur_2| 22.31291667 | 74.01347222   | Borewell    | 180                  |
| 78.       | Kasara -1      | 22.34672222  | 74.01866667   | Hand pump   | 50                   |
| 79.       | Kachhel        | 22.33877778  | 74.04855556   | Hand pump   | 40                   |
| 80.       | Gabadiya       | 22.30000000  | 74.04636111   | Hand pump   | 50                   |
| 81.       | Ganthiya       | 22.27536111  | 74.04769444   | Hand pump   | 30                   |
| 82.       | Piplej         | 22.26650000  | 73.99819444   | Hand pump   | 50                   |
| 83.       | Oliamba        | 22.28569444  | 73.97883333   | Hand pump   | 30                   |

Chloride in excess quantity is usually taken as an index of pollution and considered as a tracer for groundwater contamination. All types of natural and raw water contain chlorides. It comes from activities carried out in agricultural areas, industrial activities and from chloride stones. As per IS 10500: 2012, the desirable limit for chloride is 250 mg/L and the permissible limit is 1,000 mg/L. The concentration of chloride ranged between 21 mg/L and 615 mg/L in the pre-monsoon samples. Post-monsoon samples showed a concentration of 0 mg/L to 1,154 mg/L. The higher concentration of chloride found in one sample of groundwater may be due to pollution sources such as domestic effluents, fertilizers, septic tanks, human waste, livestock waste and due to natural resources. Continuous consumption of higher chloride concentration may cause cardiac and kidney disease. The graphical representation of the analytical results for all the monitored sources is illustrated in Figure 4.
120 mg/L to 1,290 mg/L. Figure 5 indicates the concentration of total hardness for different samples with respect to seasonal variations.

Alkalinity is the sum total of components in the water that tend to elevate the pH to the alkaline side of neutrality. It is measured by titration with standardized acid to a pH value of 4.5 and is expressed commonly as milligrams per litre as calcium carbonate (mg/L as CaCO₃). Commonly occurring materials in water that increase alkalinity are carbonate, phosphates and hydroxides. Pre-monsoon samples showed an alkalinity range of about 124 mg/L to 1,004 mg/L and post-monsoon samples alkalinity ranges of about 116 mg/L to 959 mg/L. Figure 6 indicates the value of alkalinity for different samples with respect to seasonal variations.

Fluoride is more commonly found in groundwater than in surface water. Among factors which control the concentration of fluoride are the climate of the area and the presence of accessory minerals in the rock minerals’ assemblage through which the groundwater is circulating. Pre-monsoon and post-monsoon samples showed fluoride ranges of about 0–7.23 mg/L and 0–2.16 mg/L, respectively. The fluoride concentration of approximately less than or equal to 1 mg/L in drinking water is beneficial to human health, but if the fluoride concentration is more than the permissible limit, i.e., more than 1.5 mg/L, then it may cause dental fluorosis (tooth decay), bone fractures and, more seriously, skeletal fluorosis. The graphical representation of the analytical results for all the monitored sources is illustrated in Figure 7.

Sulfate: Natural water contains sulfate ions and most of these ions are also soluble in water. Sulfate ion is one of the major anions occurring in natural water. Sulfate concentration was reported to be in the range of 0–203 mg/L in the pre-monsoon
Figure 4 | Seasonal variations of chloride in Vadodara and Chhota Udaipur districts.

Figure 5 | Seasonal variations of total hardness in Vadodara and Chhota Udaipur districts.

Figure 6 | Seasonal variations of alkalinity in Vadodara and Chhota Udaipur districts.
samples. Post-monsoon samples showed a sulfate concentration of about 0 mg/L–283 mg/L. Water with about 300 mg/L–400 mg/L sulfate concentration causes a bitter taste and if the concentration rises up to 1,000 mg/L or more it can cause intestinal disorders. Water containing appreciable amounts of sulfate can cause hard scale in boilers. The graphical representation of the analytical results for all the monitored sources is illustrated in Figure 8.

Nitrate concentration is present in raw water and, mainly, it is a form of N₂ compound (of its oxidizing state). Nitrate is produced by chemical and fertilizer factories, animal matter, decaying vegetables, domestic and industrial discharge. The method to measure quantity of nitrate is by UV spectrophotometer. As per IS 10500:2012, the desirable limit for nitrate is a maximum of 45 mg/L and there is no relaxation in permissible limit. Pre-monsoon samples showed a nitrate range of about 0–489.5 mg/L and post-monsoon samples a nitrate limit of 0–569 mg/L. A total of 12 and 21 samples of Vadodara district and 10 and 8 samples of Chhota Udaipur district analysed during pre-monsoon and post-monsoon seasons, respectively, exceeded the desirable limit. Elevated levels of nitrate found in many of the samples analysed raised concerns and have also influenced the overall groundwater quality of the region. The graphical representation of the analytical results for all the monitored sources is illustrated in Figure 9.

**Heavy metal analysis in groundwater**

Heavy metals such as lead, cadmium, iron, nickel, chromium, zinc, arsenic were analysed to detect the heavy metal pollution of groundwater. The analytical results showed that the heavy metals were within the permissible limits except for iron and...
lead, where their concentration exceeded the permissible limit of 0.3 mg/L and 0.01 mg/L, respectively, as per Indian Standards of drinking water. The maximum concentration of iron detected was 9.9 mg/L and of lead was 0.057 mg/L. However, the iron concentration exceeded mainly in the range of 0.3 mg/L–0.8 mg/L. Heavy metals more than the permissible limits can be fatal and can cause even death after prolonged exposure.

Correlation and regression

Correlation is the mutual relationship between two variables. Correlation coefficient ($r$) measures the degree of association that exists between two variables, one taken as the dependent variable (Chaubey & Patil 2015). It determines the relationship of water quality parameters with each other of the water samples analysed (Dutta & Sarma 2018). It can be calculated by the equation given below. Here, $x$ and $y$ are any two variables (water quality parameters) and $n$ the total number of observations (samples analysed). Now, between the selected variables $x$ and $y$, the correlation coefficient ($r$) can be calculated as:

$$r = \frac{n \sum (x \cdot y) - \sum x \cdot \sum y}{\sqrt{f(x) \cdot f(y)}}$$

where, $f(x) = n \sum (x^2) - (\sum x)^2$; $f(y) = n \sum (y^2) - (\sum y)^2$, and all the summations are to be taken from 1 to $n$.

Now, if the value of the correlation coefficient between two variables $x$ and $y$ is legitimately large, then it indicates that these two variables are highly correlated. In that case, it is likely to try a linear relation of the form

$$y = Ax + B$$

The constant $A$ and $B$ are to be determined in order to correlate the variables $x$ and $y$. According to the well-known method of least squares, the value of constants $A$ and $B$ are given by the relations

$$B = y_{\text{mean}} - Ax_{\text{mean}}$$

and

$$A = \frac{n \sum (x \cdot y) - \sum x \cdot \sum y}{n \sum (x - x_{\text{mean}})^2}$$

where,

$$x_{\text{mean}} = \frac{\sum x}{n}$$

$$y_{\text{mean}} = \frac{\sum y}{n}$$

Figure 9 | Seasonal variations of nitrates in Vadodara and Chhota Udaipur districts.
The linear equation we get from this is also known as regression equation. The regression equation is used as a mathematical tool to calculate different dependent characteristics of water quality by substituting the values for the independent parameters in the equations. The regression analysis is usually carried out when the water quality parameters have a better and higher level of significance in their correlation coefficient.

**Result of correlation and regression**

For the present study a total of nine parameters are taken for correlation and regression analysis and the resulting correlation coefficients (r) are specified in Tables 6 and 7 for pre- and post-monsoon, respectively. As stated before, a regression equation needs to be found if the value of the correlation coefficient is fairly large; however, in this case, there is no need to find the linear regression equation as the value of correlation coefficients are not too large (>1).

The method of linear correlation has been found to be a significant approach to get an idea of quality of the groundwater by determining a few parameters experimentally. From the result of pre-monsoon, it can be stated that alkalinity, conductivity, chloride and sulfate have strong correlation with TDS. Also, conductivity and alkalinity, chloride and conductivity, sulfate and conductivity and sulfate and chloride are strongly correlated as all these have the value of correlation coefficient >0.7. Alkalinity, conductivity, chloride, sulfate and nitrate have moderate correlation with TH. Also TH and TDS, nitrate and TDS, chloride and alkalinity, sulfate and alkalinity, nitrate and conductivity, nitrate and chloride and nitrate and sulfate are moderately correlated as the value of correlation coefficient varies between 0.3 and 0.7. Parameters other than these have a weak or negative correlation with each other.

While discussing the post-monsoon season, from the correlation analysis, it can be stated that conductivity, chloride and sulfate have strong correlation with TDS. Also, conductivity has strong correlation with chloride and sulfate and chloride has strong correlation with sulfate. These all have a value of correlation coefficient (r) >0.7. TH, alkalinity and nitrate have moderate correlation with TDS. Alkalinity, conductivity, chloride and sulfate and nitrate have moderate correlation with TH. Conductivity, chloride and sulfate have moderate correlation with alkalinity. Also, nitrate has moderate correlation with conductivity, chloride and sulfate. These can also be seen in the Table 7 as these all have correlation coefficient values between 0.3 and 0.7. Parameters other than these have a weak or negative correlation with each other.

**Water quality index (WQI)**

The Weighted Arithmetic Water Quality Index (WAWQI) was first proposed by Horton (Horton 1965), in which a weight is assigned to each parameter such that this weight influences the importance of the parameter in determining the water quality (Khatri et al. 2020a). However, WQI indicates the quality of water in terms of index number which represents the overall quality of water for any intended use (Falowo et al. 2019). It is defined as a rating reflecting the comprehensive influence of different water quality parameters taken into consideration for the calculation of WQI (Chaurasia et al. 2018). The indices are among the most effective ways to communicate the information on water quality status to the general public or to policymakers. In calculation of the WQI, the relative importance of various parameters depends on the intended use of the water (Hariharan 2007).

The calculation of WQI was made using the weighed arithmetic index method in the following steps.
Let there be \( n \) water quality parameters and quality rating \((q_n)\) corresponding to \(n^{th}\) parameter is a number reflecting relative value of this parameter in the polluted water with respect to its standard permissible value. \(q_n\) values are given by the relationship.

**Calculation of quality rating \((q_n)\)**

For calculation, the ideal value is taken as \(v_i\) and the permissible value is \(v_s\). Similarly, the ideal value is zero for other parameters and the permissible value is taken from standards. Therefore, the quality rating is calculated from the following relation:

\[
q_n = 100 \left( \frac{v_o - v_i}{v_s - v_i} \right)
\]

where,

- \(v_o\) = observed value
- \(v_i\) = ideal value
- \(v_s\) = standard permissible value.

In most cases \(v_i = 0\) except in certain parameters like pH, dissolved oxygen, etc.

**Calculation of unit weight \((W_n)\)**

The unit weight \((W_n)\) to various water quality parameters is inversely proportional to the recommended standards for the corresponding parameters.

\[
W_n = \frac{k}{s_n}
\]

where,

- \(W_n\) = unit weight for \(n^{th}\) parameter
- \(S_n\) = standard permissible value for \(n^{th}\) parameter
- \(k\) = proportionality constant
- \(k = \frac{1}{1/v_{s1} + 1/v_{s2} + 1/v_{s3} + 1/v_{s4} + \ldots + 1/v_{sn}}\)
- \(s_n = \text{‘}n\text{’ number of standard values.}\)

**Calculation of water quality index (WQI)**

WQI is calculated by the following equation:

\[
WQI = \frac{\sum_{n=1}^{n} q_n W_n}{\sum_{n=1}^{n} W_n}
\]

### Table 7 | Correlation coefficient \((r)\) among various water quality parameters for post-monsoon season

| Parameters | pH  | TDS | TH  | Alkalinity | Conductivity | Chloride | Fluoride | Sulfate | Nitrate |
|------------|-----|-----|-----|------------|--------------|----------|----------|---------|---------|
| pH         | 1   |     |     |            |              |          |          |         |         |
| TDS        | -0.22 | 1  |     |            |              |          |          |         |         |
| TH         | -0.33 | 0.66 | 1  |            |              |          |          |         |         |
| Alkalinity | -0.19 | 0.62 | 0.37 | 1         |              |          |          |         |         |
| Conductivity | -0.44 | 0.99 | 0.61 | 0.63 | 1          |          |          |         |         |
| Chloride   | -0.1 | 0.89 | 0.58 | 0.43 | 0.91       | 1        |          |         |         |
| Fluoride   | -0.05 | -0.02 | -0.2 | 0.1 | 0.19       | -0.1 | 1        |         |         |
| Sulfate    | -0.07 | 0.87 | 0.44 | 0.48 | 0.88       | 0.81 | -0.03 | 1      |         |
| Nitrate    | -0.28 | 0.54 | 0.66 | 0.22 | 0.47       | 0.37 | -0.08 | 0.44 | 1       |
Assessment of water quality based on WQI

Application of WQI is a useful method in assessing the suitability of water for various beneficial uses, hence, WQI has been classified into five categories as shown in Table 8. The suitability of WQI values for human consumption according to Mishra & Patel (2001) is shown below.

Results of water quality index

For calculation, the WQI of nine parameters, namely, pH, TDS, TH, Ca H, Mg H, fluorides, chlorides, sulfates and nitrates were taken into consideration. WQI thus calculated for the sampling points of pre-monsoon and post-monsoon seasons is listed in Table 8. Similarly, the chart representation for both seasons is given in Figure 10.

DISCUSSION

A total of 162 samples was collected from the villages of Vadodara and Chhota Udaipur districts during pre-monsoon and post-monsoon seasons to assess the overall groundwater quality of the districts. The sampling was conducted as per the GEMI’s Sampling Protocol for Water and Wastewater and the analysis of the samples was carried out in the GEMI’s

Table 8 | Water quality index of Vadodara and Chhota Udaipur districts during pre- and post-monsoon seasons

| Water quality index (WQI) | Status                  | Sample ID                          |
|---------------------------|-------------------------|------------------------------------|
| Pre-monsoon season        |                         |                                    |
| 0–25                      | Excellent               | 8, 9, 13, 16, 18, 19, 22, 23, 24, 25, 26, 27, 36, 37, 39, 49, 62, 67, 69 |
| 26–50                     | Good                    | 1, 2, 6, 7, 12, 14, 15, 17, 20, 21, 28, 29, 30, 31, 34, 35, 38, 40, 41, 42, 47, 48, 51, 53, 59, 61, 63, 70, 71 |
| 51–75                     | Moderate                | 3, 4, 5, 10, 11, 32, 33, 43, 44, 46, 50, 54, 55, 56, 57, 60, 64, 72, 73, 74, 77 |
| 76–100                    | Poor                    | 52, 75                             |
| 100 and above             | Unfit for drinking      | 45, 58, 65, 66, 68, 76, 78, 79     |
| Post-monsoon season       |                         |                                    |
| 0–25                      | Excellent               | 2, 18, 19, 29, 39, 46, 50, 53, 55, 57, 58, 63 |
| 26–50                     | Good                    | 3, 4, 5, 6, 8, 9, 12, 13, 17, 20, 25, 26, 27, 28, 30, 31, 35, 37, 38, 40, 41, 42, 47, 48, 52, 54, 59, 60, 61, 62, 65, 67, 73, 75, 77 |
| 51–75                     | Moderate                | 1, 7, 14, 15, 16, 21, 22, 23, 24, 32, 33, 34, 36, 43, 44, 45, 51, 56, 64, 66, 68, 74, 78, 81 |
| 76–100                    | Poor                    | 10, 11, 71, 79, 82                 |
| 100 and above             | Unfit for drinking      | 49, 69, 70, 72, 76, 80, 83         |

Figure 10 | Water quality index of Vadodara and Chhota Udaipur districts during pre- and post-monsoon seasons.
laboratory recognised as a ‘State Water Lab’ for different physicochemical parameters. The analytical findings were compared with Indian Standards Drinking Water-Specification (Second Revision) (IS 10500: 2012) to produce a view of overall groundwater quality of both the districts. The overall evaluation of the analytical results with standards is given in Table 9.

The limits are as per Indian Standards Drinking Water-Specification (Second Revision) (IS 10500: 2012).

Based on the analysis of results, the following inferences are drawn:

1. Overall, the pH of all the samples were found to be within the permissible limits according to Indian Standards (IS 10500: 2012) except that two samples showed a little higher pH.
2. High variations are observed in the concentration of conductivity, TDS, chloride, total hardness, alkalinity, fluoride, sulfate parameters. The concentrations of the parameters were found to be within the permissible limits as prescribed by the Indian Standards almost for all the samples for the respective parameters. Moreover, slight variation was observed in the sulfate concentration.
3. Nitrate concentrations, at places, were found to be higher than the permissible limits. High nitrate concentrations such as 569 mg/L was observed at Shihora village of Vadodara district. Moreover, many other villages have shown higher nitrate concentrations than the limits prescribed which is a matter of concern.
4. Heavy metals were analysed in a few groundwater samples to detect whether the groundwater was contaminated with heavy metals. The analytical results of heavy metals for groundwater samples were found to be within the acceptable limits except for a few samples for iron and lead. In particular, iron was found to be high, in the range of 0.2 mg/L to 9.9 mg/L, whereas the permissible limit is only 0.3 mg/L.

| S. No. | Parameters | Requirement (acceptable limit) | Permissible limit in the absence of alternate source | Vadodara district | Chhota Udaipur district |
|-------|------------|-------------------------------|-----------------------------------------------|-------------------|-----------------------|
|       |            |                               | Range of present study (pre-monsoon) | Range of present study (post-monsoon) | Range of present study (pre-monsoon) | Range of present study (post-monsoon) |
| 1     | pH         | 6.5–8.5                       | No relaxation                      | 6.84–8.74         | 6.74–8.22             | 6.65–8.39         | 6.72–7.98   |
| 2     | EC (μS/cm) | –                             | –                              | 406–3,370         | 294–6,160            | 743–2,470         | –           |
| 3     | TDS (mg/L) | 500                           | 2,000                           | 204–1,956         | 200–3,604            | 140–1,352         | 136–1,298  |
| 4     | Cl⁻ (mg/L) | 250                           | 1,000                           | 21–615            | 21–1,154             | 24–399            | 0–394      |
| 5     | TH (mg/L)  | 200                           | 600                             | 100–1,150         | 140–1,290            | 120–910           | 120–630    |
| 6     | Ca²⁺H (mg/L) | 75                         | 200                             | 20–850            | 70–860               | 70–380            | 60–330     |
| 7     | Mg²⁺H (mg/L) | 30                        | 100                             | 20–850            | 70–860               | 30–690            | 10–530     |
| 8     | Alkalinity (mg/L) | 200                 | 600                             | 156–1,004         | 116–959              | 124–858           | 168–812    |
| 9     | Turbidity (NTU) | 1                        | 5                              | 1.10–76.9         | 0.1–90               | –                 | –          |
| 10    | F⁻ (mg/L)  | 1.0                           | 1.5                             | 0–2.25            | 0.4–1.73             | 0–7.23            | 0–2.16     |
| 11    | SO₄ (mg/L) | 200                           | 400                             | 2–203             | 10–283               | 0–95.32           | 0–111.52   |
| 12    | NO₃ (mg/L) | 45                            | No relaxation                    | 0–489.5           | 0–569                | 0–100             | 0–115      |
| 13    | Pb (mg/L)  | 0.01                          | No relaxation                    | 0–0.006           | 0.057                | 0–5.447           | 0–14.06    |
| 14    | Cd (mg/L)  | 0.005                         | No relaxation                    | BDL               | BDL                  | BDL               | BDL        |
| 15    | Fe (mg/L)  | 0.3                           | No relaxation                    | 0–0.364           | 0.1–9.98             | 0–2.045           | 0–3.248    |
| 16    | Ni (mg/L)  | 0.02                          | No relaxation                    | 0.001             | 0–0.01               | BDL               | BDL        |
| 17    | Cr (mg/L)  | 0.05                          | No relaxation                    | 0–0.004           | 0                    | BDL               | BDL        |
| 18    | Zn (mg/L)  | 5                             | 15                              | 0–0.0003          | 0–2.45               | 0–0.117           | BDL        |
| 19    | As (mg/L)  | 0.01                          | 0.05                            | 0–0.005           | 0–0.005              | BDL               | BDL        |

BDL, below detection limit.
5. From the comparison study of pre- and post-monsoon groundwater quality it was concluded that EC, TDS, total hardness, alkalinity, fluoride, sulfate, nitrate concentrations, etc. were found to be a little higher in post-monsoon samples than the pre-monsoon samples.

6. Results of the WQI of Vadodara and Chhota Udaipur districts for pre-monsoon season showed that 24.05% of the water samples fell in the excellent category, 36.70% the good category, 26.53% were found to be of moderate quality, 2.53% of poor quality and 10.12% were found to be unfit for drinking purposes.

7. The results of the WQI of Vadodara and Chhota Udaipur districts for post-monsoon season showed that 14.45% of the water samples fell in the excellent category, 42.16% the good category, 28.91% were found to be of moderate quality, 6.02% of poor quality and 8.43% were found to be unfit for drinking purposes.

| Sr. No. | Characteristic | Source | Health impact |
|---------|----------------|--------|---------------|
| 1.      | pH             | Carbonate-rich rocks, effluent discharge, chemical dumping | pH < 6.5 causes aesthetic problems, metallic taste |
| 2.      | EC             | Dissolved matter of inorganic salts, acids and bases | High concentrations affect taste, damage crops, degrade drinking water |
| 3.      | TDS            | Landfill leachate, sewage | Gastrointestinal irritation, corrosive, salty and brackish taste |
| 4.      | Chloride       | Domestic effluents, fertilizers, septic tanks, human waste, livestock waste | Affects heart, kidney patients |
| 5.      | TH             | Weathering of limestone, sedimentary rocks, calcium bearing minerals, industrial effluents, application of lime to soil in agricultural areas | Urolithosis, cardiovascular disorder, kidney problems, cancer |
| 6.      | Alkalinity     | Naturally occurring alkalis like CO\textsubscript{3}\textsuperscript{2−}, HCO\textsubscript{3}, OH\textsuperscript{−}, salts of Mg, Ca, K and Na, acid rain | Bitter taste, slippery feel, dry skin |
| 7.      | Turbidity      | Inorganic sources like Fe, Mn from natural sources, geology and suspended matter | Waterborne diseases |
| 8.      | Fluoride       | Weathering of rocks, fertilizers, liquid waste, volcanic ash, fly ash, industrial effluents | Dental fluorosis, effects on skeletal tissues |
| 9.      | Sulfate        | Occurs naturally in soils, rocks, minerals, gypsum, decomposition of organic matter, fertilizers | Diarrhoea, dehydration, sulfate >250 mg/L creates medicinal taste |
| 10.     | Nitrate        | Excessive use of inorganic nitrogenous fertilizers and manures | Methaemoglobin. Long-term exposure causes pregnancy and neural tube defects, colorectal cancer, bladder, birth defects, thyroid disease |
| 11.     | Lead           | Carbonates and hydroxide complex in soil, erosion of natural deposits | Poor muscle coordination, blood pressure, reproductive problems, damage nervous system, anaemia, liver and kidney damage |
| 12.     | Cadmium        | Erosion of natural deposits, discharge from metal refineries, runoff from waste batteries and paints | Kidney damage |
| 13.     | Iron           | Naturally occurring, industrial effluents, sewage and landfill leachate | Haemorrhagic necrosis, genetic disorder (haemochromatosis) |
| 14.     | Nickel         | Leakage from metals, dissolution from nickel ore-bearing rocks | Long-term exposure causes decreased body weight, heart and liver damage |
| 15.     | Chromium       | Improper disposal of mining tools and industrial waste | Skin rashes, nose irritations and nose bleeds, ulcers, weakened immune system, kidney and liver damage |
| 16.     | Zinc           | Occurs in small amounts in almost all igneous rocks | Fever, nausea, vomiting, stomach cramps, and diarrhoea |
| 17.     | Arsenic        | By-products of agricultural and industrial activities | Cancer of bladder, lungs, skin, kidney, nasal passages |

Source: WHO (1996); Patel (2015); Ward et al. (2018).
Human health concerns

The present study shows elevated nitrate and fluoride concentrations in many sources. Availability of both the elements in the human body may be essential; although long-term consumption with excessive concentration may cause serious disease and sometimes even be life-threatening. Thus, it is important to understand the threat to human health due to elevated concentration of each parameter, as described in Table 10.

CONCLUSION

From the present study, it can be concluded that most of the groundwater sources analysed have satisfactory water quality and are suitable for human consumption as they meet the drinking water quality standards, except for the sources having elevated nitrate or fluoride concentrations. The water of the sources with elevated levels and not meeting the standards shall be consumed after receiving appropriate treatment, either at individual or village level, so as to minimize the health risk associated with consumption of such water. This study can be used to further collaborate with advanced hydrogeological and GIS studies to assess the sources and causes of such high nitrate and fluoride concentrations in the districts and ensure the safe quality of water with the application of suitable mitigation measures.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

APHA/AWWA/WEF 2012 Standard Methods for the Examination of Water and Wastewater, 22nd edn. American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF), Washington, DC, USA.

Chaubey, S. & Patil, M. K. 2015 Correlation study and regression analysis of water quality assessment of Nagpur City, India. International Journal of Scientific and Research Publications 5 (11), 753–757.

Chaurasia, A. K., Pandey, H. K., Tiwari, S. K., Ram, P., Pandey, P. & Ram, A. 2018 Groundwater quality assessment using Water Quality Index (WQI) in parts of Varanasi District, Uttar Pradesh, India. Journal of the Geological Society of India 92, 76–82.

Chourasia, L. P. 2018 Assessment of groundwater quality using water quality index in and around Korba City, Chhattisgarh, India. American Journal of Software Engineering and Applications 7 (1), 15–21.

District Ground Water Brochure: Vadodara 2011 Central Ground Water Board, West Central Region. Ministry of Water Resources, Government of India, New Delhi, India.

Dohare, D., Deshpande, S. & Kotiya, A. 2014 Analysis of ground water quality parameters: a review. International Science Congress Association, Research Journal of Engineering Sciences 5 (5), 26–31.

Dutta, B. & Sarma, B. 2018 Correlation study and regression analysis of ground water quality assessment of Nagaon town of Assam, India. International Journal of Engineering Research & Technology 7 (6), 320–331.

Falowo, O., Oluwasegunfunmi, V., Akindureni, Y., Olabisi, W. & Aliu, A. 2019 Groundwater physicochemical characteristics and water quality index determination from selected water wells in Akure, Ondo State, Nigeria. African Journal of Water Resources 7 (2), 76–88.

Harirhan, A. V. L. N. S. H. 2007 Determination of water quality of coastal area Visakhapatnam. Current World Environment 2 (2), 217–220.

History of Chhota Udaipur district. Available from: https://chhotaudepur.nic.in/about-district (accessed 24 March 2021).

History of Vadodara district. Available from: https://vadodara.nic.in/history/ (accessed 24 March 2021).

Horton, R. K. 1965 An index number system for rating water quality. Journal of the Water Pollution Control Federation 37 (3), 300–305.

Indian Standard Drinking Water – Specification (Second Revision) (IS 10500: 2012) 2012 Bureau of Indian Standards (BIS), New Delhi, India.

Kalaiyanan, K., Gurugnanam, B., Pourghasemi, H. R., Suresh, M. & Kumaravel, S. 2017 Spatial assessment of groundwater quality using water quality index and hydrochemical indices in the Kodavanar sub-basin, Tamil Nadu, India. Sustainable Water Resources Management 4, 627–641. doi:10.1007/s40899-017-0148-x.

Khatri, N. & Tyagi, S. 2014 Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. Frontiers in Life Science 8 (1), 23–39.

Khatri, N., Tyagi, S. & Rawtani, D. 2016 Assessment of drinking water quality and its health effects in rural areas of Harij Taluka, Patan District of northern Gujarat. Environmental Claims Journal 28 (3), 223–246.

Khatri, N., Tyagi, S., Rawtani, D. & Tharmavaram, M. 2020a Assessment of river water quality through application of indices: a case study River Sabarmati, Gujarat, India. Sustainable Water Resources Management 6 (6), 1–11.

Khatri, N., Tyagi, S., Rawtani, D., Tharmavaram, M. & Kamboj, R. 2020b Analysis and assessment of ground water quality in Satlasana Taluka, Mehsana district, Gujarat, India through application of water quality indices. Groundwater for Sustainable Development 10, 100321.
Khatiri, N., Raval, K. & Jha, A. 2021 Integrated water quality monitoring of Mahi river using benthic macroinvertebrates and comparison of its biodiversity among various stretches. *Applied Water Science* **11**, 143.

Mishra, P. C. & Patel, R. K. 2001 Study of the pollution load in the drinking water of Rairangpur, a small tribal dominated town of North Orissa. *Indian Journal of Environmental and Ecoplanning* **5**(2), 293–298.

Patel, S. V. 2015 *Assessment of Groundwater Quality in and Around MSW Dumpsite of Pirana, Ahmedabad (Report – 5 Part – I)*, Report. Gujarat Environment Management Institute, Gandhinagar, India.

Shah, S. M. & Mistry, N. J. 2013 Evaluation of groundwater quality and its suitability for an agriculture use in, District Vadodara, Gujarat, India. *International Science Congress Association* **2**(11), 1–5.

Shah, P. L. 2016–17 *District Industrial Potentiality Survey Report of Chhota Udepur District*. Ministry of Micro, Small & Medium Enterprises, MSME – Development Institute, Ahmedabad, India.

Sharma, D. A., Rishi, M. S. & Keesari, T. 2016 Evaluation of groundwater quality and suitability for irrigation and drinking purposes in southwest Punjab, India using hydrochemical approach. *Applied Water Science* **7**, 3137–3150. doi:10.1007/s13201-016-0456-6.

Ward, M. H., Jones, R. R., Brender, J. D., De Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M. & Breda, S. G. 2018 Drinking water nitrate and human health: an updated review. *International Journal of Environmental Research and Public Health* **15**, 1557.

World Health Organization 1996 *Zinc in Drinking-Water*. Background document for development of WHO Guidelines for Drinking-water Quality. World Health Organization, Geneva. WHO/SDE/WSH/03.04/17.

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