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Assessing the Groundwater Reserves of the Udaipur District, Aravalli Range, India, Using Geospatial Techniques

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Abstract: Population increase has placed ever-increasing demands on the available groundwater (GW) resources, particularly for intensive agricultural activities. In India, groundwater is the backbone of agriculture and drinking purposes. In the present study, an assessment of groundwater reserves was carried out in the Udaipur district, Aravalli range, India. It was observed that the principal aquifer for the availability of groundwater in the studied area is quartzite, phyllite, gneisses, schist, and dolomitic marble, which occur in unconfined to semi-confined zones. Furthermore, all primary chemical ingredients were found within the permissible limit, including granum. We also found that the average annual rainfall days in a year in the study area was 30 from 1957 to 2020, and it has been found that there are chances to receive surplus rainfall once in every five deficit rainfall years. Using integrated remote sensing, GIS, and a field-based spatial modeling approach, it was found that the dynamic GW reserves of the area are 637.42 mcm/annum, and the total groundwater draft is 639.67 mcm/annum. The deficit GW reserves are 2.25 mcm/annum from an average rainfall of 627 mm, hence the stage of groundwater development is 100.67% and categorized as over-exploited. However, as per the relationship between reserves and rainfall events, surplus reserves are available when rainfall exceeds 700 mm. We conclude that enough static GW reserves are available in the studied area to sustain the requirements of the drought period. For the long-term sustainability of groundwater use, controlling groundwater abstraction by optimizing its use, managing it properly through techniques such as sprinkler and drip irrigation, and achieving more crop-per-drop schemes, will go a long way to conserving this essential reserve, and create maximum groundwater recharge structures.

Keywords: groundwater hydrology; groundwater resource evaluation; groundwater management; groundwater reserves; sustainable water resource management

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1. Introduction

On Earth, water is an essential resource for the existence of life. Among the various components of the hydrological cycle, groundwater is an essential reserve of freshwater, particularly in regions that do not have any other freshwater sources. As rainfall is the source of groundwater, an area's geological setting governs its existence and determines the stocks or reserves of groundwater in any region [1,2]. At a global scale, 71% of Earth's surface is covered with 326 million cubic miles of water [3]. Around 97% of it lies in the oceans, i.e., around 320 million cubic miles, which is too mineralized to be useful for consumptive uses in sustaining life such as drinking, agriculture, and other activities. Only 3% of water is freshwater suitable for consumptive use. Of this, 2.5% is locked in ice caps, glaciers, soil, atmosphere, and hence unavailable [4]. The remaining 0.5% of freshwater is available for direct consumptive use when sourced from lakes, ponds, streams, rivers, and groundwater [5].

Groundwater is sometimes the solely available water supply in desert areas that supports or grows agricultural production. Increased groundwater extraction (groundwater draft) for irrigation has significantly contributed to the agricultural revolution and an enhanced global food supply, since irrigated agriculture accounts for around 40% of world food production [6]. However, in many places, this has resulted in a permanent drop in storage (the volume of water stored in aquifers), known as groundwater depletion [7]. Although the consequences of groundwater extraction are most acute and visible at local scales, due to worldwide distribution, possible ramifications for water and food security, and sea-level rise, groundwater decline is considered to be a global problem [8]. However, there is a paucity of scientific literature regarding the severity of this problem [9–11]. Given that worldwide groundwater extractions are minimal relative to global recharge, the problem of global groundwater quantity has recently been addressed by water conservationists [12,13].

Locally, aquifer depletion is an established fact in many areas, as demonstrated by significant lowering in the groundwater table measured in wells and, more recently, through gravity observations from the GRACE satellites at the basin or watershed scale [14,15]. Groundwater depletion has a variety of repercussions that vary depending on the aquifer and its water-holding capacity [16,17]. As stated, one of the most apparent effects is a lowering of water tables. This results in the drying up of wells, and higher pumping costs that ultimately affect users. It also results in lower groundwater flow to streams, springs, and wetlands, affecting ecosystem services [18]. This can lead to land subsidence, reducing storage irreversibly and potentially damaging infrastructure [19]. Lower water tables cause groundwater movement, which can cause salinization in coastal areas due to saltwater intrusion or leakage from neighboring layers containing saline water [20]. Therefore, there is a need to assess and evaluate groundwater reserves to help conserve and efficiently manage this essential source of freshwater [21].

Globally, various studies have been carried out to assess groundwater reserves. Rehmati et al. (2016) investigated the groundwater potential in the Mehran region of Iran using the maximum entropy (ME) and random forest (RF) models. The study used various groundwater conditioning parameters to determine potential sites for groundwater, namely altitude, slope aspect, slope percentage, drainage density, topographic wetness index (TWI), distance from rivers, land use, topographic wetness index (TWI), plan curvature, lithology, and soil texture, all of which affect groundwater storage. The analysis discovered several zones with extremely high groundwater reservoirs [22]. Lezzaik and Milewski (2018) used a distributed ArcGIS-based model to estimate groundwater reserves in the Middle East and North Africa (MENA), based on derived aquifer saturation thickness and effective porosity estimates. The authors calculated changes in groundwater storage between 2003 and 2014 using monthly gravimetric datasets (GRACE) and land-surface parameters (GLDAS). They found that groundwater reserves in the region were estimated at 1.28 × 106 cukm, with an uncertainty range between 816,000 and 1.93 × 106 cukm [23]. Based on an exhaustive study of available maps, publications, and data, MacDonald et al. (2012) demonstrated continental-scale aquifer reserves and possible borehole yields in Africa. According to their calculations, total groundwater storage in Africa was estimated to be 0.66 million cukm. They demonstrated that boreholes located and constructed properly in numerous African countries would support handpump abstraction and contain enough storage to support abstraction over inter-annual recharge changes. Their maps also demonstrated that the possibility for higher-yielding boreholes is significantly reduced. This study indicated that plans based on extensive drilling of high-yielding boreholes that aim to enhance irrigation or supply water to rapidly urbanizing cities are likely to fail [24]. In India, Singh et al. (2017) used the Gravity Recovery and Climate Experiment (GRACE) to examine the water budget by monitoring gravity anomalies to predict changes in total water storage (TWS) content over India's north-west. From 2003 to 2012, the surface and groundwater estimates indicated a loss of 86.43 km^3/y on average over a ten-year period [15].

Due to an increase in population, urbanization, industrialization, and agricultural activities, India has encountered an extraordinary demand for groundwater in recent decades [25–29]. Therefore, following global trends, the need to regulate the use of groundwater for all activities in India is of utmost importance. Groundwater management is a challenge in a country such as India where the demand for water is greater than its replenishing rates [30]. Moreover, due to the loss of potential groundwater recharge zones to urbanization, the long-term sustainability of this essential ecosystem is in jeopardy [31,32]. Therefore, quantifying the groundwater resource in India is significant to understand the storage of groundwater and its projected life [25,33]. This will help set up new efficient systems for GW allocation for all activities, along with techniques for the management of groundwater reuse and recycling for long-term sustainability [34,35].

The present work evaluated the current and projected groundwater reserves in the Udaipur region, India, and assessed its use for human consumption using chemical assessment. Udaipur is in Rajasthan's agro-climatic zone IV-A and has a tropical, semi-arid, and hot environment. May is the warmest month of the year, with daily maximum and minimum temperatures of 38 °C and 24 °C, respectively. January is the coldest month, with typical daily maximum and minimum temperatures of 24 °C and 7.8 °C, respectively. The average annual rainfall is 624 mm. As it is arid, there is huge demand for groundwater in this region. There are various methodologies involved in evaluating groundwater reserves, as described in previous sections. GRACE data are mainly used for this purpose; however, due to issues of local scale uncertainties in the estimations, various authors have preferred water-balance equation-based approaches [36,37]. The water equation is based on the assessment of groundwater hydrology equations, and involves the assessment of the topography of the area, geomorphological conditions, climate variations, rainfall distributions, drainage characteristics, and hydrogeological characteristics [38–40]. The complete method involves assessing the geological formation of the area, the type of the aquifers with its hydraulic parameters, water levels, water-level fluctuation, water-level trends, groundwater flow direction, and all major chemical ingredient distribution and its concentration in groundwater [41–43]. Together, all this information is essential for assessing the availability of the groundwater and its usage characteristics. Overall, an integrated methodology involving the hydrological, hydrogeological, and hydrochemical characterization of the Udaipur region was adopted to evaluate groundwater reserves and assess their fitness for human consumptive use [44,45]. Using water-balance equations and statistical analysis in a spatial modeling framework, we assessed the groundwater reserves of Udaipur, Rajasthan.

2. Materials and Methods

Udaipur (the Lake city of Rajasthan) falls between 23°48′05.79″ to 25°06′16.75″ North and 73°01′23.10″ to 74°26′20.87″ East (11,773 km^2) in southern Rajasthan (Figure 1). The Precambrian-age Aravalli range circumscribes the entire district [42,43]. The elevation of the study area falls in the range 155–1313 m above mean sea level (AMSL). The overall physiographic gradient is towards the south and south-east of the Udaipur district. Rocky hills mainly cover the most north-west to central portion of the district belonging to Aravalli range, with elevation ranging from 1313 m to 155 m AMSL, and are considered to be good runoff zones [46,47].

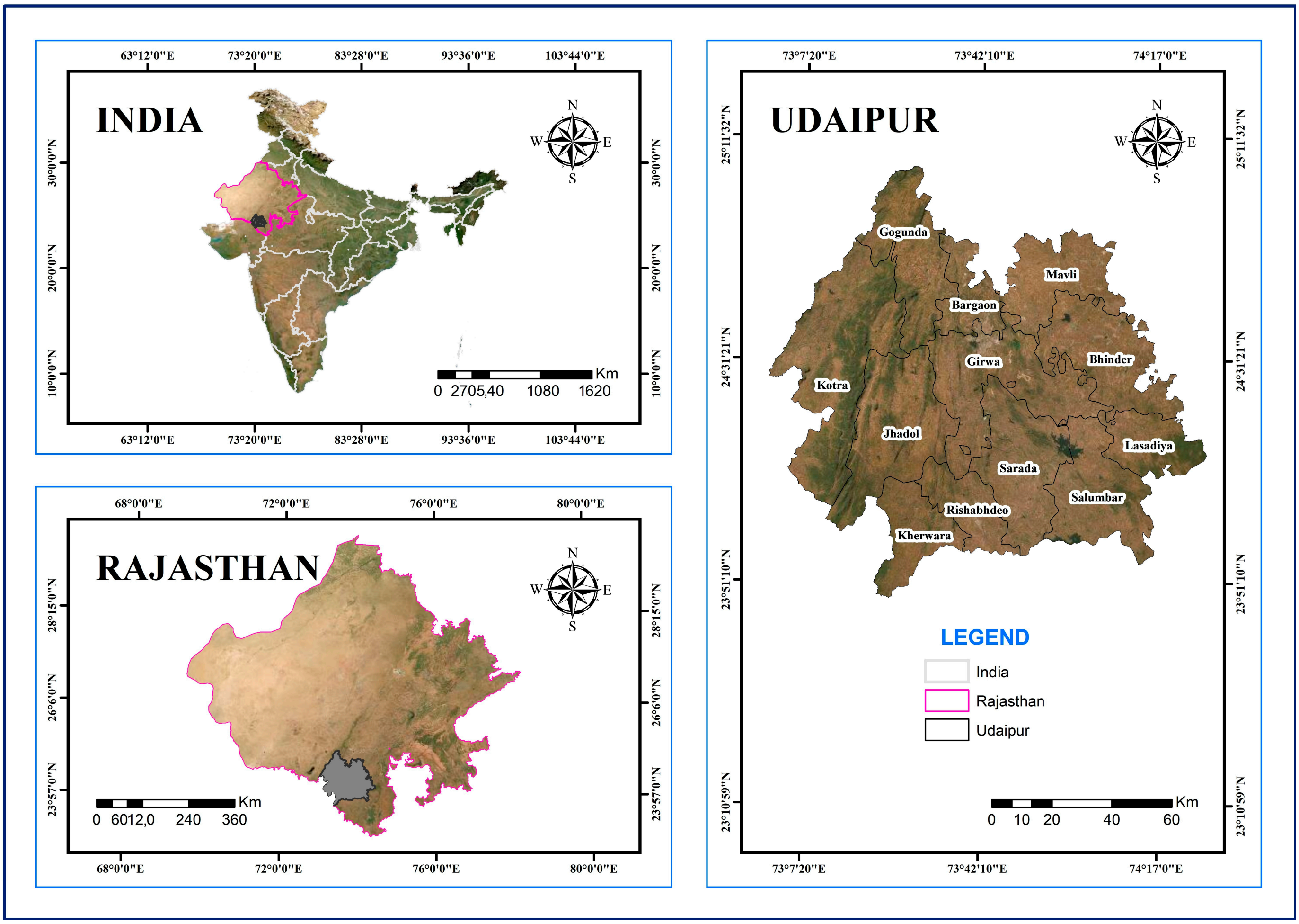

Figure 1. Location of Udaipur with respect to the State of Rajasthan and, overall, India.

Primary data, i.e., observation of physical conditions, vegetation growth, water level, groundwater yield, water quality in terms of TDS, and type of aquifer, using a hydro-inventory for the studied area, was collected during a field visit. Secondary data about rainfall, geology, geomorphology, groundwater level, groundwater quality, aquifer parameters, and groundwater draft was gathered from different sources such as the Water Resource Department (WRD) Govt. of Rajasthan India, Central Groundwater Board (CGWB), and Indian Metrological Department (IMD) [48]. Primary GIS layers were prepared in a vector format using ArcGIS 10.8.

We also performed a chemical analysis of the groundwater to establish its suitability for consumptive use. Electric conductivity (EC), pH, carbonate (CO_3), chloride (Cl), sulfate (SO_4), nitrate (NO_3), phosphate (PO_4), total hardness (TH), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), fluoride (F), iron (Fe), silicon dioxide (SiO_2), total alkalinity, total dissolved solids (TDS) and uranium (U) of groundwater were interpolated, and their limits were assessed for quality purposes. In the studied area, about 32 groundwater samples from 2016 to 2020 have been collected from existing representative wells/bore wells, and analyzed for various chemical ingredients.

The point locations of the observation stations (water depth and chemical analysis samples) were used for interpolation using the inverse distance weighted (IDW) technique in ArcGIS. Inverse distance weighted (IDW) is a probabilistic estimating interpolator that uses a linear set of attributes at known places to compute unknown values [49]. IDW produces surfaces by generating a neighborhood search of points and weighting these points by a power function, assuming that every input point has a local influence that reduces with distance [50]. Since the observation points were almost equally distributed, IDW was considered to be the appropriate interpolation technique as reported by various other workers [49–55]. Interpolation of the water table estimates was used to evaluate groundwater flow direction in pre- and post-monsoon seasons and determine the hydraulic gradient for estimating groundwater reserves.

Analysis of average rainfall distribution, number of rainy days, peak daily rainfall, and drought years was carried out using historical rainfall data. Physiographic studies related to topography, drainage, and geomorphology were carried out using SRTM DEM (90 m) [56]. The water-level fluctuation and groundwater-level trends were analyzed using hydrograph analysis techniques and aquifer distribution.

To assess the age of groundwater reserves and sustainability of available reserves for long-term use, we evaluated the total groundwater resource. The methodology adopted in the current study is shown in Figure 2. It involves the use of the water-balance equation and statistical analysis and is a standard method laid down by the Groundwater Estimation Committee (2015), India [57–60].

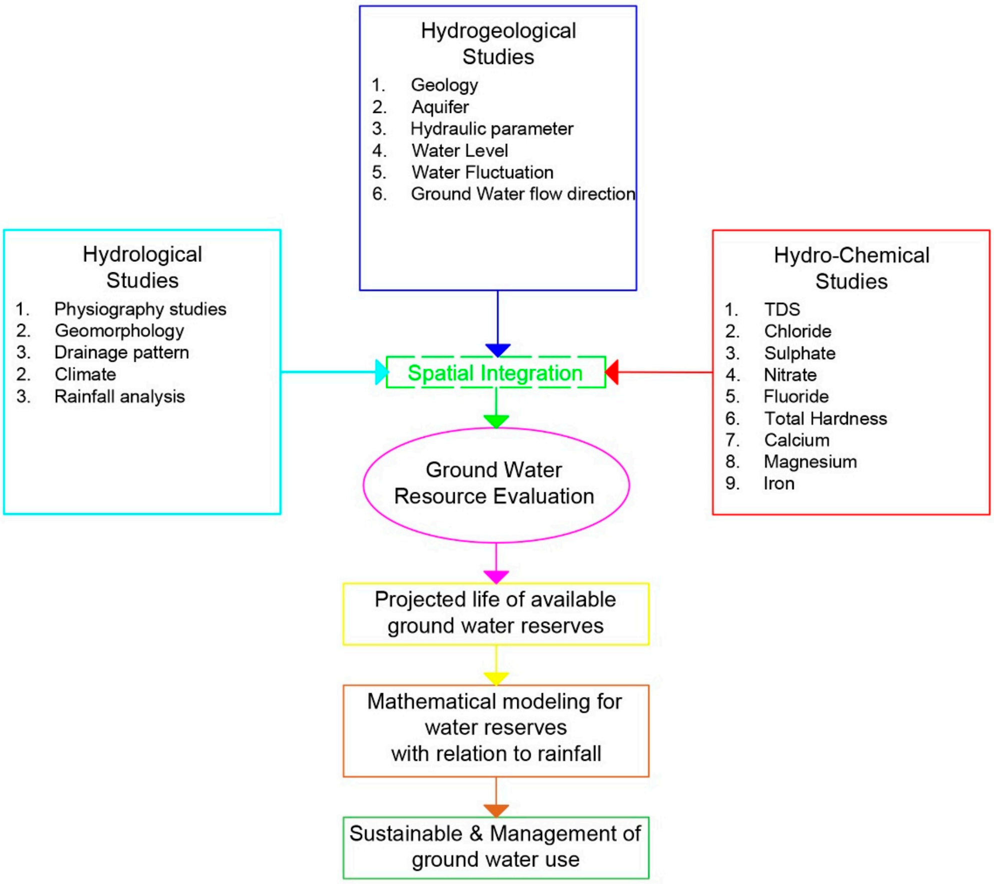

Figure 2. The overall methodology employed in the present study.

The methodology for groundwater resource assessment is based on the principal water-balance equation as given below [47–50]:

$$\text{Inflow} - \text{Outflow} = \text{Change in Storage (of an aquifer)} \quad (1)$$

The equations for estimation of total dynamic reserves (RT), groundwater draft (DT), surplus/deficit reserves, stage of groundwater development, and static reserves are given in Table 1.

Table 1. The equations for estimation of Groundwater Resource Evaluation.

	Dynamic Reserves (RT)	**Rr + RR + Rp + Ri**
Where	Rr = Recharge due to rainfall	Rr = A × S.F. × Sy Rr = Recharge due to Rainfall A = Total rechargeable area S.F. = Average Seasonal Fluctuation in the studied area Sy = Specific Yield
	RR = Recharge due to river	T × ΔH/ΔI × L × no. of days T = Transmissivity (As per APT results) ΔH/ΔI = Hydraulic Gradient (As per Water-Level Contour Map) L = length of river section, No. of days of river flow as reported in field = 30 days
	Rp = recharge due to ponds	Spread area of pond × Seepage factor × No. of days of water storage Seepage rate = 1.4 mm/day = 0.0014 m/day (As per GEC)
	Ri = recharge due to applied irrigation	Irrigated area (As per collected data from Revenue Department of Jaitaran and Raipur) × Recharge factor for Paddy/Non-Paddy
	Groundwater Draft (DT)	Dd + Di + DI + De
Where	Draft due to domestic consumption (Dd)	Population × Water requirement per day in m^3 × no. of days
	Draft due to applied irrigation (Di)	Average irrigated area × Average crop factor for general mixed crops
	Draft due to Industrial consumption (DI)	Water requirement per day in m^3 × no. of days
	Draft due to natural outflow (Do)	Do = T × ΔH/ΔI × L × No. of days in a year T = Average Transmissivity of all aquifers ΔH/ΔI = Average Hydraulic Gradient L = Length of out flow boundary
	Draft due to Evapotranspiration (De)	Replenishable reserves × Evapotranspiration Factor
	Surplus/Deficit Reserves	Total dynamic groundwater reserves–Total present groundwater draft
	Stage of Groundwater Development	$\frac{\text{Total groundwater Draft} \times 100}{\text{Total groundwater reserves}}$
	Static Reserves (Sr)	A × S.T. × Sy where A = Area of different aquifers S.T. = Average saturated thickness

3. Results and Discussion

3.1. Geomorphological Characterization

The study area's north-east, east, and south-east zones have plain, gentler slopes with an elevation between 700–155 m AMSL and are considered to be good recharge zones because they facilitate the percolation of the rainfall events (Figure 3a). These zones help with the movement, transportation, and deposition of erosion of soils/sediments using streams in the studied area. The Sabarmati, Mahe, Banas, and Luni are the principal rivers to carry rainfall-runoff water in the studied area. These rivers are seasonal, with dendritic to sub-dendritic drainage (stream order between 5 and 6) (Figure 3b). The area has been classified into three parts as per the flow direction of the surface water during rainfall events, i.e., from central to south and south-east, north and north-west to east, and north-central to west of the district, and each zone with stream order between 5 and 6.

The area is subtropical and subhumid, with semi-arid climatic conditions. The average annual rainfall in the study from 1957 to 2020 was 627.77 mm, with the annual lowest and highest rainfall being 234.04 mm (1969) and 1282.15 mm (1973), respectively (Figure 4a). As per rainfall analysis, 57.17% of overall time series of annual rainfall years have a below-average rainfall (627.78 mm), whereas the remaining 42.86% have surplus rainfall. This suggests surplus rainfall following 5 successive deficit rainfall years. The average number of rainy days in a year is 30 (Figure 4b), with maximum daily rainfall being 299 mm (2015) (Figure 4c).

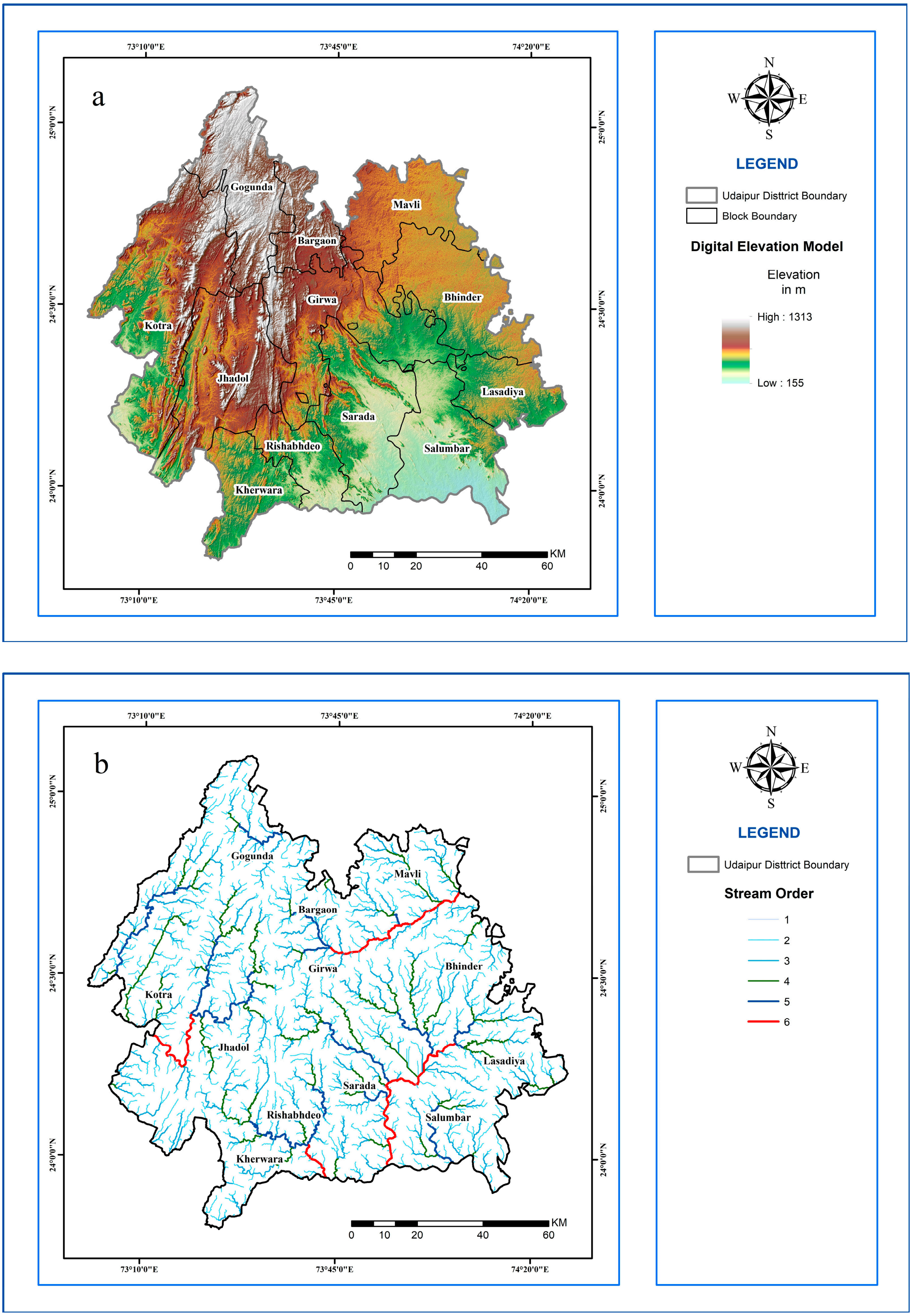

Figure 3. (**a**) Elevation, and (**b**) drainage characteristics of the study area.

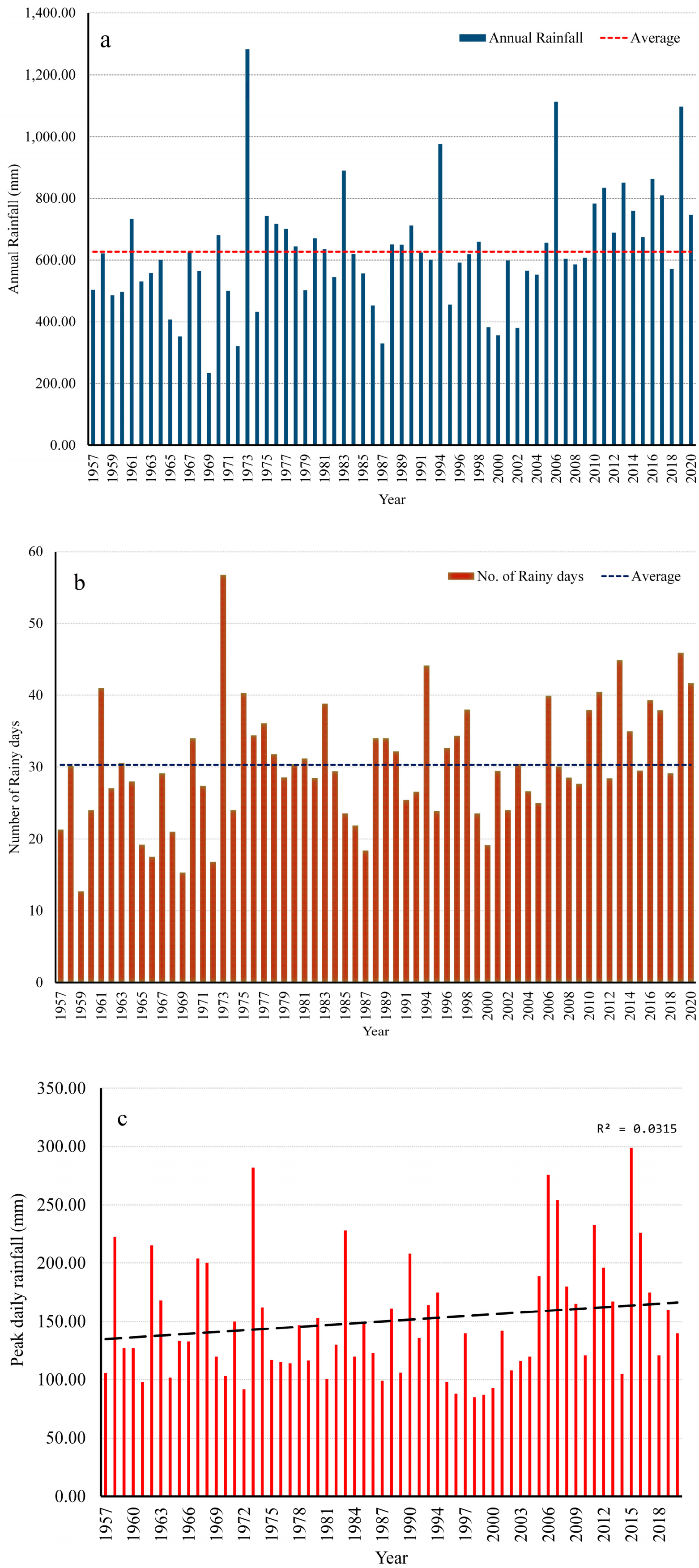

Figure 4. (**a**) Average rainfall, (**b**) number of rainy days, and (**c**) peak daily rainfall of the study area.

Geomorphologically, the area can be sub-divided into three major geomorphological units, i.e., hills (structural/linear/denudational), denudational origin (pediment/buried pediment), and fluvial origin (valley fill) (Figure 5). Most of the area is covered by hills, mostly runoff zones; the north-east and south of the district are covered by denudational origin, which is formed by erosion, stripping, and leaching, and serves as good recharge zones. Nearby the water bodies, the area is covered by fluvial origin, which is formed by the mass movement, transportation, and deposition and erosion of soil/sediment by streams, and serves as good recharge zones [25].

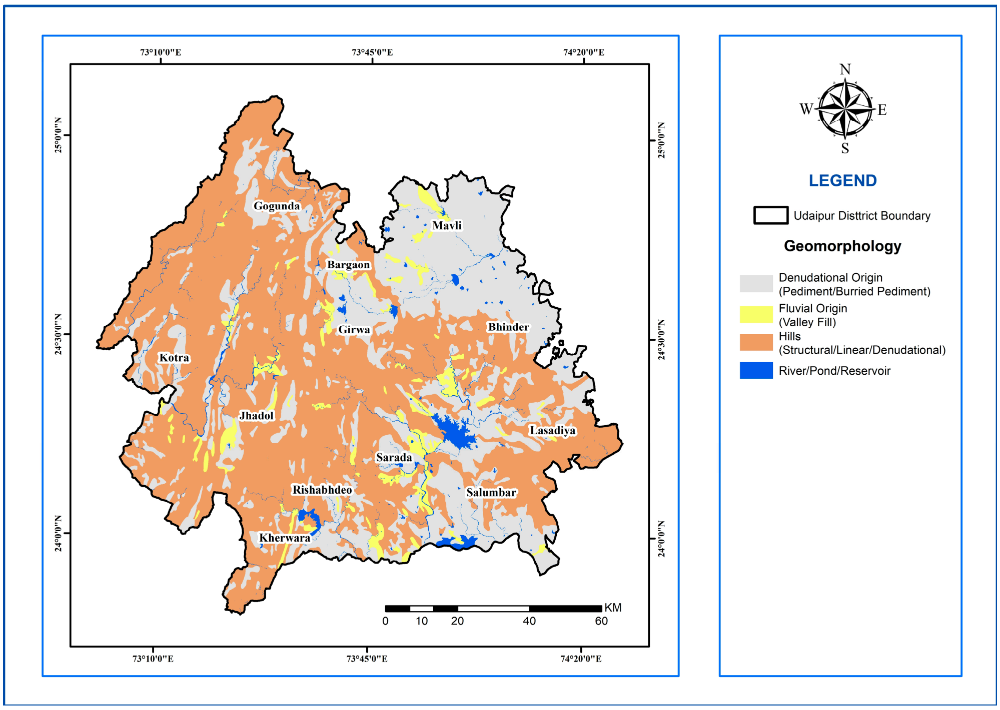

Figure 5. Geomorphological classes of the study area.

3.2. Hydrogeological Characterization

As per field observations and the available literature in the studied area, the northern to southern portion of the studied area belongs to the younger formation of the Aravalli supergroup of the Palaeoproterozoic age. The north-east and east of the area belongs to the oldest formation of the Bhilwara supergroup of the Palaeoproterozoic and Archaean age. The western and small part of the central zone belongs to the younger formation Delhi supergroup of the Palaeoproterozoic–Mesoproterozoic age. Isolated pockets in western, central, and eastern portions of the area belong to the extrusive/intrusive formation of the Palaeoproterozoic, Palaeoproterozoic–Mesoproterozoic, and Archaean age [47]. Table 2 summarizes the stratigraphic geological succession of the area.

Table 2. Summary of the classes of the stratigraphic geological succession of the study area.

Age	Super Group	Group	Lithology
Palaeoproterozoic	Aravalli	Barilake	Meta volcanics, chlorite schists, amphibolite, quartzite, and conglomerate
		Debari	Meta arkose, quartzite, phyllite, dolomitic marble, and dolomite
		Jharol	Chlorite-mica schist, calc shist, and quartzite
		Nathdwara	Banded gneissic complex (BGC)
		Udaipur	Phyllite, mica schists, meta siltstone, quartzite, dolomite, gneisses and migmatites
Palaeoproterozoic	Bhiwara	Rajpura-Dariba	Meta-volcano-sedimentory rocks of banded gneissic complex (BGC)
Palaeoproterozoic–Mesoproterozoic	Delhi	Gogunda	Calc schist, gneisses, mica shists, garnetiferous biotite-schists, quartzites, and migmatites
		Kumbhalgarh	Carbonate, mafic volcanic, and argillaceous rocks
Palaeoproterozoic–Mesoproterozoic	Extrusive/Intrusive	Phulad Ophiolite Suite	Banded gneissic complex (BGC)
Palaeoproterozoic		Rakhabdev Ultramafic Suite	Serpentinite, talc-chlorite-schist, actinolite-tremolite schist, and asbestos
Mesoproterozoic		Sendra-Ambaji Granite and Gneiss	Schists, gneisses, and composite gneiss Quartzites
Palaeoproterozoic		Udaipur/Salumbar/Udaisagar/Darwal Granite	
-		Undifferentiated Granite	
——Unconformity——			
Archaean	Bhiwara	Hindoli	-
		Mangalwar Complex	Migmatites, gneisses, quartzite, felspathic granite ferrous mica shists and para-amphibolites
-	Extrusive/Intrusive	Untala and Gingla Granites	Politic gneiss, quartzite, marble, calc-silicates

The groundwater availability in the district is generally maintained by topographic and structural units existing in the geological formation, i.e., quartzite, phyllite, gneisses, schist, and dolomitic marble, which are the principle aquifers in the district. The availability and movement of groundwater creates pore spaces between grains, fractures, and bedding plains in the geological formation. The distribution of aquifer in the Udaipur district is given in Figure 6.

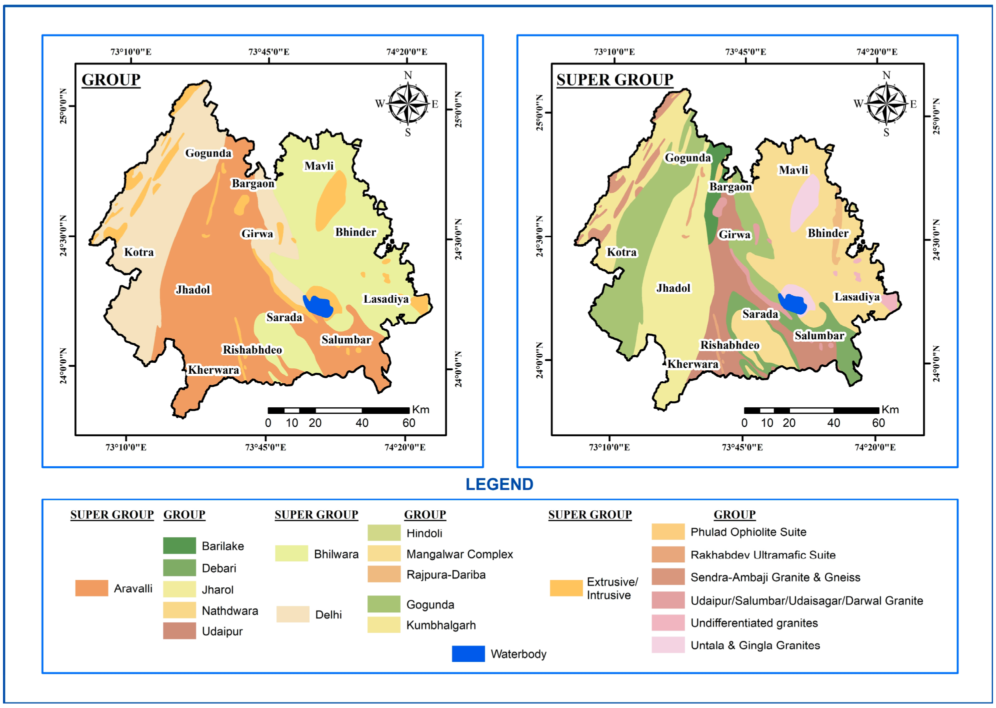

Figure 6. The distribution of aquifer in different groups in the Udaipur district.

The average groundwater yield from all aquifers through groundwater abstraction structures, such as tube wells/bore wells/dug-cum-bore wells at different locations is, per the reported information, of the order of 47 m^3/day, and the data are given in Table 3. The combined hydraulic parameters of all aquifers, i.e., transmissivity (15.63 m^2/day) and specific yield (1.5%) are also presented.

Table 3. The Average Yield of Groundwater at different locations.

Type of Aquifer	Name of the Location	Yield Range in m^3/day	Depth Range of Groundwater Abstraction Structure in m
Calc schist and gneiss	Gogunda	40–60	15–20
	Kotra	40–50	15–20
Granite	Kotra	35–50	15–20
Quartzite	Jhadol	25–35	20–25
Phyllite and schist	Bargaon	40–60	15–20
	Girwa	50–80	25–30
	Gogunda	50–80	20–25
	Jhadol	40–60	25–30
	Kherwara	40–60	20–25
	Kotra	40–60	20–25
	Mavli	40–60	25–30
	Salumbar	40–60	15–20
	Sarada	40–60	15–20
	Bhinder	35–50	15–20
Granites and gneiss	Sarada	35–45	15–20
	Salumbar	35–45	20–25
	Mavli	35–45	20–30
	Girwa	35–45	20–25

The locations of hydrograph stations for 2016–2017, 2017–2018, 2018–2019, and 2019–2020 are given in Figure 7, and the corresponding lithology classes are shown in Figure 8.

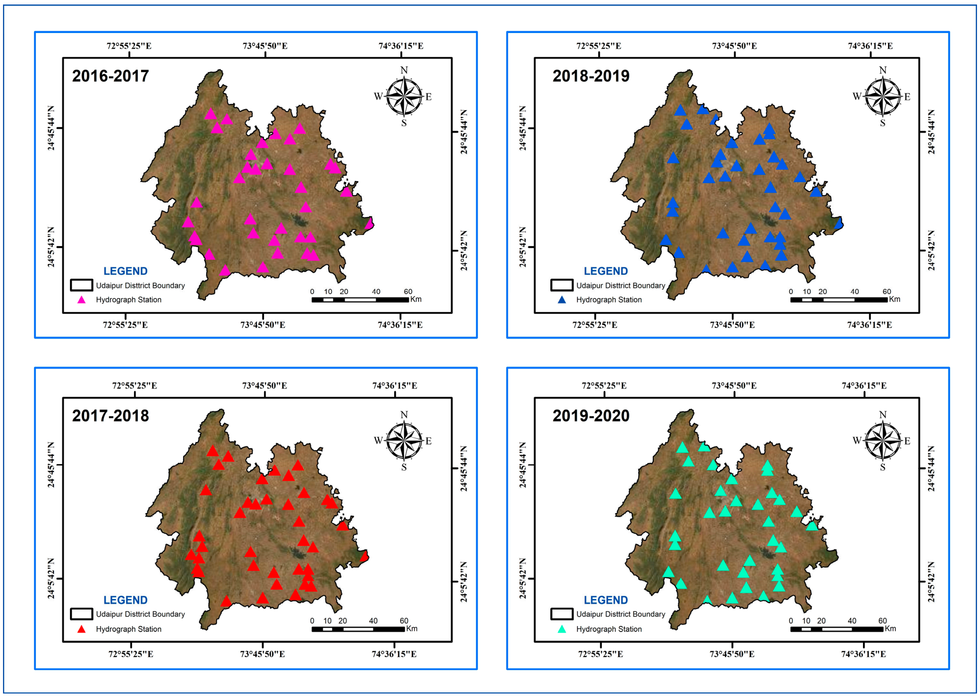

Figure 7. The distribution of hydrograph stations in the Udaipur district.

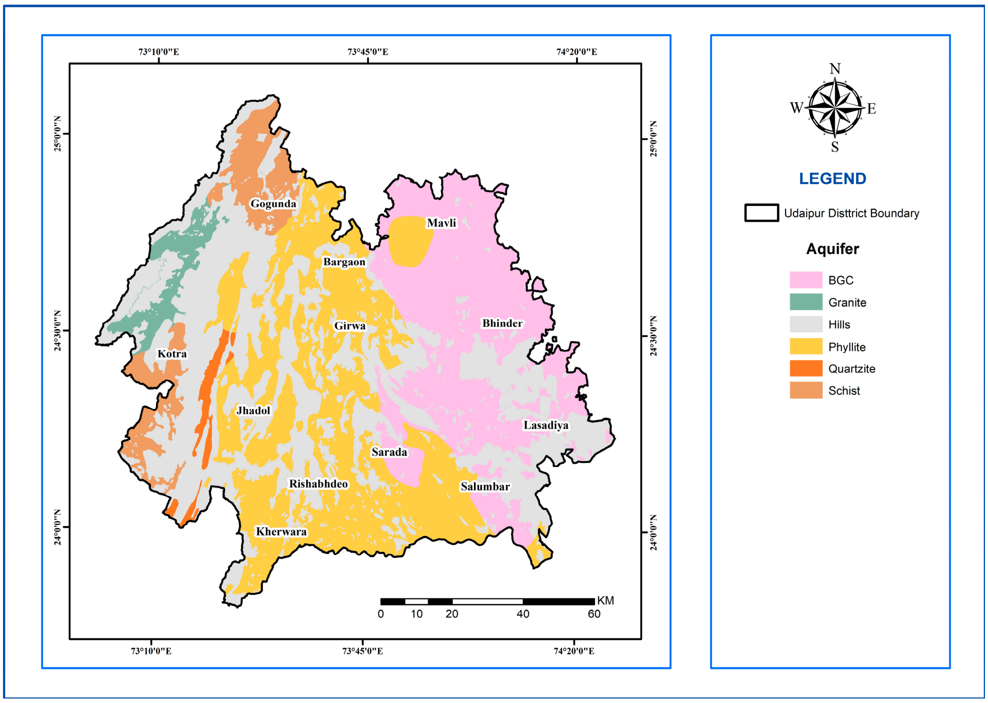

Figure 8. The distribution of different lithologies in the Udaipur district.

As per the available data, the distribution of water level below groundwater level, and water-level contour map (AMSL) for pre- and post-monsoon has been prepared to show the water zones and the groundwater flow direction in the area (Figures 9 and 10).

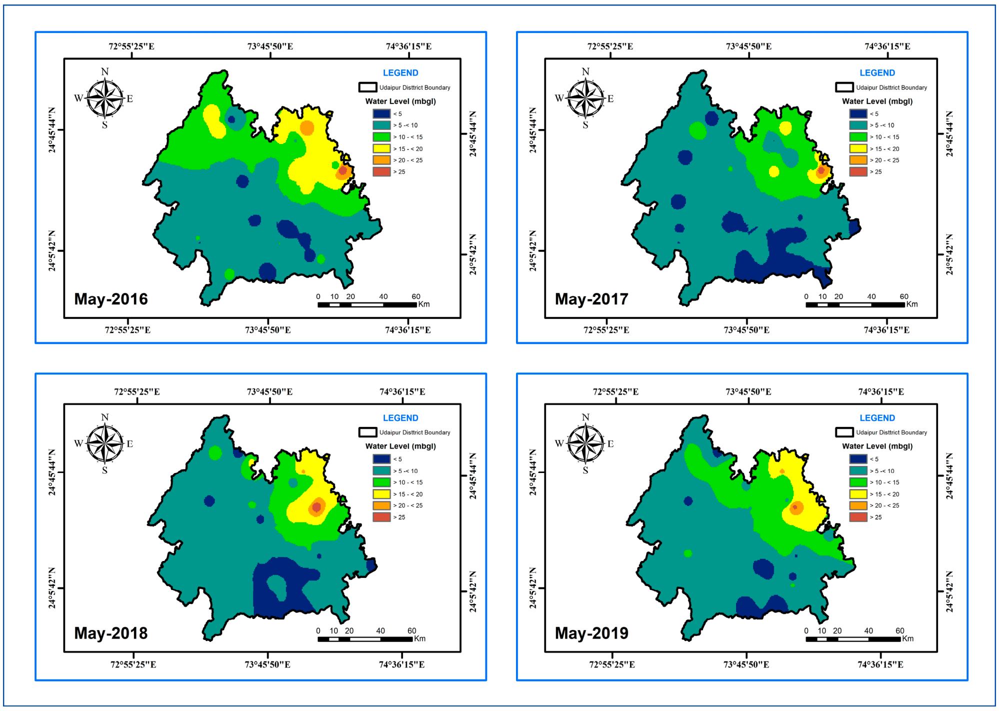

Figure 9. The water-level distribution during pre-monsoon season in the Udaipur district.

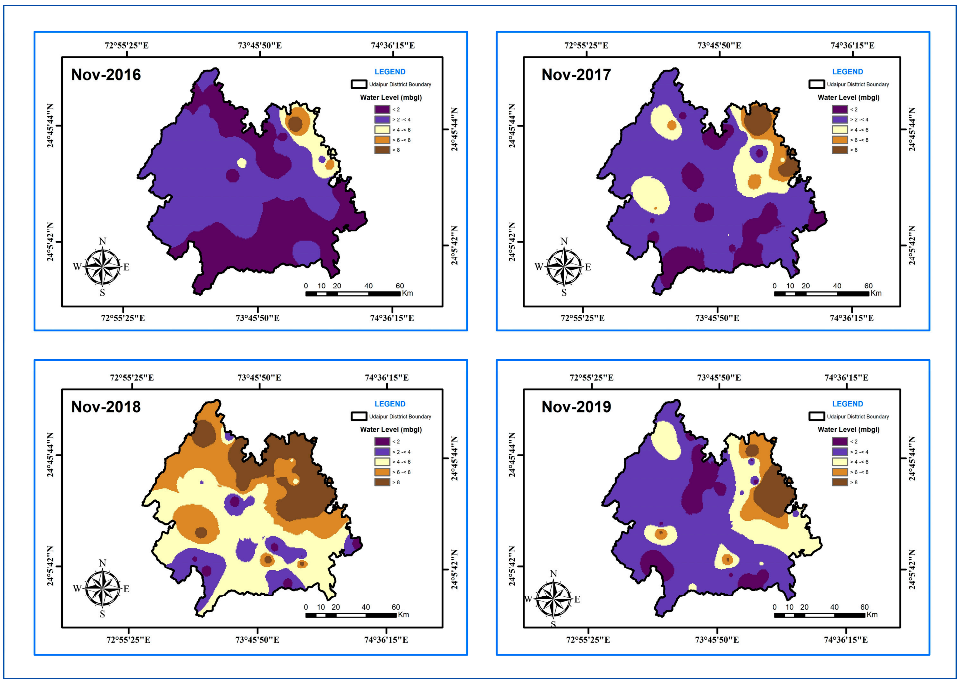

Figure 10. The water-level distribution of during post-monsoon season in the Udaipur district.

In pre-monsoon (May 2016 to 2019), most of the depths of water levels are less than 25 m. However, in the northern and north-eastern parts of the district, the water-level zones are slightly decreased. Similarly, for post-monsoon, the water levels in the area are shallow, which is less than 10 m, as per data collected from the hydrograph station. However, the general groundwater flow direction in the studied area is south-eastwards (Figures 11 and 12). According to the water-level contour map, the hydraulic gradient is 1/127.5, equivalent to 1/130. Water-level fluctuation in the area is around 3 m.

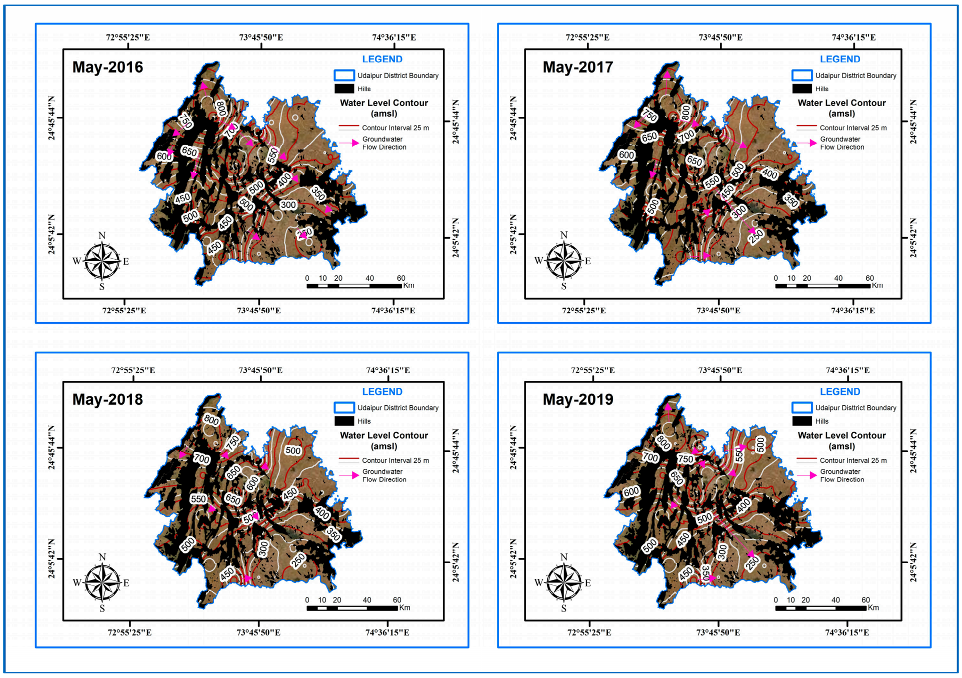

Figure 11. The water-level distribution, specifically contour information during pre-monsoon season in the Udaipur district.

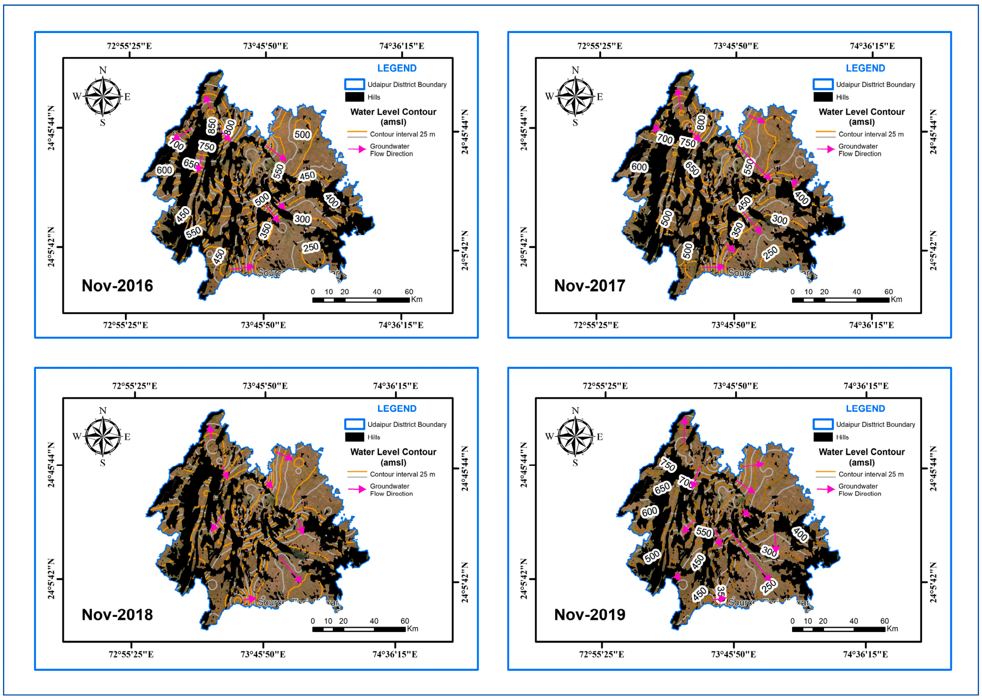

Figure 12. The water-level distribution, specifically contour information during post-monsoon season in the Udaipur district.

In the Aravalli formation, the central part consists of phyllite, quartzite, and dolomite, and are the principal aquifer lithologies for groundwater availability have low to medium permeability. Under unconfined zones, the availability and movement of groundwater is limited to weathered zones such as schistosity, joints, fissures, fractures, and bedding plains. The yield from these aquifers ranges from 20 to 200 cum/day [47]. In the Bhilwara formation, the eastern part of the studied area is characterized by schist, gneisses, and granite rocks. In a few places, extrusive/intrusive formations also exist with low permeability. Groundwater in this zone is in weathered joints and foliation planes under unconfined to semi-confined zones. The yield from these formations is 20 to 60 cum/day [61]. In the Delhi formation, the western-most zones consist of quartzite, biotite schist, calc schist, and calc gneiss with medium permeability. The groundwater occurs in joints and fractures with yields ranging from 12 to 250 cum/day under a semi-confined nature [62]. In the Alluvium formation, water occurs under unconfined zones and is highly permeable. However, due to overexploitation, these zones are dried out in the studied area. In these unconsolidated formations, sand, gravel, cobbles, and boulders exist and are found close to rivers. Most of the study area is covered by hard pavements of rocks consisting of weathered portions, fractures, joints, and bedding plains. During rainfall events, the recharge of rainfall-runoff water is directly percolated into the ground by natural seepage and infiltration [63].

3.3. Hydrochemical Characterization

The location of collected samples for chemical analysis is shown in Figure 13. The groundwater quality in terms of TDS is under permissible limits as per drinking water norms IS 10500:2015, except for a few isolated pockets in the north-east for 2016 to 2018 [64]. However, in 2020, the total area was under the permissible limits, indicating the impact of groundwater recharge on its quality. Similarly, all other parameters improved in 2020 compared to previous years. The distribution of major chemical ingredients is shown in Figures 14–22. The measurement of uranium levels in the district is less than 30 µg/L, as per the prescribed norms of the WHO [65].

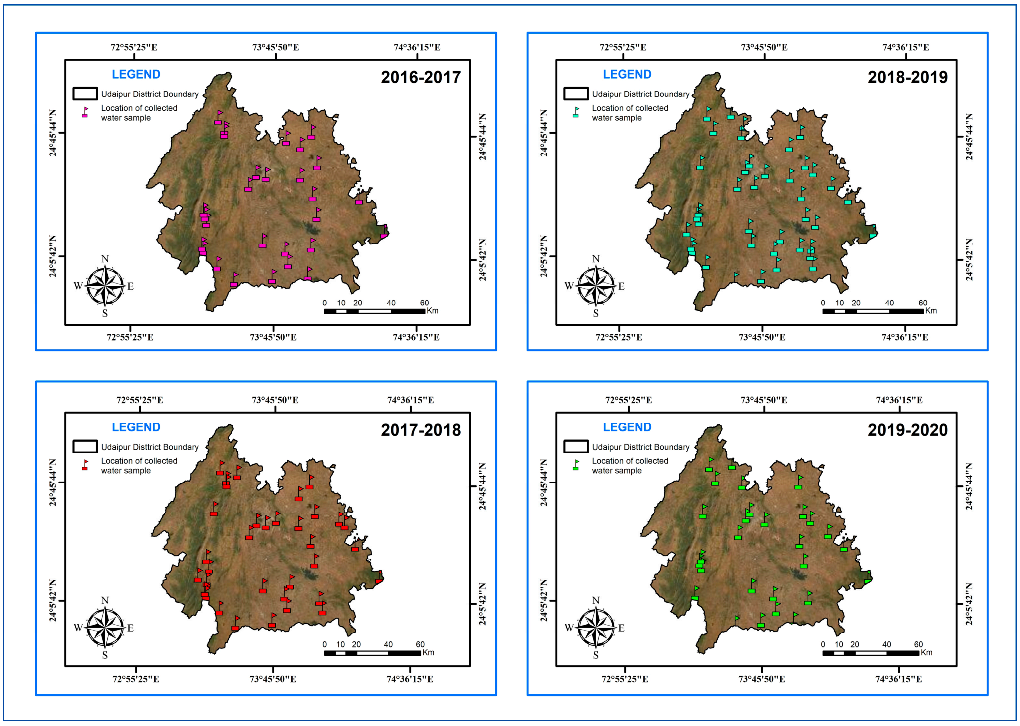

Figure 13. The location of collected samples for chemical analysis.

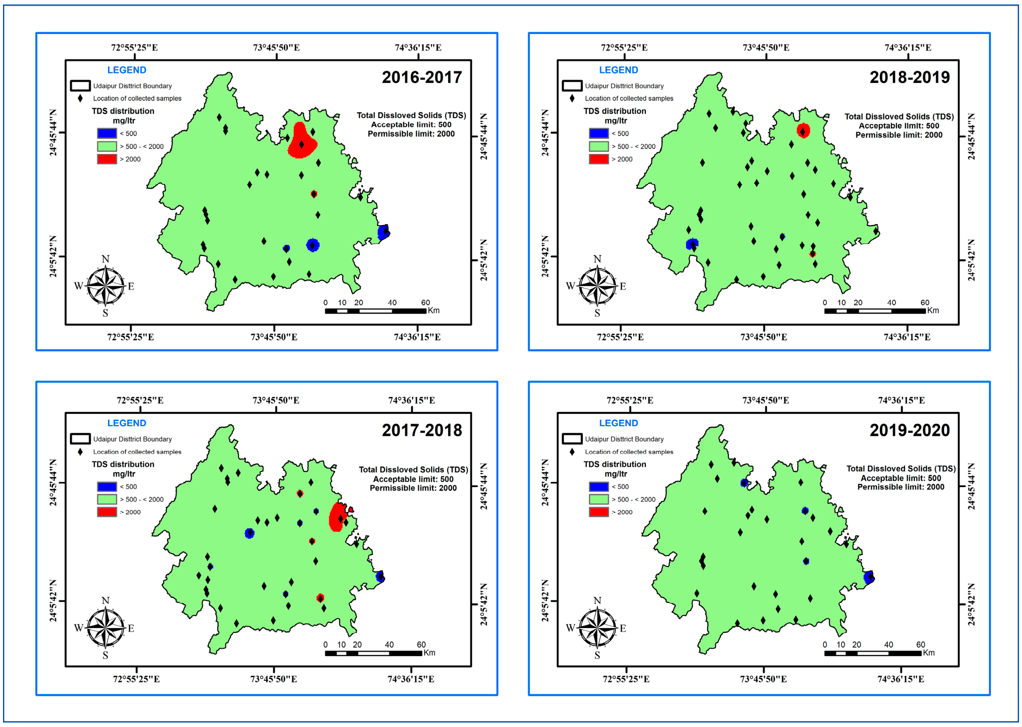

Figure 14. The changing distribution of TDS from 2016–2018 in the study area.

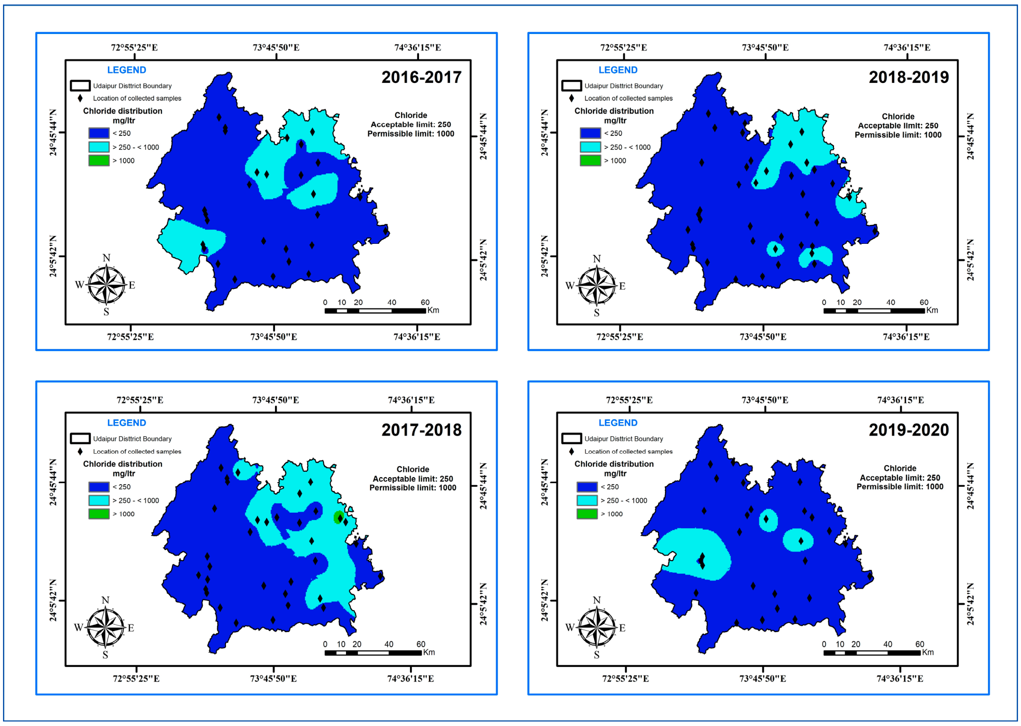

Figure 15. The changing distribution of chloride from 2016–2018 in the study area.

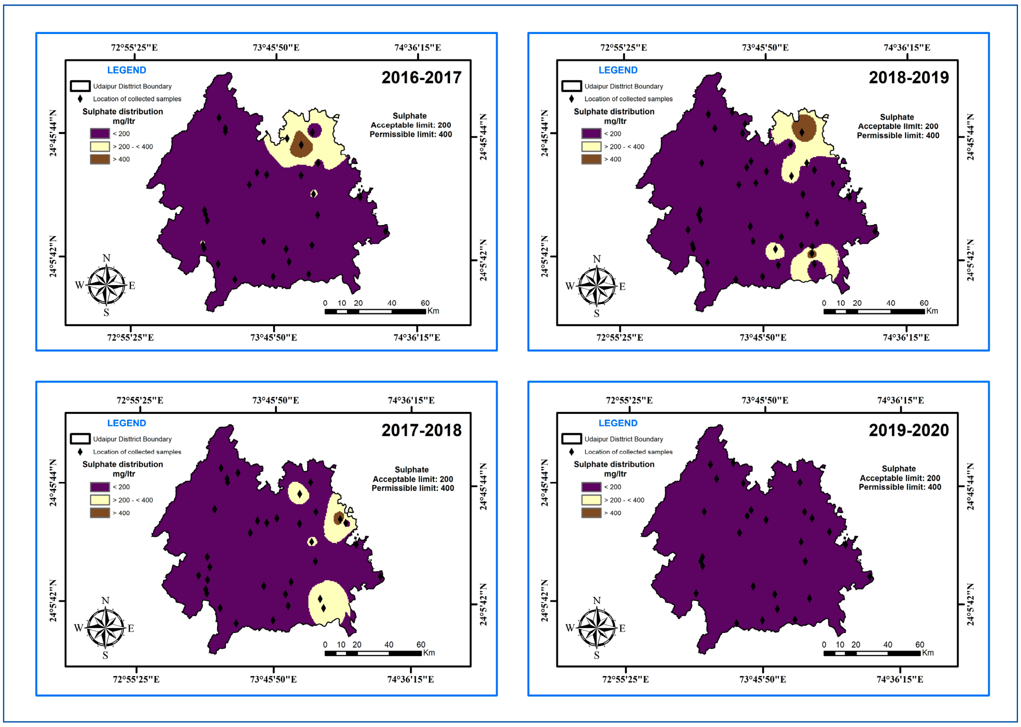

Figure 16. The changing distribution of sulfate from 2016–2018 in the study area.

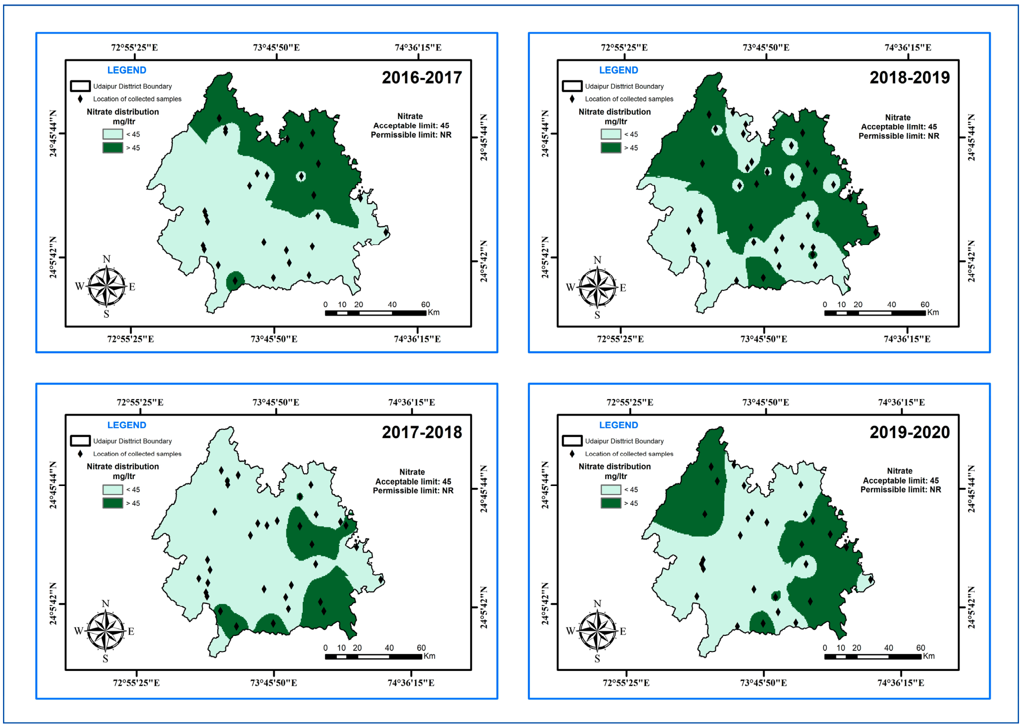

Figure 17. The changing distribution of nitrate from 2016 to 2018 in the study area.

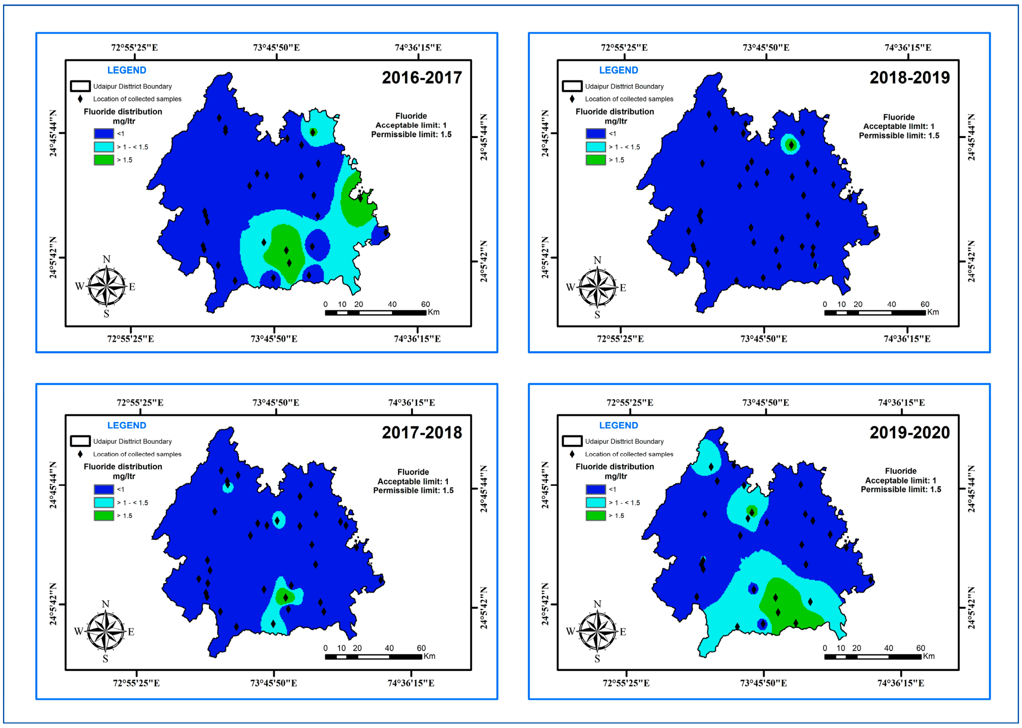

Figure 18. The changing distribution of fluoride from 2016–2018 in the study area.

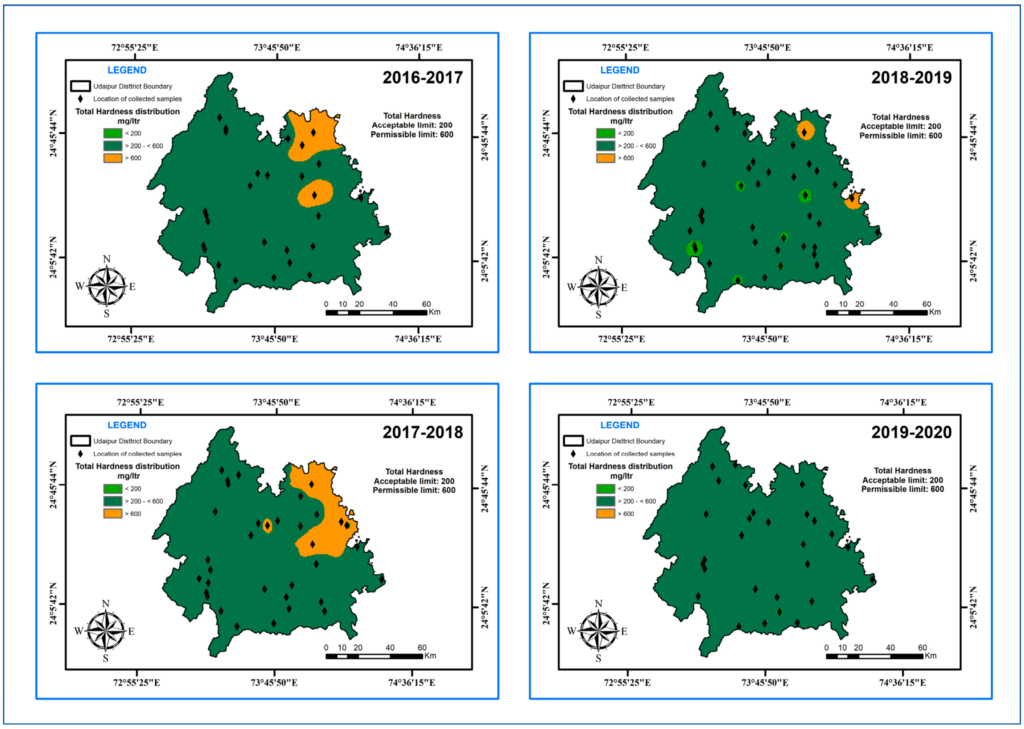

Figure 19. The changing distribution of total hardness from 2016–2018 in the study area.

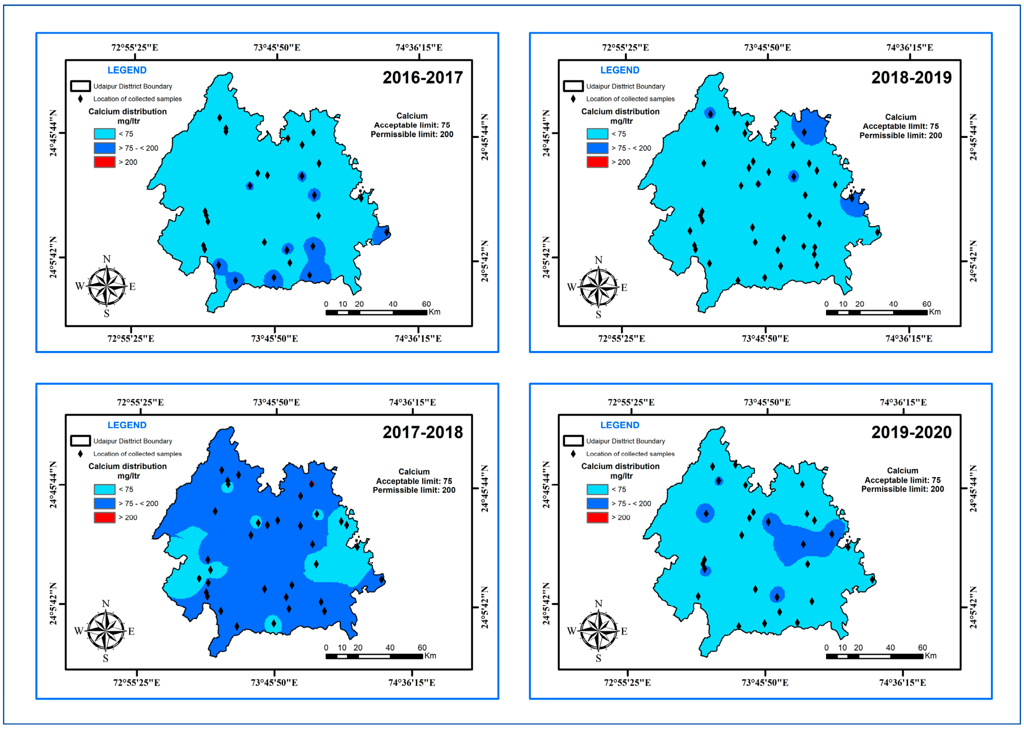

Figure 20. The changing distribution of calcium from 2016–2018 in the study area.

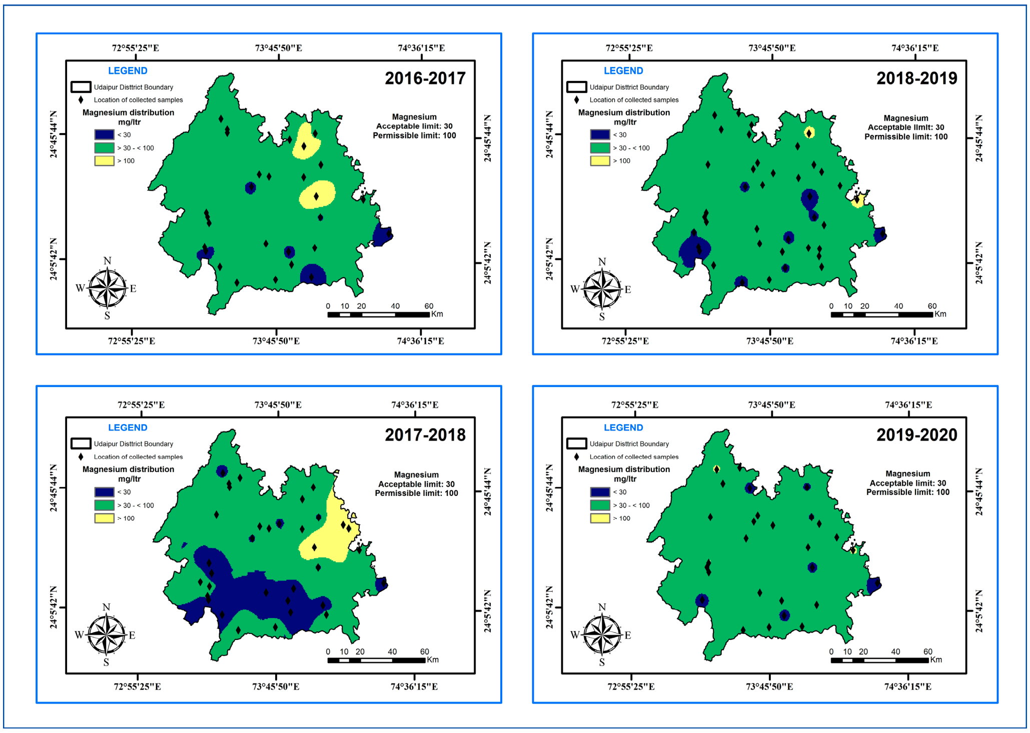

Figure 21. The changing distribution of magnesium from 2016–2018 in the study area.

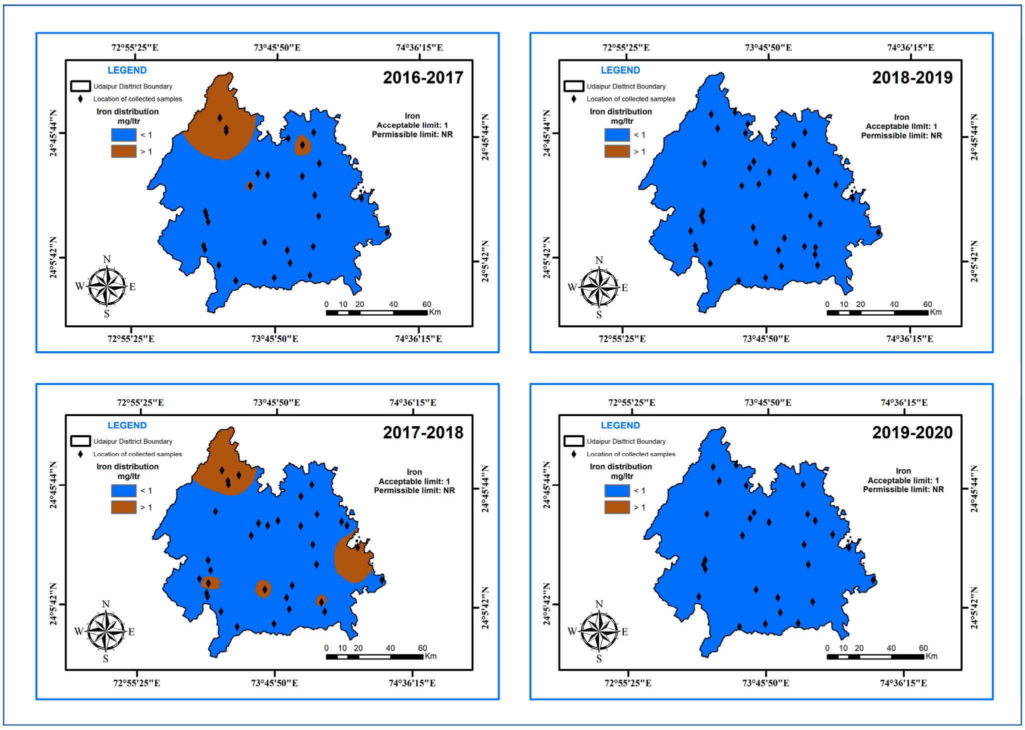

Figure 22. The changing distribution of iron from 2016–2018 in the study area.

3.4. Groundwater Resource Evaluation

As per the adopted methodology for the estimation of groundwater resource evaluation, the dynamic reserves of the area are 637.42 mcm/annum, consisting of recharge due to rainfall—353.19 mcm/annum, recharge due to river/stream—14.90 mcm/annum, recharge due to ponds—0.33 mcm/annum, and recharge due to applied irrigation—247.22 mcm/annum. The total groundwater draft is 639.67 mcm/annum, consisting of the draft due to domestic and other activities such as cattle—46.57 mcm/annum, draft due to industrial and mining projects—14.67 mcm/annum, draft due to applied irrigation—543.88 mcm/annum, draft due to evapotranspiration—0 mcm/annum, and draft due to natural outflow—34.55 mcm/annum.

The calculation reveals that there is a deficit of 2.25 mcm/annum. The stage of groundwater development is 100.67%, rendering the area in the over-exploited category, which is in line with categorization as a dynamic groundwater resource of India in 2020. However, there are enough static reserves to sustain consumptive groundwater use during the drought periods.

3.5. Projected Life of Reserves

The total deficit reserves are 2.25 mcm/annum based on average rainfall (627 mm). Using the linear equation model, the established relationship between rainfall and deficit/surplus reserves was used to project the availability of GW. The model is useful for predicting utilizable reserves in any nth year based on that year's rainfall. With the help of random number theory and correlation regression analysis, the following mathematical relationship has been calculated to estimate total water reserves in the region for a minimum to maximum rainfall [66–71]. The equation governing the above relationship is

$$Y = 1.10274\,X - 638.84 \tag{2}$$

where Y = water reserves in mcm/annum and X = rainfall in mm/annum. With the help of the above analysis, total water reserves are predicted for various rainfall values, as given in Table 4. Figure 23 reveals that if rainfall is below average, there would exist deficit reserves, and if the rainfall is above 700 mm, there will be surplus reserves available on the present groundwater draft (10% growth rate of groundwater draft on every year) [72–74].

Table 4. Deficit/Surplus reserves at different rainfall events.

Rainfall in mm/annum (X)	Dynamic Reserves in mcm/annum	Groundwater Draft in mcm/annum	Total Deficit/Surplus Reserves in mcm/annum (Y)
100	101.66	639.67	−538.01
200	203.32	639.67	−436.35
300	304.99	639.67	−334.68
400	406.65	639.67	−233.02
500	508.31	639.67	−131.36
600	609.97	639.67	−29.70
627	637.42	639.67	−2.25
700	711.63	639.67	71.96
800	914.96	639.67	275.29
900	914.96	639.67	275.29
1000	1016.62	639.67	376.95
1100	1118.28	639.67	478.61
1200	1219.94	639.67	580.27

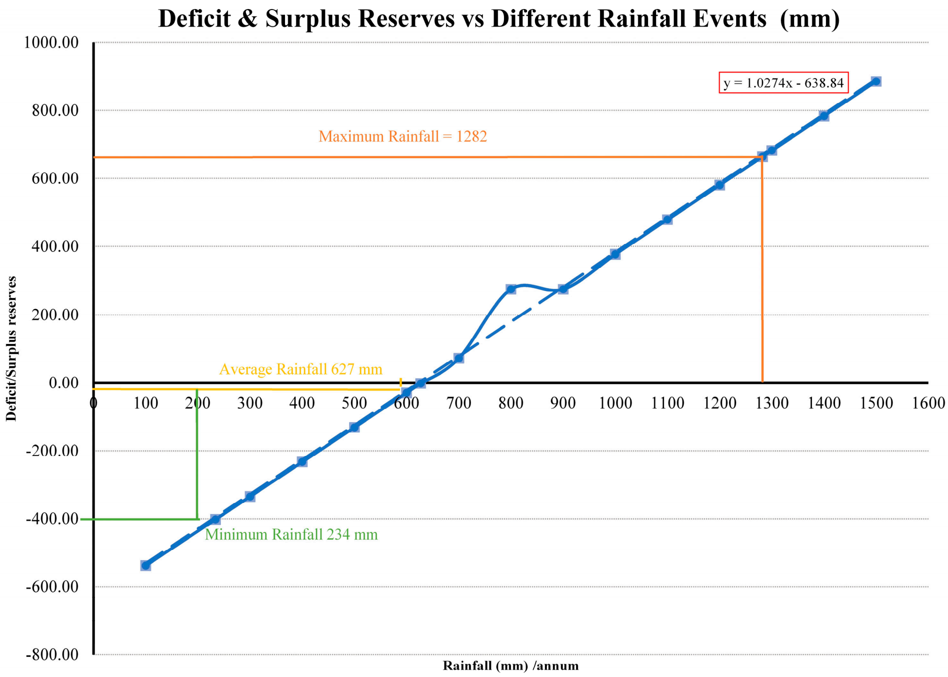

Figure 23. Regression model between deficit/surplus reserves and the rainfall.

3.6. Sustainability Management of Groundwater Reserves

The total deficit reserves are 2.25 mcm/annum based on average rainfall (627 mm). In such a situation, for sustainable groundwater development, groundwater recharge measures equivalent to deficit reserves are required from large rainwater-harvesting structures, water conservation, reuse–recycle measures, and regulation of existing groundwater draft [75–78]. The draft may increase in future scenarios due to growth in population, industrial development/expansion of existing industrials, mining/expansion of mining, and agriculture sectors. Therefore, the net groundwater draft will be more than what is required at present [78,79].

The available dynamic reserves are 637.42 mcm/annum, and the deficit reserves are drawn from static reserves. Hence, it is essential to control groundwater abstraction and optimize groundwater use by modernizing the existing irrigation practices using a sprinkler-drip irrigation system, thus achieving more crop per drop. Recycling and reusing water through STP at the municipal/panchayat level is the most pressing current need. Moreover, creating maximum groundwater recharge structures and diverting floodwater to different places where groundwater is not available can be useful strategies to sustain long-term use [80,81].

4. Conclusions

As per hydrological observations, the Precambrian Aravalli range occupies an area with elevation range between 155–1333 m AMSL. The main rivers in the studied area are the Sabarmati, Banas, Mahe, and Luni, which are the principal rivers carrying rainfall-runoff water. These rivers are seasonal rivers, with dendritic to sub-dendritic drainage conditions with 5–6 stream order that flow from central to south and south-east, north and north-west to east, and north-central to west of the district. Geomorphologically, the area can be sub-divided into hills (structural/linear/denudational), denudational origin (pediment/buried pediment), and fluvial origin (valley fill). The area is climatically subtropical and subhumid, with semi-arid conditions. The average annual rainfall is 627.77 mm. The peak daily rain is 299 mm. The yearly average rainfall events were 30 days from 1957 to 2020. This reveals that there are chances to receive surplus rainfall year once following five consecutive rainfall deficit years. As per hydrogeological studies, the area belongs to the Aravalli, Bhilwara, and Delhi supergroup formations, consisting of quartzite, phyllite, gneisses, schist, banded gneissic complex, carbonate rocks, and dolomitic marbles. The principal aquifer in the studied area is quartzite, phyllite, gneisses, schist, and dolomitic marble, which are under unconfined to semi-confined. The combined hydraulic parameters of all aquifers are transmissivity (15.63 m^2/day), specific yield (1.5%), and hydraulic gradient (1/130). The average water levels for pre- and post-monsoon are less than 25 m BGL. The general groundwater flow direction is towards the south-east of the district, and the fluctuation in water level is around 3 m. The average yield from all aquifers is 47 m^3/day. As per hydrochemical studies, all primary chemical ingredients, such as pH, electric conductivity (EC), chloride (Cl), carbonate (CO_3), nitrate (NO_3), sulfate (SO_4), phosphate (PO_4), calcium (Ca), total hardness (TH), magnesium (Mg), sodium (Na), fluoride (F), potassium (K), iron (Fe), silicon dioxide (SiO_2), total alkalinity and total dissolved solids (TDS) are in under permissible limits as per drinking water norms of ISO 10500–2015. Similarly, uranium (U) is also under prescribed norms as per the WHO. This reveals that excess rainfall years have water quality under the permissible limit, and with deficient rainfall events, groundwater quality is slightly bad. The dynamic reserves of the area are 637.42 mcm/annum, and the total groundwater draft is 639.67 mcm/annum. Hence, with deficit reserves of 2.25 mcm/annum on average rainfall of 627 mm, the state of groundwater development is 100.67%, and categorized as over-exploited. However, as per the relationship between reserves and rainfall events, surplus reserves are available if rainfall is at or above 700 mm. Meanwhile, enough static reserves are available in the studied area to sustain the drought period. For the long-term sustainability of groundwater use, the control of groundwater abstraction and optimization of its uses by replacing existing irrigation practices with sprinkler-drip irrigation and achieving more crop per drop, adopting recycling and reuse of water through STP at the municipal/panchayat level, is the most pressing current need. Moreover, it is also necessary to create maximum groundwater recharge structures as feasible and interlinking rivers for diverting floodwater to different places where groundwater is not available, or unable to sustain long-term use.

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