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Article

Geophysical Investigation, Quality, and Sustainability Analysis of Groundwater in Mewat (Nuh) District, Haryana, India

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Abstract: This study utilizes geophysical investigations, combining both surface and subsurface methods, assessing quality and mapping aquifers in Haryana's Mewat district, India. The primary objectives are to delineate the interface between freshwater and saline water, both horizontally and vertically and to perform a quality and sustainability analysis. It has been observed that topsoil, approximately 12 m thick, has resistivity values ranging from 11 to 35 ohm-m, where higher values indicate lower soil saturation. Resistivity exceeding 15 ohm-m correlates with granular zones housing fresh groundwater, while values below 15 ohm-m signal saline to brackish groundwater. Approximately 55% of the region features saline groundwater, mainly in central, western, and southern areas. Freshwater resources within a depth of 30 m cover 26–30% of the area, mainly in the northwest and southwest parts. Beyond 40 m, freshwater availability drops significantly, with depths exceeding 100 m likely encountering hard rock or saline horizons. This study also highlights low freshwater yield challenges due to thin granular zones and variable bedrock depths, some as shallow as 90 m. Additionally, the research examines infiltration rates, ranging from 90 mm/h to 660 mm/h initially and 5 mm/h to 164 mm/h ultimately, with an average rate of 151 mm/h, highlighting sandy soils with some clay limitations. Utilizing available data, a three-dimensional hydrogeological model was constructed, shedding light on groundwater-related issues, such as depletion, waterlogging, water quality, and excess salinity. Groundwater development reached ~80%, categorized as semi-critical. Depletion affects areas with fresh groundwater, and waterlogging is a concern in central and north-eastern regions. In addition to salinity, other water quality issues are higher nitrate, sodium, and chloride concentrations, leading to salt-affected soils in specific blocks like Nuh and Nagina. In summary, this study offers a comprehensive assessment of groundwater resources in Mewat, Haryana, emphasizing sustainable utilization and tailored management of localized challenges. This underscores the importance of integrated water resource management to ensure prudent use while preserving the environment for future generations.

Keywords: geophysical investigations; aquifer mapping salinity; groundwater quality; sustainability

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1. Introduction

Groundwater resources across the planet can be utilized for various uses in domestic, industrial and agricultural sectors, and other developmental purposes. Groundwater acts as an important source of freshwater in various parts of India, catering to a number of vital purposes, such as irrigation and drinking water supply. Furthermore, it is a verified reality that India holds the title of being the world's foremost consumer of groundwater [1], utilizing approximately 205 cubic kilometers of it annually [1]. In India, the surge in groundwater demand has risen significantly due to the rapid expansion of the population, industrialization, and urban development [2]. India relies extensively on groundwater across a multitude of sectors, with agriculture being the most crucial. Consequently, there is significant interconnection between groundwater and agriculture in India [3]. Agriculture plays a pivotal role in India's economy, contributing approximately 15–20% to the national

GDP. Agriculture has been a cornerstone of the country's economic advancement and efforts to reduce poverty. Groundwater serves as a source of freshwater for more than fifty percent of the irrigated areas in India as well [4,5]. Nonetheless, the continuous use of polluted water for irrigation can lead to a decline in soil quality, rendering it less fertile or even unsuitable for agricultural purposes [6]. Approximately 200 districts spanning 19 Indian states exhibit groundwater pollution [7], encompassing issues such as elevated salinity levels [8], heavy metal presence [9], fluoride contamination [10], and arsenic contamination [11]. The Mewat district in the Indian state of Haryana is representative of a semi-arid area, where the annual precipitation typically falls within the range of 200–500 mm [12], with temporary lakes and a moderate level of groundwater found in alluvial aquifers, faces the problem of integral widely spread groundwater salinity problem [13–16]. The implementation of groundwater initiatives in regions with limited and unpredictable rainfall is a vital environmental factor to enhance agricultural productivity [3]. This study in Haryana's Mewat district serves multiple significant purposes. There have been many studies conducted by various researchers on the salinity issues and the mechanisms involved in Mewat, Haryana and adjoining areas [13–16] but no work has been reported on geophysical investigations. Therefore, this study was carried out to address a need for a thorough hydrogeological evaluation and comprehension of aquifer distribution, interfaces between freshwater and saline water, and geological attributes. These insights are crucial for informed, sustainable water management. A primary outcome is identifying freshwater resources through meticulous aquifer mapping, empowering local communities and policymakers to manage water use effectively in the face of scarcity. The primary objective of this study is to offer essential data and insights for informed water resource management in Mewat, equipping decision makers to tackle unique water challenges and ensure long-term security.

2. Material and Methods

2.1. Study Area

Mewat (Figure 1) is located in the northwestern part of India within Haryana state, covers an area of 1859.61 km^2 and is the 16th largest district in the state. Its geographic coordinates are approximately 27°39′ to 28°20′ latitude, 76°51′ to 77°20′ E longitude, and an elevation of approximately 199 m above sea level. The district was cleft from the Gurgaon district and Hathin block of Faridabad district 4 April 2005. As per the 2011 census, the district has a population of 1,089,406 with a population density of 723 persons/km^2, whereas the decennial growth rate is 37.93%. There are 443 villages in the district. In total, there 160,280 households in the district as per the 2011 census. The district touches administrative boundaries with the Gurgaon, Faridabad, Palwal, and Rewari districts of Haryana State. The Mewat district comprises five Tehsils, namely Nuh, Ferozepur jhirka, Punhana, Tauru and Nagina. There are seven administrative development blocks, namely Taoru, Nuh, Indri, Nagina, Pingwan, Punahana and Ferozepur Zirka.

The district falls under a semi-arid climate zone, which is marked by extremely hot summers and dry air. The hottest month in the district is June, with temperatures reaching up to 48 °C, whereas January is the coldest month, with temperatures dropping to 2 °C. Rain mostly occurs during the monsoon period, with scattered showers throughout the rest of the year. The district has an average annual rainfall of 594 mm. The district forms a part of the Ganga Sub Basin, i.e., Yamuna, and is occupied by alluvial plains of the Quaternary age. Physiographically, the district is more or less bowl shaped. The district has an undulating topography and is traversed by a ridge of Delhi quartzites, which runs from north–south to north–northeast–south–southwest directions. The district is drained by the distributaries of the Gurgaon canal and artificial drains named Nuh, Ujjina, and Kotla drains. Most of the district is covered by loamy textured soils with a predominance of silt and clay over sand. As the organic content of these soils is very low, they are categorized as vertisols, and their salt-affected variant is known as salanchalk. The Nuh and Nagina blocks have an abundance of salanchalk-type soil, which is easily identifiable by the absence of vegetation.

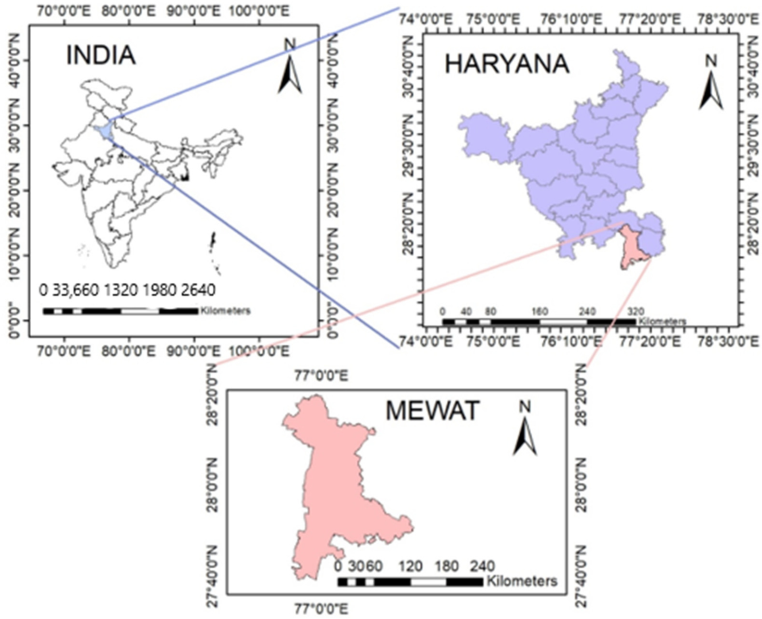

Figure 1. Map showing the study area, Mewat, Haryana.

2.2. Geophysical Data Collection

Geophysical investigations were conducted to determine the principal aquifer system of the Mewat district. A total of 28 Vertical Electrical Soundings (VES), 5 borehole logging, and 8.4 line-km ERI were carried out to delineate the fresh–saline water interface both laterally and vertically. The locations of VES conducted can be seen in (Figure 2). The instrument used for this purpose was ABEM Terrameter-SAS 300C, made in Sweden. The VES was carried out using the Schlumberger configuration, and the range of current electrode separation was within 200 m to 1000 m. During the VES, different types of multilayered VES curves such as K, KH, HK, and Q types were recorded, and their interpretation was carried out by matching them with master curves [17] to determine the true resistivity and thickness of different geo-electrical layers. The interpreted resistivity data have been standardized with the existing hydrogeological data on the groundwater quality of the boreholes located near the location of VES.

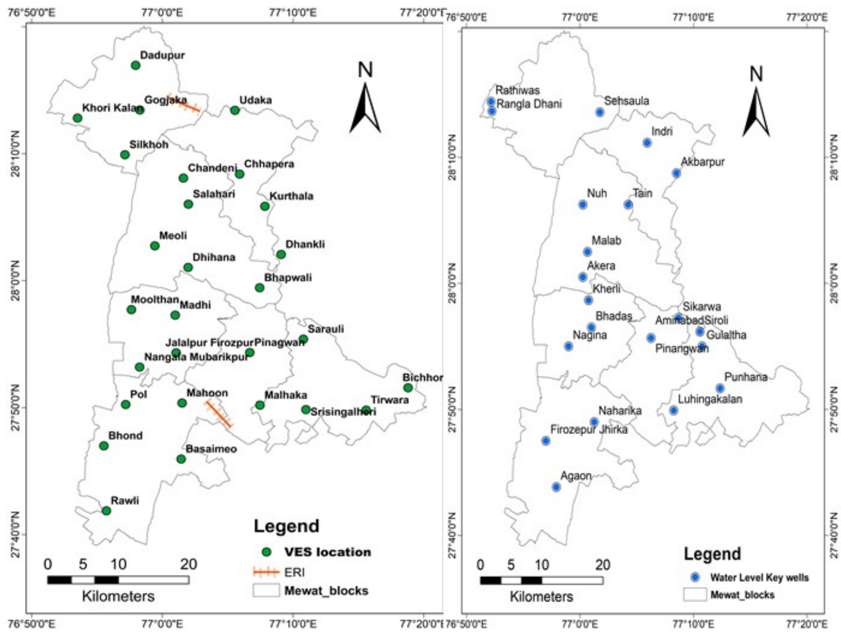

Figure 2. Location map showing VES conducted and water level wells in Mewat, Haryana.

2.3. Soil Infiltration

The infiltration rate depends on soil texture (the size of the soil particles) and soil structure (the arrangement of the soil particles) [18]. The infiltration rate is a useful way of categorizing soils from an irrigation point of view. Soil infiltration tests using a double-ring infiltrometer at sixty-seven locations were carried out in the Mewat district of Haryana.

2.4. Groundwater Level Monitoring

Groundwater levels were monitored through dedicated groundwater monitoring stations (GWMS) of dug wells and piezometers in Mewat district manually through a water level sounder (Figure 1).

2.5. Water Sampling and Analysis

A total of 11 groundwater samples were collected from dedicated groundwater monitoring stations (GWMS) that consisted of dug wells and/or hand pumps of shallow depth. At the site, pH, EC using a handheld pH/EC meter, and HCO_3 using a titration method were measured. The water samples were then analyzed for major cations (Ca, Mg, Na, K) and anions (F, Cl, NO_3, SO_4, PO_4) as well as SiO_2 and heavy metals at the Regional Chemical Laboratory. The analysis was conducted following 'Standard Analytical Procedures' as per the guidelines mentioned in the American Public Health Agency [19] 23rd Edition of 2017 and Bureau Indian Standards (BIS), 2012 [20]. Data accuracy was verified by checking the charge balance error (CBE) of the major ions, which was found to be within −0.49 to +2.52% for all samples in the Mewat district.

2.6. Map Preparation

The maps were prepared using ARC—GIS 10.7, whereas Rockworks 15 is used to prepare the Aquifer map and profile section.

3. Results and Discussions

3.1. Geophysical Investigation

Geophysical investigations were conducted to determine the principal aquifer system of the Mewat district by using both the surface and subsurface techniques. Surface techniques used were Vertical Electrical Soundings (VES) and 2D electrical resistivity imaging (ERI), whereas the subsurface technique used was Boregole logging. A total of 28 VES, 5 borehole logging, and 8.4 line-km ERI were carried out to delineate the fresh–saline water interface both laterally and vertically. The geophysical methods determine the resistivity of the subsurface rocks. The instrument used for this purpose was ABEM Terrameter-SAS 300C, made in Sweden. The VES was carried out using the Schlumberger configuration, and the range of current electrode separation was within 200 m to 1000 m. The locations of VES conducted can be seen in (Figure 2). During the VES, different types of multilayered VES curves such as K, KH, HK, and Q types were recorded, and their interpretation was carried out by matching them with master curves [17] to determine the true resistivity and thickness of different geo-electrical layers. The interpreted resistivity data have been standardized with the existing hydrogeological data on the groundwater quality of the boreholes located near VES. The 2D electrical resistivity imaging was carried out in Mewat district to produce two-dimensional subsurface resistivity image in a short time (continuous subsurface resistivity picture), to substantiate the sounding results across the geologic structures where the conventional approach of sounding or profiling may not yield fruitful results. Imaging was carried out using a multielectrode resistivity imaging system AGI Super sting R-8. The raw data were processed using RES2DINV ver 4.07 software to prepare the final inversion image of resistivity values. Once the inversion was complete, the subsurface classification was carried out based on the general resistivity values for different lithology as shown in Table 1. The locations of ERI conducted can be seen in (Figure 2). During geophysical borehole logging, the self-potential (SP) and electrical resistivity along with natural gamma radioactivity were used while drilling the exploratory borehole.

Resistivity values ranging between 11 and 35 ohm-m indicate the presence of clay in the topsoil. An increase in resistivity suggests that the topsoil has a low degree of saturation [21]. Typically, the thickness of this layer is approximately 12 m. Groundwater quality can be determined by resistivity values > 15 ohm-m, indicating fresh groundwater, while <15 ohm-m indicates saline to brackish quality water. The granular zones are composed of sand and kankar [22].

Based on surface geophysical studies carried out in Mewat district, it can be inferred that the district mainly has saline groundwater quality within a depth of 30 m. These areas are predominantly found in the southern, central, and western parts of Mewat district. Only approximately 26 to 30% of the total district area, covering Tauru block, Mohun, and Ghata-Shamsabad, has freshwater within a depth of 30 m.

Freshwater can only be found below a depth of 40 m in the Tauru block located in the northwest, as well as in Patkhori and Patan-Udaipuri in the southwest. At a depth range of 20–30 m, freshwater zones have been identified from Ghata- Shamsabad, Gharot, Mohun, Palla, Ritath, Righor, Naharka, Tigaon, Bhond, Dhundkhurd, Dhanwala, Mandkola, Rangala-Rajpur, Nangal- Mubarakpur, Jahidpur, Luhinga Kalan and Ghagaskhori.

According to the VES data, freshwater can be found between the depths of 40 and 80 m in Langra, Dhulawat, Charora, Didhara, and Kankarka. However, in these areas, groundwater becomes saline beyond 80 m below ground level. In the northwest of the district, specifically at Patkhori, Patan-Udaipur, Kalbari, Tauru, Chahalka, Sarai, and Kankarka in the Touru Block, there is a possibility of finding freshwater at approximately 100 m deep. A geo-electrical section was prepared based on the VES carried out in the district, and it is shown in Figure 3.

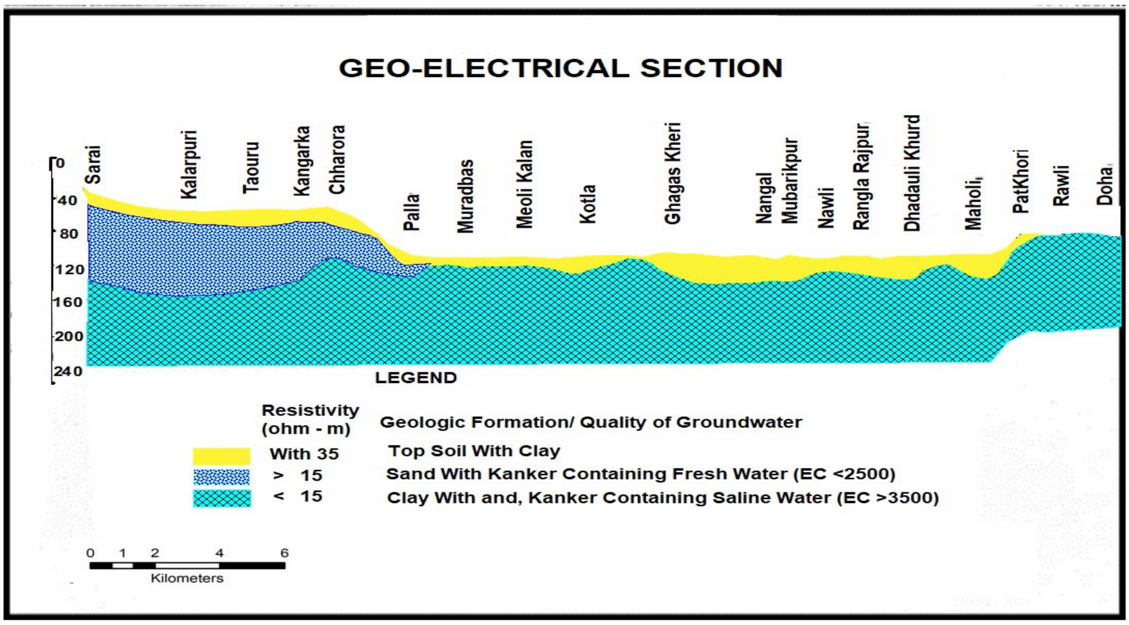

Figure 3. Geo-electrical section in parts of Mewat, Haryana.

Resistivity values ranging between 11 and 35 ohm-m indicate the presence of clay in the topsoil. An increase in resistivity suggests that the topsoil has a low degree of saturation [21]. Typically, the thickness of this layer is approximately 12 m. Groundwater quality can be determined by resistivity values > 15 ohm-m indicating fresh groundwater, while <15 ohm-m indicates saline to brackish quality water. The granular zones are composed of sand and kankar. Table 1 shows the general resistivity ranges of the inferred lithological predominance and groundwater quality.

Electrical resistivity imaging (ERI) conducted in 8.4 km in the Mewat district and the resistivity image section for ERI carried out in hard rock are prepared (Figure 4) and

ERI in the alluvial part in Mewat district is shown in Figure 5. At approximately 400 and 600 line-m, there is a thickening of the weathered zone and a sudden deepening of the weathered zone. In these weathered zones, the boreholes can be drilled to tap the saturated weathered and deep fracture zones.

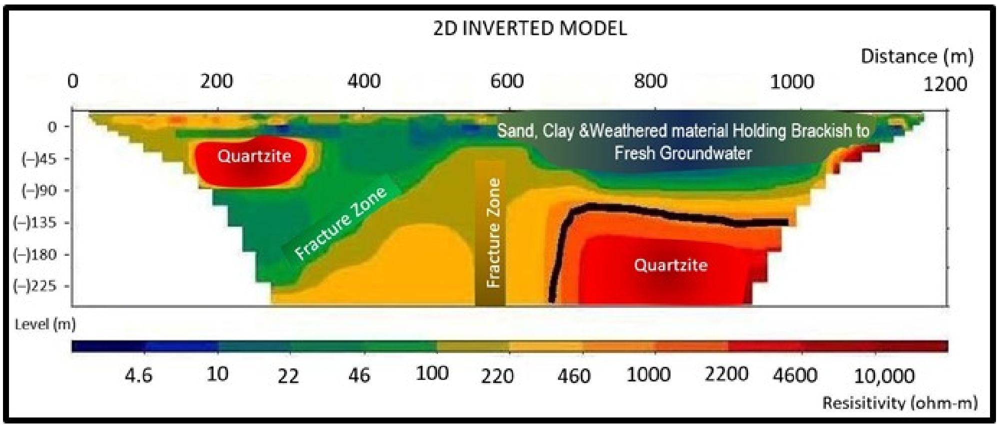

Figure 4. Resistivity image section from the hard-rock area, Mewat, Haryana.

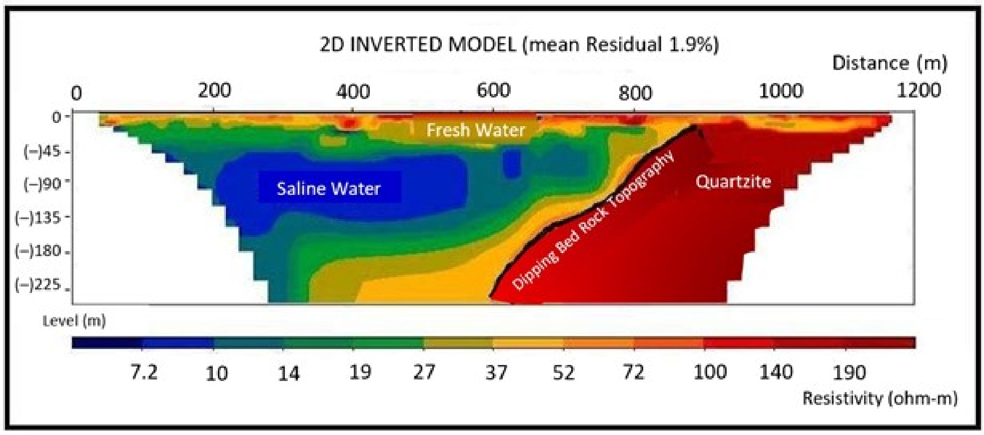

Figure 5. Resistivity image section from the alluvial area, Mewat, Haryana.

Table 1. General resistivity ranges for different lithological predominance and interstitial water quality (source: Kellerand Frischknecht, 1996 [23]).

Resistivity (ohm.m)	Inferred Lithological Predominance	Inferred Groundwater Quality in the Formation
1 to 3	Clay	Saline
4 to 6	Clay with kankar	Saline (at a deeper level) to brackish (at a shallow level)
7 to 9	Clay with fine sand and kankar	Brackish
10 to 15	Clay with fine sand and kankar	Marginally fresh
>15	Fine sand and silt	Fresh
10–150	Surface soil of different lithology and varied moisture contents	
≈25	Weathered and ridge derived material	Fresh
100–150	Fractured rock	Fresh
High (bottom most layer delineated)	Igneous/metamorphic bedrock	----

The details of boreholes drilled in alluvium and hard rock with aquifers encountered at different depth ranges, groundwater salinity and depth of bed rock are given in Table 2 based on borehole logging.

Table 2. Geophysical borehole logging carried out in Mewat district.

S. No	Site Name	Depth Drilled	Depth to Bedrock	Cumulative Thickness of Aquifer (in meters)		
				0–100	100–200	200–300
1	Sehsaula	178.5		Fracture Zones 103.9–108.5, 163.3–170.9		
2	Salaheri	243.68	231.27	Saline	Saline	Saline
3	Jalapur	158.8	156	Saline	Saline	
4	Dungeja	200		Fracture Zones 39–39.5, 112–112.5		
5	Sohalpur	200		12.81–14.81 (Saline)	(0.5) (174–174.5) (Saline)	Weathered Zone: 12.81–14.81, Fracture Zone −174–174.50

In hard rock areas, the conventional resistivity sounding does not yield much information on the deeper saturated fracture zones for which parallel gradient resistivity profiles across lineament, followed by resistivity sounding would possibly be required.

Electrical logging is used as substitute of lithological core sample analysis carried out during exploration; but these logs are incapable of differentiating between saline patches and clay. As both the clay and saline water have low resistivity, so it is difficult to differentiate them as per their resistivity. To differentiate between clay and saline patches, further gamma logging must be carried out along with the lithological core sample analysis. Well assembly designed only on the basis of geophysical logging is the main reason for well failure nowadays. So, geophysics is a good technique to enhance knowledge, but it cannot be solely used to draw inferences. Its results must be correlated with exploration drilling carried out in that area. A composite log must be prepared and further interpretation should be carried out on that basis. The same has been added to text.

3.2. Soil Infiltration Tests

To determine tectonic influences, a digital elevation map and a slope map of the study area are shown in Figures 6 and 7. Soil infiltration studies in the district have inferred that the water infiltration capacity of the soil initially ranges between 90 mm/h and 660 mm/h (Figure 8), whereas the final rate of infiltration in the district varies between 5 mm/h and 164 mm/h (Figure 9). The average rate of infiltration of the Mewat district is estimated to be 151 mm/h. The higher initial rate of water infiltration at a few sites indicates the presence of cracks and the sandy nature of local soil. With further water application, the infiltration rate started reducing quickly due to the presence of clay in the soil [24]. Due to the expansion of clay minerals, there is a reduction in pore spaces, which disturbs pore connectivity and decreases infiltration [25,26]. The low infiltration rates are also observed at a few sites, indicating poor percolation of excess water through the subsurface, which results in water logging and salinity in that area. The texture of the soil is loamy clay with a predominance of sand at a few places. The statistical power function yielded a coefficient of determination (r^2) between 0.75 and 0.99 for the observed 67 infiltration rate data points (y, mm/h).

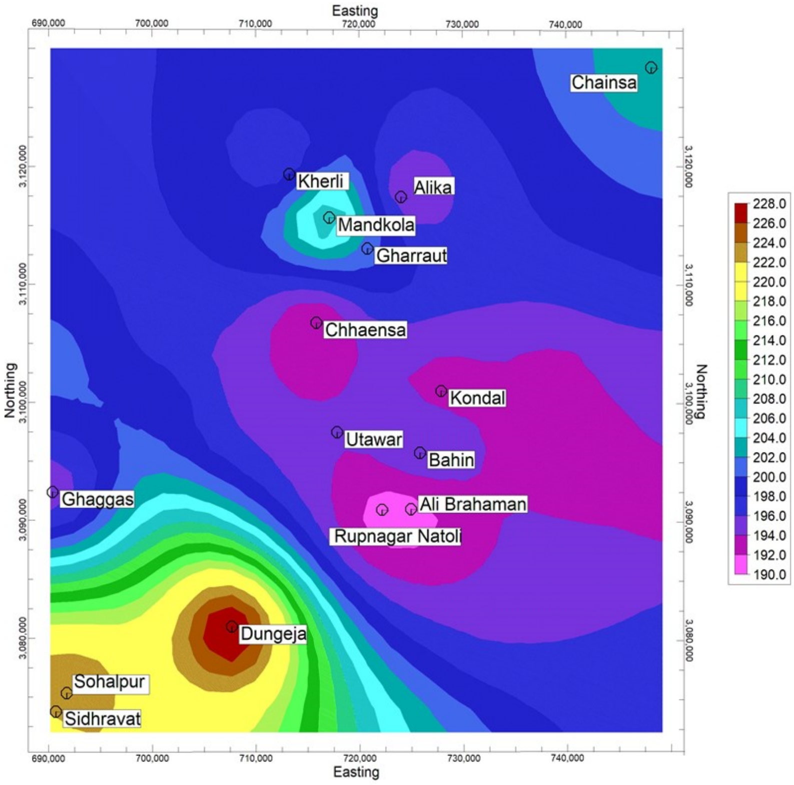

Figure 6. Elevation contour map of Mewat, Haryana.

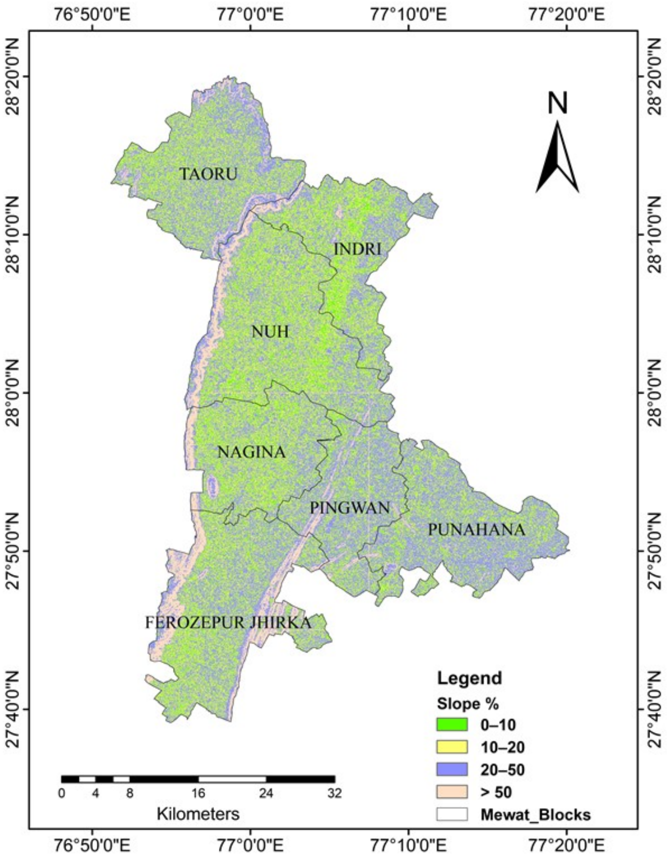

Figure 7. Slope map of Mewat, Haryana.

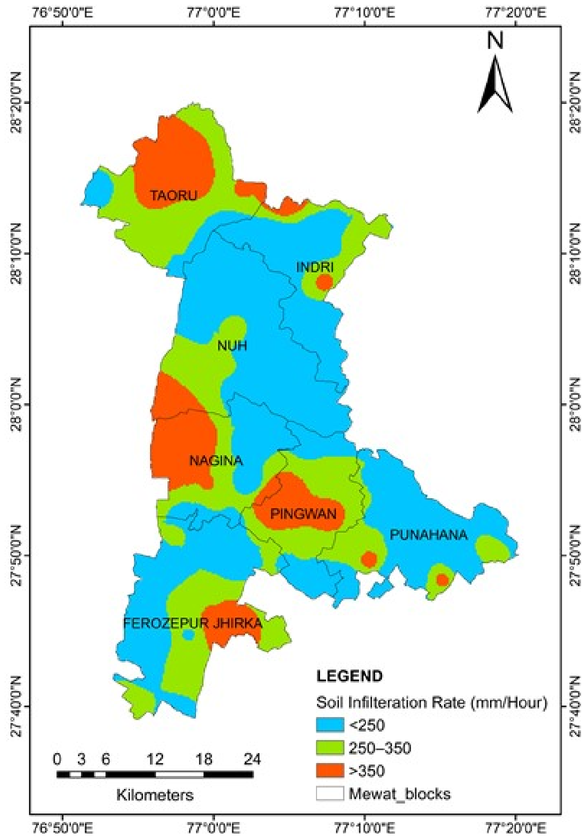

Figure 8. Soil infiltration map showing the initial rate of infiltration, Mewat, Haryana.

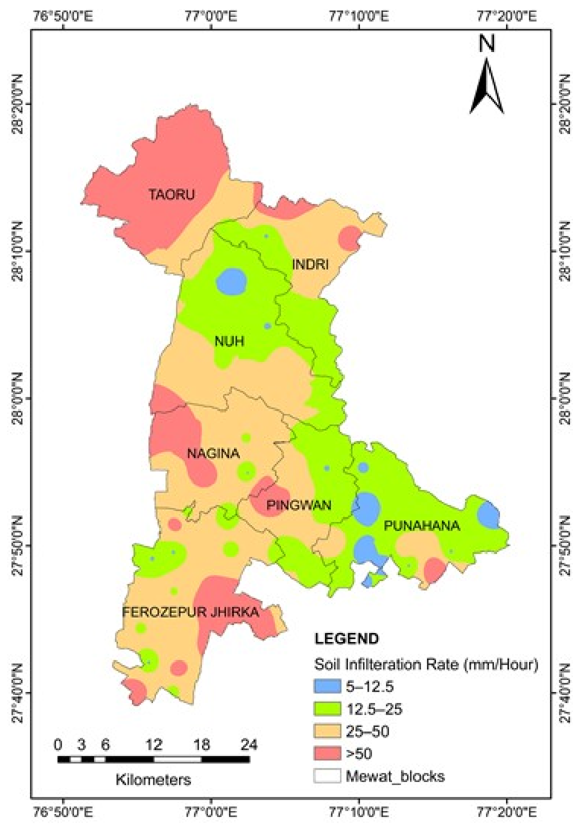

Figure 9. Soil infiltration map showing the final rate of infiltration, Mewat, Haryana.

3.3. Aquifer Mapping

On the basis of available lithological exploration and geophysical data of the study area, a 3D hydrogeological model is generated by using the RockWorks version 15 software to understand the lithological framework and aquifer disposition of the district. The lithology data of exploration and observation wells drilled in house by the Central Groundwater Board [26,27], the Public Health and Engineering Department (PHED), and private agencies are integrated and optimized. A contour map is prepared based upon the difference in elevation of the optimized wells. The 2D cross-sections of lithology have been prepared. The three-dimensional lithological fence diagram provides a clear representation of subsurface lithology in space and has also been prepared using the lithology model and is discussed in the following section. The lithology and its geometry define the nature of aquifer formation in the region and thus provide the basic parameters for determining the occurrence and movement of groundwater.

3.4. Aquifer Characteristics and Analysis of Groundwater

The 3D lithological model of the Mewat district was prepared based upon the lithological information gained through exploration carried out in Mewat district and the results of geophysical logging carried out in these wells. The composite logs were prepared; and further, with the help of Rockworks software version 15.0, the lithological 3D model and fence diagram were prepared. The interpretation of the fence diagram and the lithological model indicates the presence of thin granular zones in the entire district until the basement is reached. However, these granular zones are not present near the quartzite outcrops. The granular material forming the aquifers is mostly very fine to fine-grained and medium-grained sands in places.

Tube wells constructed in this area tap the aquifer between a depth of 15 and 60 m, with a yield ranging between 150 and 750 L per min for moderate drawdown. Most of these tube wells are either of the cavity type or filter type. The cross-sections depict the detailed lithological aquifer based upon the groundwater quality are shown in Figures 10 and 11, respectively.

There were 2 slim holes and 14 exploratory boreholes drilled in the study area. Out of these, six were abandoned due to the lack of good-quality freshwater aquifer. The borehole drilled at Palri and Hathangaon in Punhana block provided freshwater with a good granular zone in the alluvium areas of the district. The tube well drilled at Hathangaon tapped into aquifers between the depths of 21 and 33 m and yielded 910 L per min with a drawdown of 5.64 m. The calculated transmissivity value of the aquifer is 593 m^2/day, and the specific yield is 2.63×10^{-2}.

The tube wells drilled at Ghagas (Nagina block) and Sidhravat (Firozpur Jhirka) are up to depths of 175 m and 130 m in the quartzite, respectively. The aquifer parameters determined at Ghagas show an aquifer discharge of 103 L per min for a drawdown of 54 m, and the transmissivity calculated is 0.5811 m^2/day. On the other hand, the aquifer parameters determined at Sidhravat show an aquifer discharge of 144 L per min for a drawdown of 28 m, and the transmissivity calculated is 1.9202 m^2/day. The data suggest that the formation water is brackish to saline in nature.

On the basis of lithology information gained, the 3D lithological model of Mewat district is prepared as shown along with its fence in Figure 12. The 3D disposition of aquifers based upon the chemical quality and geophysical data is prepared as shown in Figures 13 and 14.

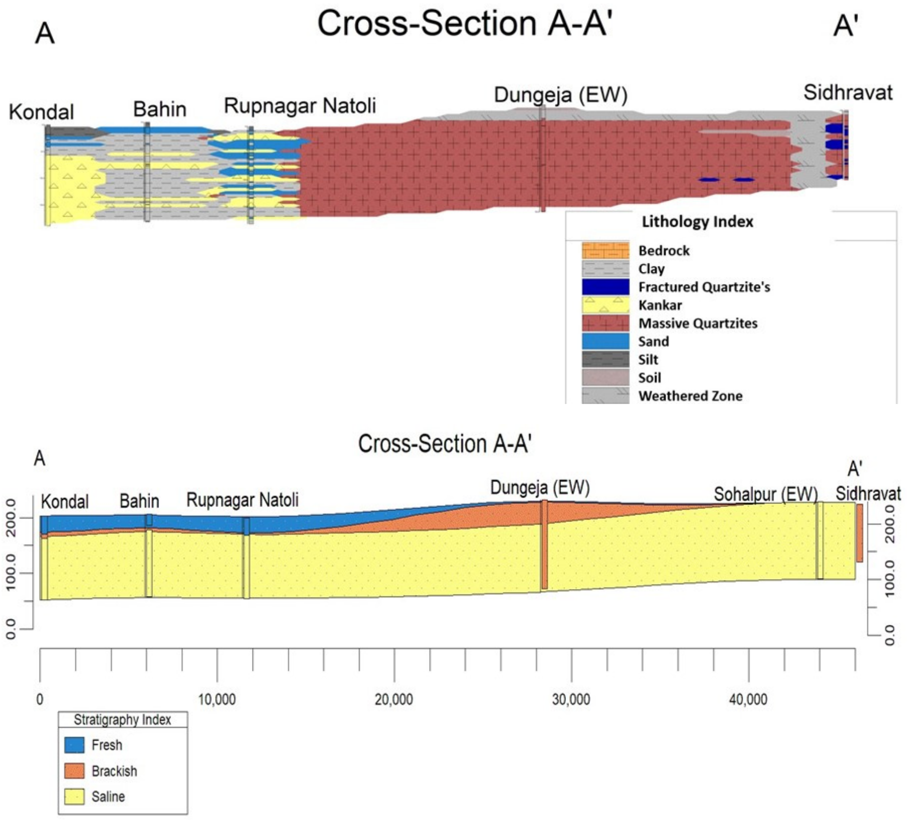

Figure 10. Two-dimensional lithological section along Kondal and Sidhravat.

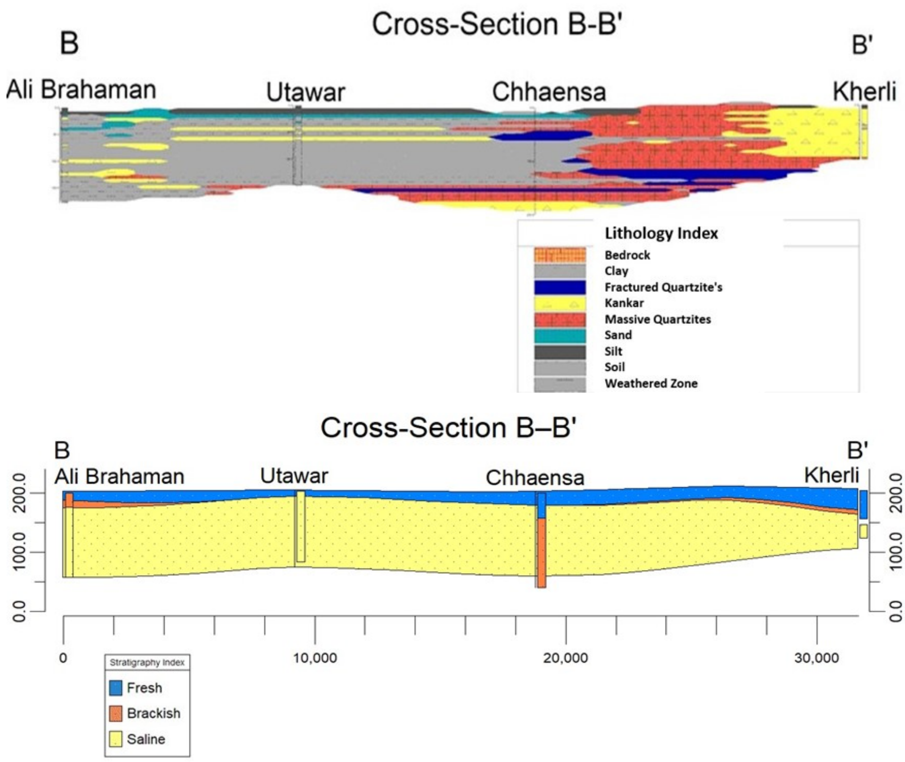

Figure 11. Two-dimensional lithological section along Ali Brahaman and Kherli.

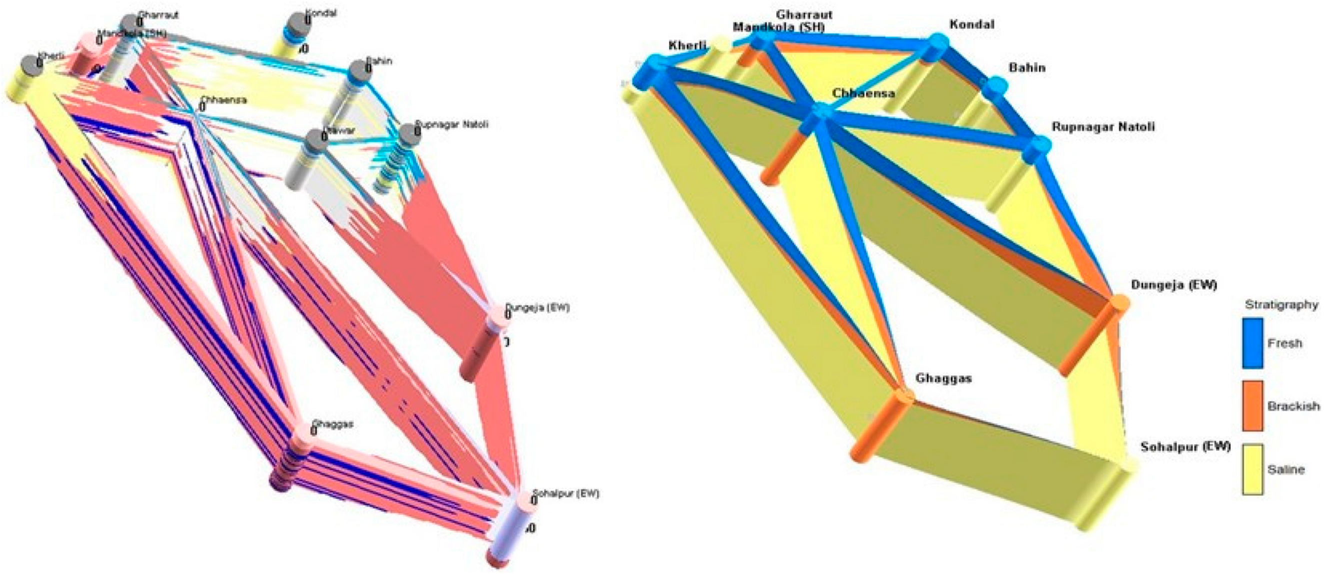

Figure 12. Three-dimensional lithological fence of Mewat, Haryana.

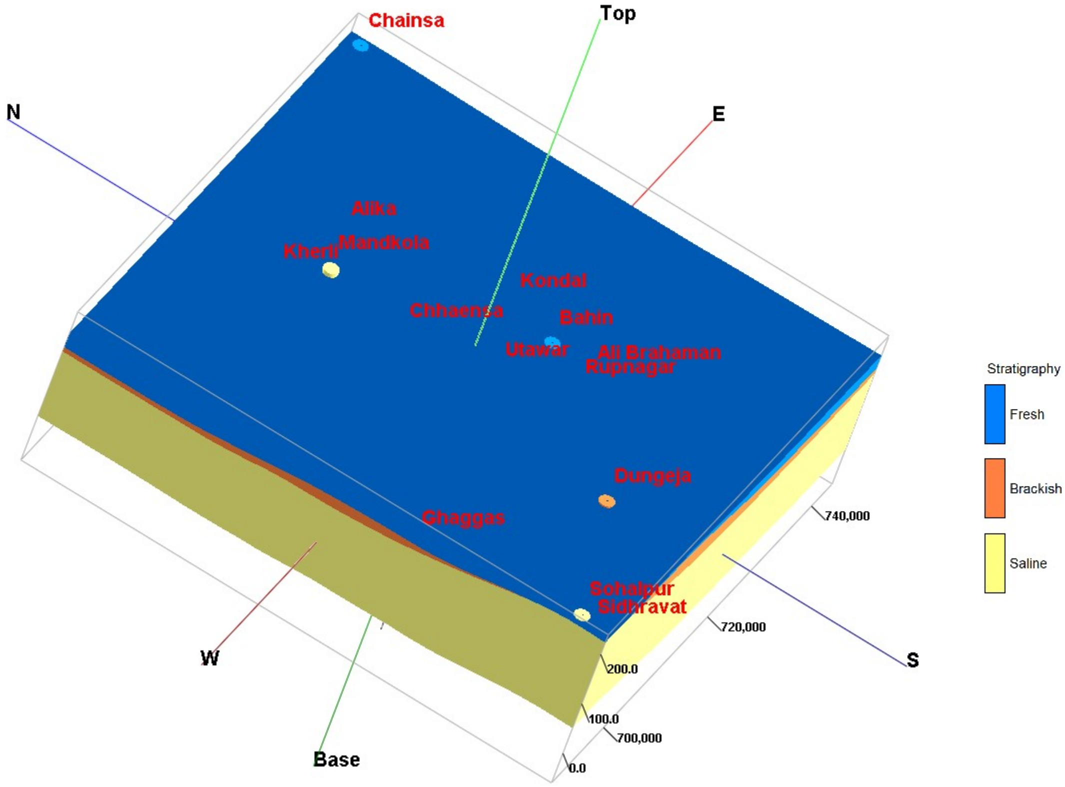

Figure 13. Geophysical model of Mewat, Haryana.

The chemical quality of groundwater samples collected during drilling and after the well completion, from dedicated groundwater monitoring stations and geophysical methods, was used for preparing the 3D stratigraphic model depicting groundwater quality and its fence diagram. It was inferred that the groundwater is in shallow and deeper horizons in most parts of the district and is not fresh. Most parts of the Nuh, Firozpur Jhirka, and Nagina blocks have brackish/saline groundwater even at shallow levels, while the Taoru block has freshwater. As a result, the tube well density is higher in the Taoru block compared to in the Firozpur-Jhirka, Punhana, Nuh, and Nagina blocks.

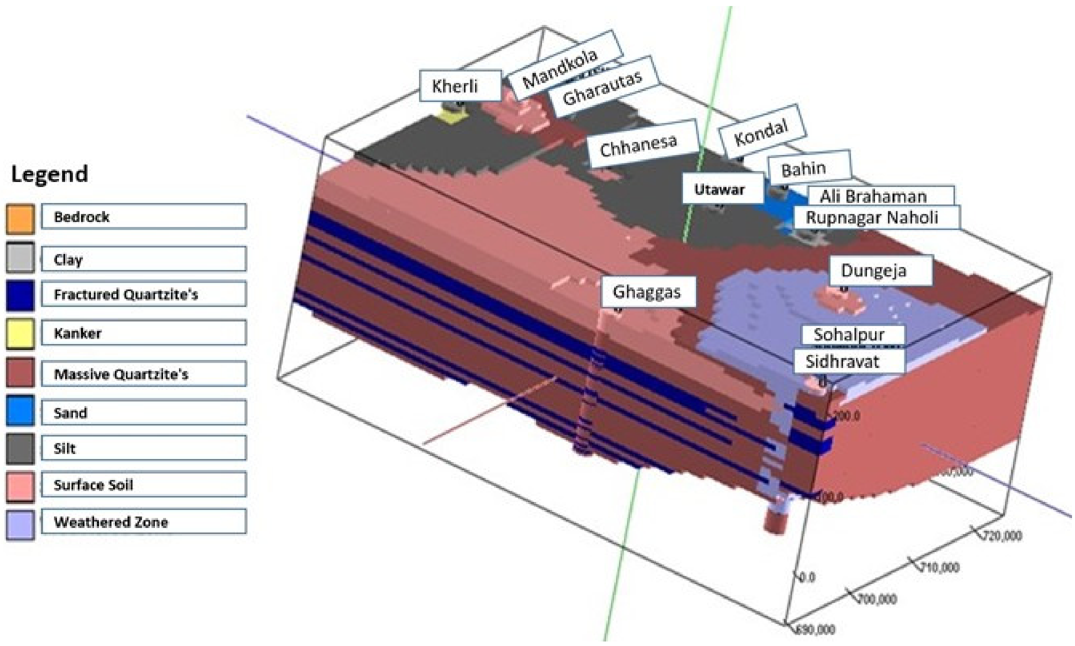

Figure 14. Three-dimensional lithological model of Mewat, Haryana.

The details of boreholes drilled in alluvium and hard rock with aquifers encountered at different depth ranges, groundwater salinity and depth of bed rock are given in Table 2.

On the basis of the above observations, the final geophysical model was developed and is shown in Figure 13.

The groundwater potential of the district has been assessed as per GEC-2015 year 2022 [3,26]. The primary source of recharge in the area is rainfall. The net groundwater availability of the district is 18942.56 and the present net groundwater draft in the district is 13,936.29 mcm. The net groundwater availability of the district for future use is 4345.4 mcm, of which 1696.35 mcm is kept reserved for future domestic and industrial purposes. In Tauru block (123.79%) and Firozpur Jhirkha block (103.62%), which fall in the overexploited category, no further development of groundwater should be conducted (Figures 15–18). Since a large area has shallow groundwater levels within 5.0 m, there is substantial potential recharge in the district. The details are provided in Table 3.

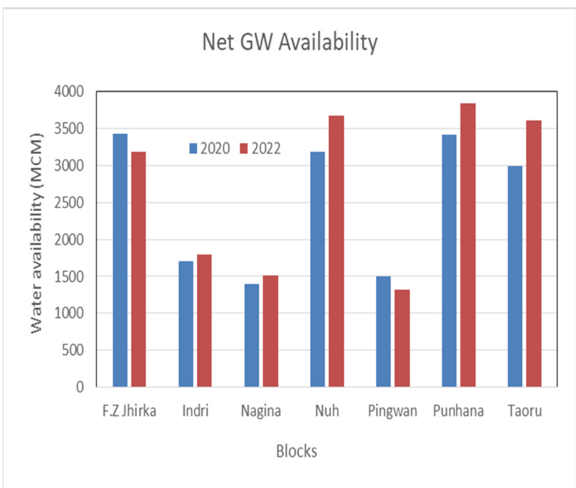

Figure 15. Comparison of net GW availability in 2020 vs. 2022 in Mewat, Haryana.

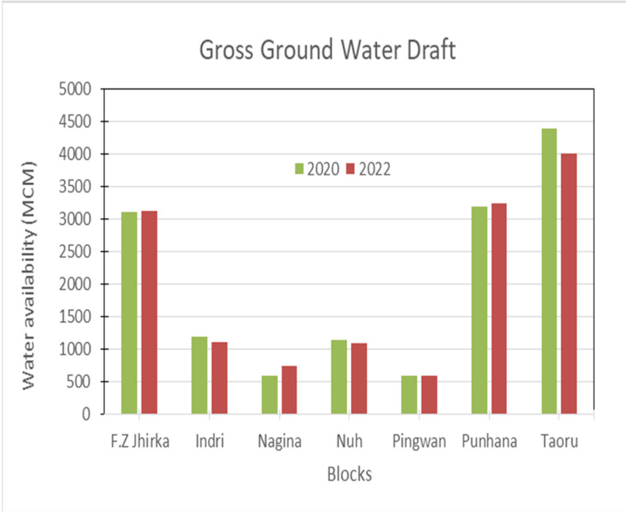

Figure 16. Comparison of gross GW draft for all uses in 2020 vs. 2022 in Mewat, Haryana.

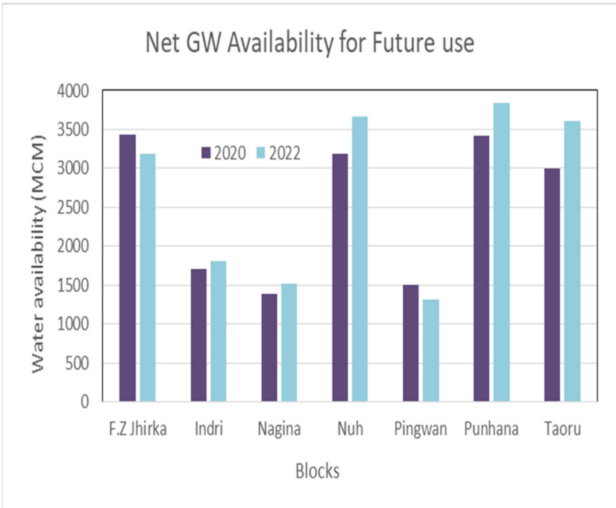

Figure 17. Comparison of net GW availability for future use in 2020 vs. 2022 in Mewat, Haryana.

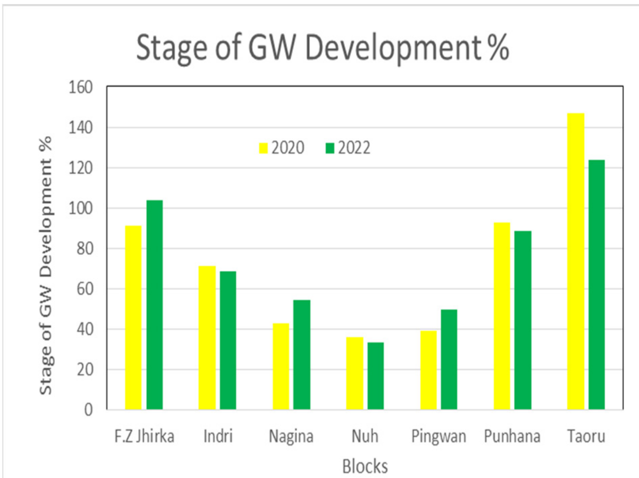

Figure 18. Comparison of stage of GW development in 2020 vs. 2022 in Mewat, Haryana.

Table 3. Ground water resource and development potential (31 March 2022) in MCM.

Block Name	Annual Extractable Groundwater	Irrigation Draft	Domestic and Industrial Water Supply Draft	Gross Draft for All Uses	Future Domestic, and Industrial Draft for 2025	Availability of Groundwater for Future Use	Stage of Groundwater Extraction (%)	Category
Firozepur Jhirka	3186.42	2847.24	289.6	3136.84	289.6	00.00	103.62	Over Exploited
Indri	1800.54	818.75	294.63	1113.38	294.63	507.11	68.70	Safe
Nagina	1517.41	513.75	228.06	741.81	228.06	623.85	54.31	Safe
Nuh	3670.43	764.4	333.04	1097.44	314.94	2205.95	33.22	Safe
Pingwan	1318.7	436.8	152.82	589.62	152.82	597.21	49.68	Safe
Punhana	3843.27	3031.67	208.15	3239.82	208.15	411.28	88.73	Semi Critical
Taoru	3605.79	3807.42	209.96	4017.38	208.15	00.00	123.79	Over Exploited
Total	18,942.56	12,220.03	1716.26	13,936.29	1696.35	4345.4	80.09	Semi Critical

3.5. Groundwater Issues

The groundwater-related issues in the Mewat district are groundwater quality and its depletion, groundwater rise causing water logging especially in the post-monsoon season, excess salinity, salt encrustation, and groundwater irrigation.

3.5.1. Groundwater Quality

The groundwater in the study area is generally alkaline and moderately to highly saline, except in the Taouru and Ferozpur Jhirkha blocks, where it is low to medium saline. This makes groundwater suitable for irrigation purposes in these blocks. Although the majority of parameters are within permissible limits, nitrate, sodium, and chloride concentrations exceed allowable limits. Nitrate concentrations above permissible levels are mainly found in Sikharwa (48 mg/L), Gulalta (231 mg/L), Nagina (127 mg/L), and Malab (109 mg/L). Chloride concentrations above permissible limits (mg/L) are found in Nagina (1947 mg/L), Kheri Kanker (16,481 mg/L), Gulalta (1640 mg/L), Akaira (1478 mg/L), Malab (1564 mg/L), and Indri (1234 mg/L). High levels of sodium are found in all the samples, except Sehsaula in the Taouru block. Geogenic and anthropogenic activities have caused groundwater quality degradation and salinity is a significant concern in the district [14].

3.5.2. Groundwater Depletion

The Taoru and Ferozpur Jhirkha blocks have fresh groundwater that is regularly pumped for irrigation and drinking purposes. This results in the deepening of groundwater levels, causing these blocks to be categorized as overexploited due to the high demand for extraction in relation to rainfall recharge. Hydrographs depict the declining water level trend over the years in the district (Figure 19a–c). The phreatic aquifers are drying out due to declining water levels, leading to the failure of shallow tube wells and dug wells. In addition to groundwater depletion, deteriorating groundwater quality and rising water table/waterlogging [28] are also issues in the study area.

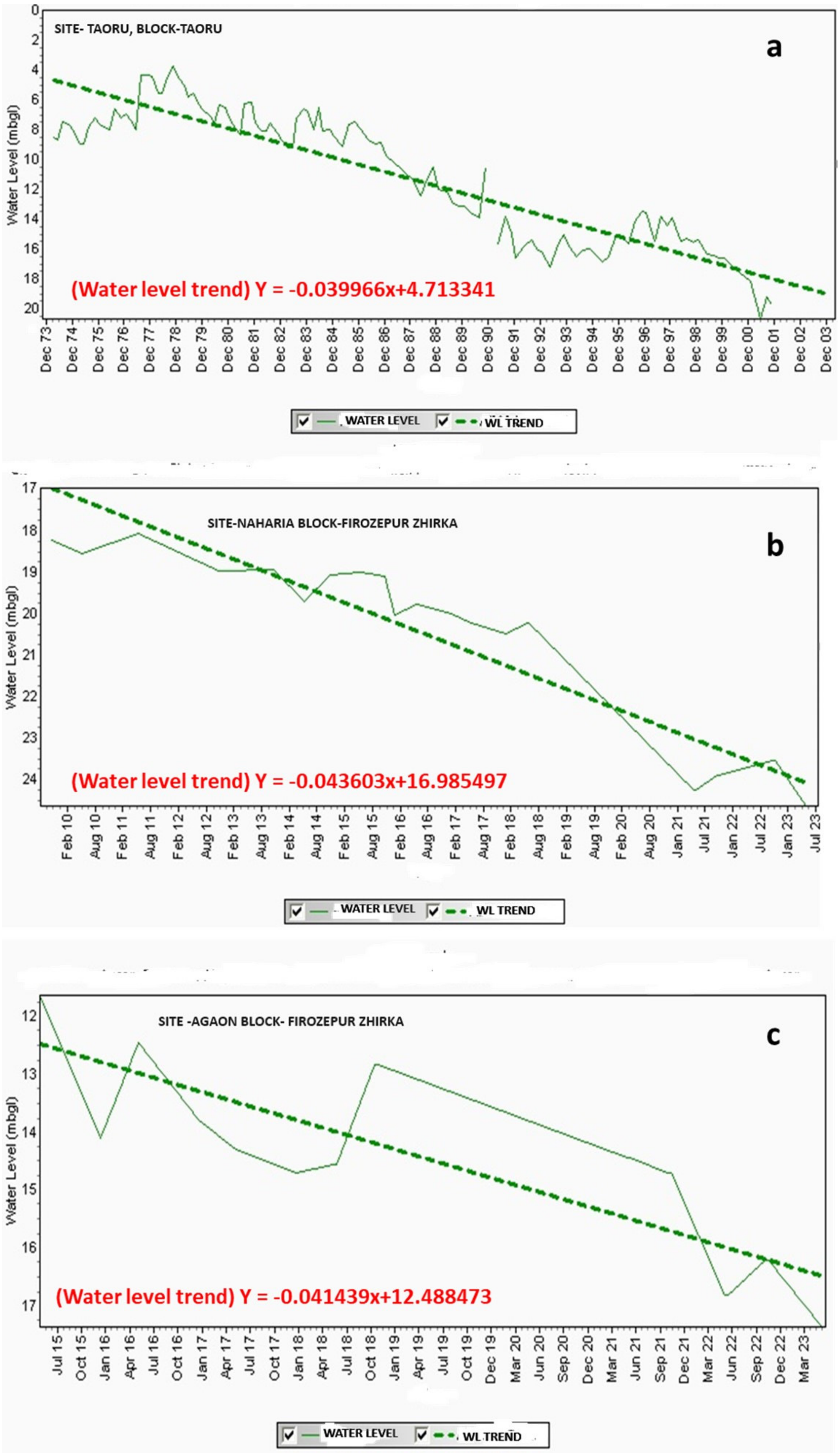

Figure 19. (**a**–**c**): Long-term groundwater table variation.

3.5.3. Rising Water Level/Water Logging

There are certain areas in the Indri, Nuh, Nagina, Pingwana, and Punhana blocks where groundwater extraction is limited due to high salinity and the presence of canal networks. As a result, water levels tend to rise, especially during the post-monsoon season, leading to waterlogging in these areas. The increased salinity caused by waterlogging has also adversely affected the productivity of soil. The hydrographs of the district, as depicted in Figure 20a,b, show a trend of rising water levels over the years, which is quite evident.

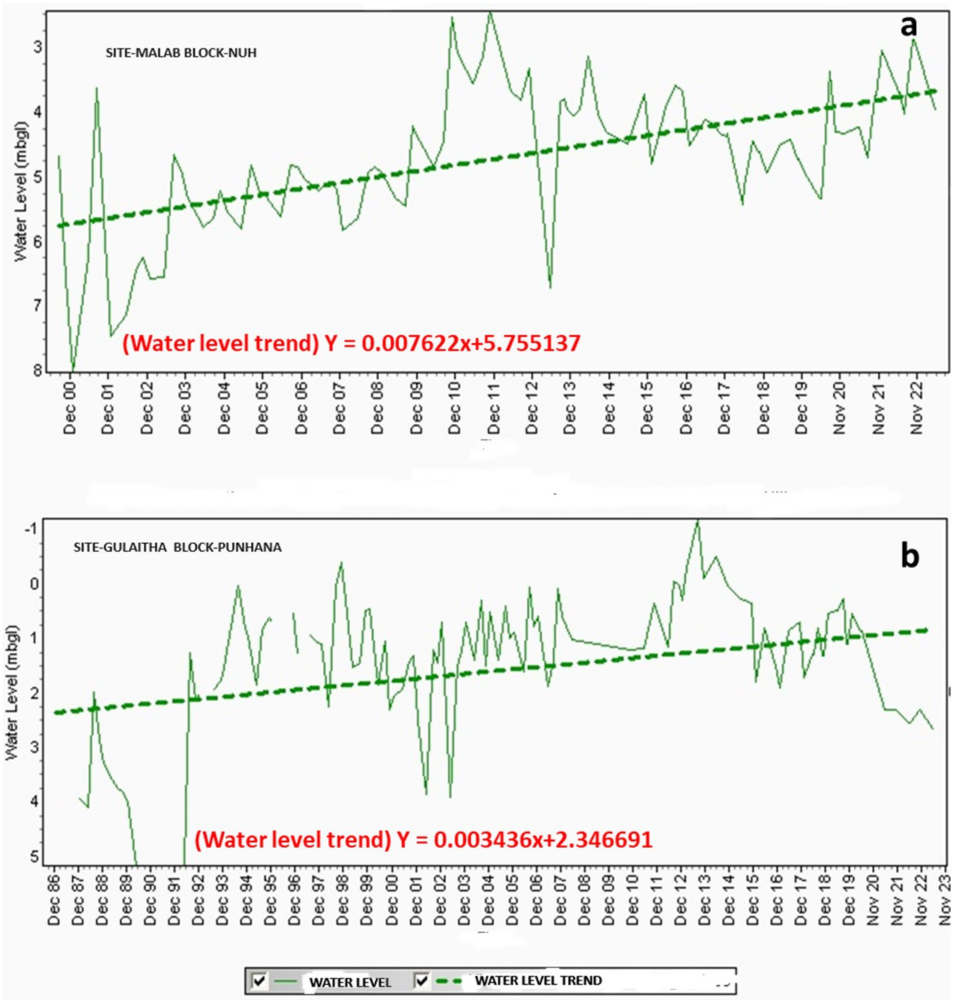

Figure 20. (**a**,**b**) Long-term groundwater table variation showing the rise in water level.

3.5.4. Salt Encrustation

The district's soil is dominated by vertisol, a dark-colored soil containing high levels of clay. While these soils are known for their stickiness in humid conditions and their hardness during the summer months, they are also highly susceptible to salinity. In fact, high salinity levels, particularly in the Nuh and Nagina blocks, can cause changes in soil characteristics, resulting in Solonchalk. This soil can be seen turning white during the summer months due to salt deposits, and it generally lacks the drainage necessary for vegetation to flourish. As a result, areas dominated by vertisol are often considered waste lands.

However, these soils also have their advantages. They contain a plethora of soluble ions such as Mg, SO_4, HCO_3, Ca, and Cl, with a pH range of 7.26–8.25, making them ideal for certain crops. Although agricultural yields are lower in these soils when compared to their non-saline counterparts, there are still benefits to be had from utilizing this fertile land. With proper care and maintenance, these soils can become a valuable resource for farmers in the district.

3.5.5. Groundwater Irrigation

Groundwater development has remained steady over the years to provide water for drinking, industry, and irrigation. However, the stage of groundwater extraction has slightly decreased from 80.81% in 2020 to 80.08% in 2022. As of 31 March 2022, the groundwater potential in Mewat district has been extracted to varying degrees, ranging from 33.22% (Nuh) to 123.79% (Taoru) depending on the block. The Ferozpur Jhirkha area has shifted from a semi-critical to an overexploited category due to increased groundwater utilization for agricultural activities through the use of bore wells/tube wells. As a result, groundwater draft has increased. To maintain this precious natural resource without harming the environment, a scientific approach to its management is urgently needed. In areas where the water level is gradually decreasing, optimizing groundwater needs for irrigation is essential. Planned groundwater development is only possible if we can precisely quantify its potential and estimate the demand for various uses in projected development scenarios for urban and rural areas over the next 25 years.

Tables 4–6 provide information on the distribution of tube wells based on land holdings, depth of tube wells and the lining of water distribution canals ((6th MI Census, (2017–19)).

Table 4. The distribution of tube wells based on the size of the landholding of the well owner, Mewat, Haryana.

	<1 Hectare	1–2 Hectare	2–4 Hectare	4–10 Hectare	10 Hectare	Private	Total
Shallow TW	16	5	265	172	30	681	1169
Medium TW	2	38	91	38	2	1184	1355
Deep TW	37	206	370	499	22	1581	2715
Total	55	249	726	709	54	3446	5239

Table 5. The distribution of tube wells based on their depth in Mewat, Haryana.

Depth Range	Depth (meters)										Total depth Range 0–150 m
	0–20 m	20–35 m	35–40 m	40–60 m	60–70 m	70–90 m	90–110 m	110–130 m	130–150 m	>150 m	
Tube wells	590	579	322	701	332	1347	990	193	96	89	5239
Tubewells (%)	11	11	6	13	6	26	19	4	2	2	100

Table 6. System of a groundwater distribution device in Mewat, Haryana.

Type of Tube Well (TW)	Open Water Channels					
	Lined//Pucca	Unlined//Kutcha	Underground Pipe	Surface Pipes	Others	Total
Shallow	6	403	11	612	135	1167
Medium	29	171	40	913	203	1356
Deep	87	1066	149	854	560	2716
Total	122	1640	200	2379	898	5239

3.6. Effective Management of Groundwater

Proper management of groundwater resources is crucial for the sustainable development of Mewat district. The district's groundwater management plan has two key components. Firstly, the management of blocks with a groundwater development stage greater than 80% is critical for ensuring that water resources are utilized efficiently. Secondly, the management of saline waters is vital for preserving the quality of groundwater. By implementing these two components effectively, we can ensure that the groundwater resources of Mewat district are managed sustainably, ensuring a brighter future for the district and its people.

3.6.1. Management Plan for Exploited Blocks

Groundwater resources in Ferozpur Jhirkha and Taoru have been exploited beyond 100%, while Punhana block is at the brink of experiencing the same fate Therefore, there is an urgent need to implement effective water management interventions based on an integrated approach. This includes improving groundwater resources through appropriate techniques, along with implementing suitable water extraction measures. This can be achieved by promoting water use efficiency, creating additional water storage facilities, maintaining or renovating existing water bodies, and changing cropping patterns to less water-intensive crops. Water awareness and capacity building of stakeholders are also important attributes of water management interventions as envisaged in the National Water Policy. Aquifer mapping is a key step towards developing groundwater management plans that can be implemented, including demand-side management and improving groundwater use efficiency.

3.6.2. Management Plan for Supply Side

Supply side management aims at increasing the amount of groundwater available by interventions like artificial recharge of groundwater, conservation of groundwater and activities carried out in field.

Artificial Recharge and Conservation of Surplus Canal Water

Rainfall is the prime area of recharge in the district and as the district falls under semi –arid zone, groundwater must be artificially recharged. To recharge groundwater excess, surplus canal water available to the tune of 14 MCM may be recharged to groundwater through the construction of 933 injection wells. Groundwater can also be recharged through the construction of rooftop rainwater harvesting structures in houses with a roof area of more than 200 m^2, Govt buildings and institutes. As estimated, 0.86 MCM rainwater can be harvested considering the normal rainfall of the district if 13,998 houses in the district adopt a rooftop rainwater harvesting system. The district artificial recharge plan of Mewat district is shown in Figure 21.

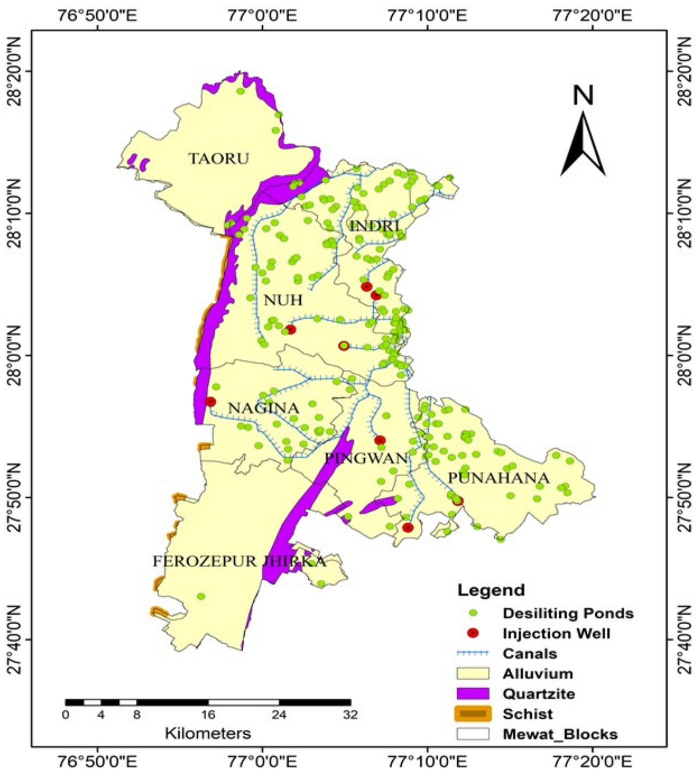

Figure 21. District artificial recharge plan of Mewat, Haryana.

Enhancing Storage Capacity

The work is carried out to enhance the storage capacity of the existing numerous ponds and lakes in the district and the conservation of rainfall. Due to natural and anthropogenic activities, these ponds and lakes are losing their water holding capacity. These structures must be de-silted to enhance their rainfall storage capacity and a recharge shaft must be constructed in them to increase rainfall recharge to groundwater. Farm ponds must be constructed in large farms to reuse the available water on the farm itself during rainy seasons.

3.6.3. Management Plan for the Demand Side

The aim is to improve water use efficiency and reduce groundwater depletion through demand-side management and on-farm practices. Before planting crops, fields must be leveled correctly to ensure even water distribution, which can save 10–30% of applied irrigated water [29,30]. Less water-intensive crops like maize, pulses, and floriculture are encouraged to conserve groundwater and improve financial gains. Afforestation is also promoted as vegetation roots help keep topsoil intact and recharge groundwater. These practices are particularly important in areas where groundwater levels are declining (such as Ferozpur Jhirkha, Taoru, and Punhana Blocks) and where groundwater extraction exceeds 80%. Flood/furrow irrigation is wasteful, losing nearly 50% of applied water through seepage and localized inundation. Sprinkler and drip irrigation are better alternatives and can minimize wastage of fresh irrigation water. Utilizing HDPE pipes can save up to 25–40% of conveyance losses (primarily seepage and evaporation) [31].

3.6.4. Management of Saline and Alkali Waters

In Mewat district, fresh groundwater is situated beneath saline or brackish water. Out of the total groundwater resources of Mewat district, estimated to be 13,491 MCM, 10,284 MCM including 19 MCM of replenishable resource is saline. Therefore, it is crucial to manage these saline reserves of groundwater effectively. When using saline water for agriculture, it is essential to prevent the accumulation of sodicity and salinity in the root zone of the crops. The management of saline waters involves the conjunctive use of water, rainwater conservation, and on-farm practices [32].

Conjunctive Use of Groundwater and Surface Water

Mixing highly saline groundwater with canal water in proportion can make the groundwater suitable for irrigation. This approach not only helps to address irrigation problems, but also reduces soil salinity. To ensure maximum efficiency and effectiveness, irrigation should be carried out using furrows, drips and sprinklers, instead of flood irrigation. For saline soils, irrigation should be more frequent as it reduces cumulative water deficits (both matric and osmotic) between irrigation cycles [33].

On-Farm Practices

Groundwater with high SAR values can be used for irrigation by adding amendments such as gypsum, sulfuric acid or pyrites. Gypsum increases the concentration of calcium in the water, which reduces the sodium-to-calcium ratio and lowers the SAR values. Similarly, sulfuric acid or pyrites release Ca^{2+} in the water, which disrupts the sodium-to-calcium ratio. To reduce salinity in soil, mulching with locally available plant material or adding green/organic manure can be effective. This helps to reduce evaporation and increase infiltration [34–37]. In addition, crops such as wheat, cotton, mustard, and sorghum that are tolerant to salt can be grown in these areas [38].

4. Conclusions

In conclusion, the geophysical investigations conducted in the Mewat district have provided invaluable insights into the hydrogeological landscape of the region. Through a combination of surface and sub-surface geophysical methods, the principal aquifers were meticulously mapped, and the interface between freshwater and saline water was delineated both horizontally and vertically. The analysis revealed that the topsoil in Mewat, primarily composed of clay, exhibited resistivity values ranging from 11 to 35 ohm-m. Higher resistivity values indicated lower soil saturation levels, and this topsoil layer was generally around 12 m thick. Resistivity values exceeding 15 ohm-m were associated with granular zones containing fresh groundwater, predominantly composed of sand and kankar. Conversely, resistivity values below 15 ohm-m corresponded to formations with saline to brackish groundwater, containing clay, sand, and kankar. Surface geophysical studies illuminated the distribution of groundwater quality in Mewat, with approximately 55% of the area characterized by saline groundwater, primarily concentrated in the central, western, and southern regions around Nuh, Malab, and Punhana. In contrast, only 26% to 30% of the area featured freshwater within a depth of 30 m, mainly in the northwest and southwest regions, including Tauru block, Mohun, and Ghata-Shamsabad. Only 13% of the area contained freshwater below 40 m depth. However, it was evident that the potential for a significant yield of fresh groundwater was limited in Mewat due to the insufficient thickness of granular zones. The depth to bedrock varied across the district, with some areas having bedrock within 90 m. The study also examined soil infiltration rates, revealing significant variability across the district. These rates were influenced by soil texture and structure, with initial infiltration rates ranging from 90 mm/h to 660 mm/h and final rates from 5 mm/h to 164 mm/h, averaging 151 mm/h. Furthermore, a 3-D hydrogeological model was developed, calibrated with elevation data, to better understand the complex groundwater dynamics in the region. This model served as a critical tool for synthesizing and interpreting the vast dataset.

The assessment of groundwater-related challenges in Mewat unveiled pressing issues such as groundwater depletion, rising water tables leading to waterlogging, groundwater quality concerns, and elevated salinity levels. Notably, overexploitation of freshwater was observed in areas like Taoru and Ferozpur Jhirka blocks, while waterlogging was a significant concern in central and north-eastern regions. Groundwater quality issues, including high nitrate, sodium, and chloride concentrations, particularly in Nagina and other areas, demanded attention. Salinity has even led to the formation of salt-affected soils in certain localities. Addressing these multifaceted challenges, the report proposed a range of groundwater management strategies. These encompass artificial recharge techniques, water conservation measures, on-farm activities to increase storage capacity, and rainwater harvesting. Additionally, the adoption of efficient irrigation methods like drip and sprinkler systems was recommended for enhanced water use efficiency. Chemical amendments, such as gypsum, were proposed to mitigate soil salinity, along with crop selection and mulching to manage saline water for agriculture. In summary, this study serves as a comprehensive assessment of groundwater resources in Mewat, Haryana, with a thorough emphasis on sustainable utilization and addressing the unique challenges faced by the region. These findings are invaluable for local stakeholders, providing a roadmap for responsible groundwater management and ensuring access to clean and reliable water sources.

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