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EFFECTS OF LONG-TERM IRRIGATION ON THE WATER TABLE DECLINE IN SEMI-ARID REGION USING GEO-SPATIAL TECHNIQUE

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Abstract: *Groundwater-based irrigation plays a crucial role in sustaining agricultural production, particularly in semi-arid regions. However, intensive groundwater extraction for irrigation often leads to significant declines in water levels. This study addresses the critical issue of groundwater depletion in the semi-arid region of Churu district, Rajasthan, where dryland agriculture is practiced during the Kharif season and Rabi cultivation relies almost entirely on groundwater irrigation. Despite its importance, the relationship between irrigated agriculture and groundwater depletion has received limited attention in both water resource research and agricultural science. The present research makes an original and scientific contribution by analysing the spatial extent of irrigated agricultural areas and their impact on groundwater depth. Using geo-spatial techniques, the study evaluates the patterns of groundwater extraction and identifies the areas experiencing the highest depletion. The findings reveal a consistent and alarming increase in stress on groundwater resources, directly linked to the expansion of irrigated agriculture. The continuous decline in groundwater levels poses a long-term threat to agricultural productivity, especially in regions where groundwater forms the backbone of irrigation. The study highlights the urgent need for sustainable groundwater management to mitigate the adverse impacts of overexploitation. It emphasizes the adoption of efficient irrigation methods, crop diversification, artificial recharge structures, and policy interventions tailored to semi-arid environments. These measures are essential to ensure long-term water security and agricultural sustainability in the region.*

Key words: Groundwater Depth, Rabi Crops, Geo-Spatial Technique, Over-exploitation

Introduction

Groundwater is highly useful for the human beings and is ecologically important (Sagar, 2015; Tran et al., 2019). Water in agriculture is central to feeding the planet, providing livelihoods, and building resilience to climate shocks and extremes (World Bank, 2021). Groundwater is used to buffer drought impacts in arid and semi-arid regions, due to its generally larger reliability and availability compared to surface water (Garrido et al., 2006; Siebert et al., 2010; Glendenning and Vervoort, 2011; Dalin et al., 2019). The growing world population and food demand have intensified agriculture and irrigation, leading to widespread overexploitation of groundwater resources (Scanlon et al., 2012; Cao et al., 2013; Kidane et al., 2019). Irrigation accounts for 70 percent of water withdrawals and 90 percent of consumptive water use globally (Shiklomanov, 2000; Molden et al., 2007; IAASTD, 2009; Serra-Wittling, 2019). In India, for example, the groundwater irrigated area has increased 500 percent since 1960 (Shah, 2009). The Groundwater crisis in north-western India is the result of over-exploitation of groundwater resources for irrigation purposes (Shekhar, 2020). Paria et al. (2021) examined the impact of irrigation and crop diversification on future groundwater dynamics in India. Overexploitation has led to drastic declines in groundwater levels, threatening to push this vital resource out of reach. Due to increased competition, there is need for efficient use of irrigation water in agriculture (Clothier & Green, 1994). The limitation of available surface water resources has put an onus on groundwater to meet the requirement (Anonymous, 2020). The effective management of groundwater resources required to understand the impact of irrigated agriculture on groundwater level.

Literature Review

The use of Geo-spatial techniques has led to better water management systems in agriculture. Liaqat et al., 2016, Bhadra et al., 2018 and Saha et al., 2021 have stated the importance of Geo-spatial techniques in groundwater management for crops and land resources on a sustainable basis. Assessment of irrigated lands by conventional means of survey requires a great deal of time, but the application of geospatial analysis using remote sensing data & GIS techniques have minimized time consumption and improved the possibility of rapid production of maps & models (Ojo and Ilunga, 2018). Reddy et al. (2016) and Xie et al. (2020) tried to establish linkages between the natural groundwater and the anthropogenic irrigated system through hydrological modelling. The specific objective of this study is to examine the decadal changes in irrigated agricultural area for Rabi crops and to determine its impact on groundwater depth at district as well as Tehsil level.

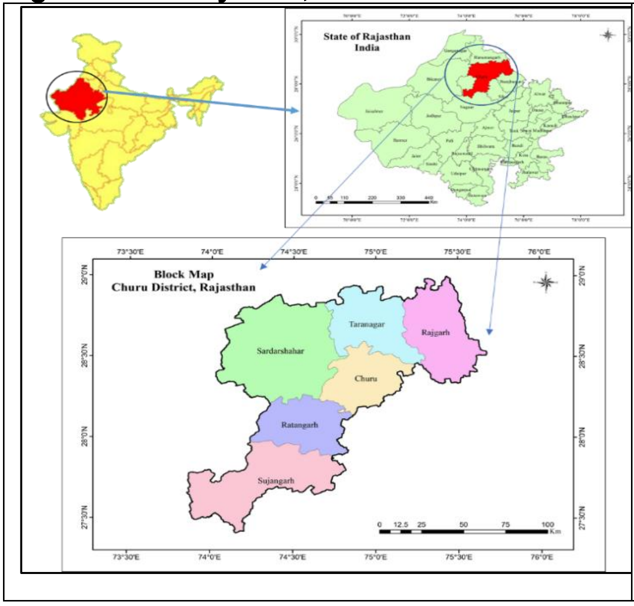
Study Area

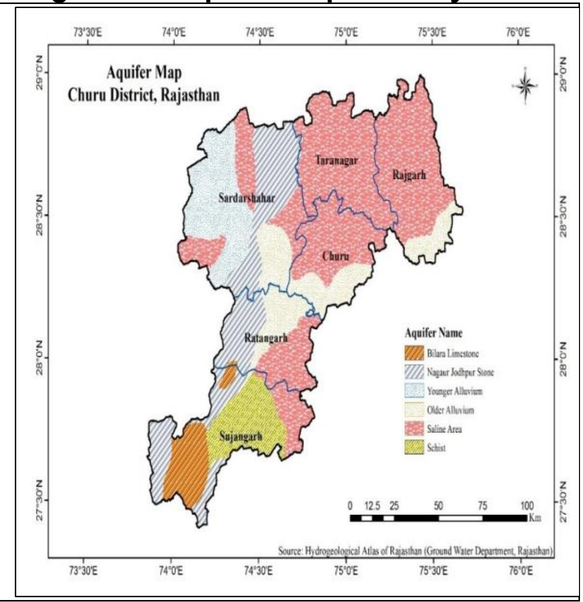
Churu district is situated in the north-eastern part of Rajasthan, India. It is located between 27º 24' 31.50"N to 29º 00' 01.74"N latitudes and 73º 50' 39.45"E to 75º 40' 31.85" Longitudes with total geographical area of 13,844 Km^2. The district is the part of semi-arid region. It has dry climatic conditions with extreme temperature conditions. Average annual rainfall is 353.9mm, mostly during monsoon season from July to September. It is administratively divided in six Tehsils namely Churu, Rajgarh, Ratangarh, Sardarshahar, Sujangarh and Tarangar. Subsistence agriculture is the main occupation in the district having plain area with sand dune topography which increases from east to west.

Aquifer Mapping

Dryland agriculture is mostly practiced in kharif season but Rabi crops are totally dependent on groundwater-based irrigation except in small part of Taranagar tehsil where Sahwa lift canal supplies some water for irrigation. Due to increasing exploitation, groundwater depth is increasing continuously. Aquifer map (Fig 2) provides the aquifer zonation of the district. The areas of Taranagar, Rajgarh and Churu have more saline areas. most of the irrigated Rabi crop areas lies in older and younger alluvium aquifers, which are also suitable for exploitation of ground water.

Figure 01: Study area, Churu district **Figure 02: Aquifer map of study area**





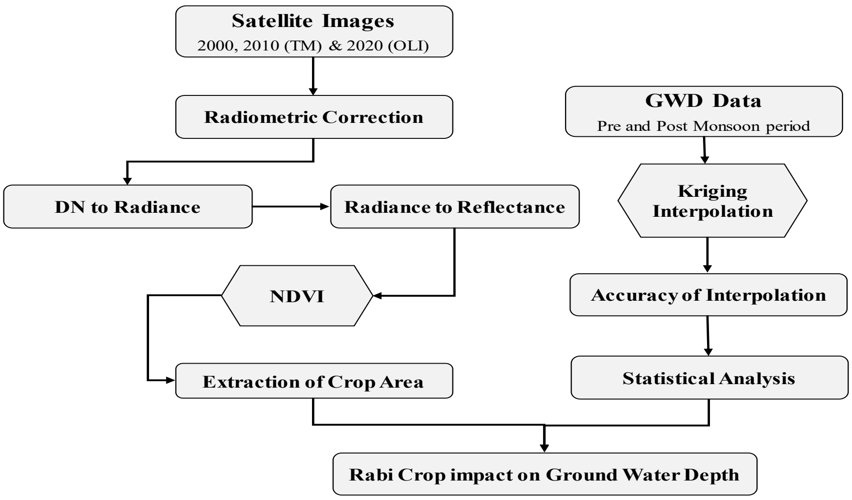
Data Use

Satellite Imageries: Geometric corrected satellite images are downloaded from earth explorer USGS (United State Geological Survey, website https://earthexplorer.usgs.gov). All the imageries covering project site with Row 148 and Path 40 and 41 are downloaded for the purpose of this study. Landsat-TM (Thematic Mapper) and Landsat-OLI (Operational Land Imager) of January and February month for the years 2000, 2010 and 2020 with 30m spatial resolution are used to examine the irrigated agricultural area.

Groundwater Level: Groundwater level data are provided by Central Ground Water Board (CGWB), Western Region, Jaipur (Rajasthan) for Churu district. The data used here are for Pre-monsoon and post-monsoon for the years 1999 to 2019. This data has been used in this study to analyse the impact of irrigated rabi crops on Ground Water Level.

Rainfall: Rainfall data were acquired for analysis from Water Resource Department (Government of Rajasthan,https://water.rajasthan.gov.in/content/water/en/waterresources department/Water Management/IWRM/annualrainfall.html#).

Methodology: Figure 03: Flow-chart of Methodological processing of the study



Pre-processing of satellite imageries

Landsat-5 (TM) and Landsat-8 (OLI) images are used and radiometric correction has been done to obtain reflectance value. It involves two steps (a) DN to Radiance conversion (b) Radiance to Reflectance conversion.

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is spectral measurements of remote sensing data for quantitative assessment of the vegetation cover area and vegetation health analysis (Yousaf et al., 2020). It is a formulation which uses highest absorption (Red) and reflectance regions (NIR) of chlorophyll. NDVI is defined by formula:

$$\boldsymbol{NDVI} = \frac{\boldsymbol{\rho NIR - \rho RED}}{\boldsymbol{\rho NIR + \rho RED}} \quad \text{(Rouse et al., 1973; Erener, 2011)}$$

Where

ρNIR = The Near-infrared Channel (NIR-Band)

ρRED = Red Channel (Red-Band)

Rule for NDVI-based Crop Classification

The delineation of crop areas from non-crop areas was performed using a straightforward binary classification approach based on the Normalized Difference Vegetation Index (NDVI). A fixed threshold of 0.30 was applied to the NDVI image. Specifically, any pixel exhibiting an NDVI value less than or equal to 0.30 was classified as a non-crop area, while pixels with an NDVI value greater than 0.30 were classified as the target crop area. This methodology provided a clear separation between vegetated agricultural land and other land cover types for subsequent analysis using conditional model.

CONDITIONAL {(Image <= $NDVI_{Min}$) 1, (Image >$NDVI_{Min}$) 2}

Were

$NDVI_{Min}$= NDVI Minimum Value 1 = Non-crop Area 2 = Crop Area

Kriging Interpolation Technique

Interpolation is the statistical method to estimate the values of sum unknown points using values of known point. The Kriging interpolation method has been reported sound for groundwater analysis (Jassim, 2013; Choudhury, 2021). Thus, for the present study ordinary Kriging interpolation method is used. The Kriging interpolation includes following two steps to generate a raster surface from point data:

1. Fitting model: Vario-grams and covariance function to estimate the statistical dependence creation.
2. Making an estimation of unknown value

A semi variogram shows statistical correlation of neighbour points and is defined as a mathematical model to generate semi variance as a function of lag (Ozturk, and Kilic, 2016). This may be calculated using formula as suggested in ESRI 2014a.

$$Semivariogram\ (Disatance\ h) = 0.5\ \times average\ \{(Value\ at\ location\ i - Value\ at\ location\ j)^2\}$$

This analysis provides us the weight ($\boldsymbol{\lambda_i}$) for further calculation. The basic equation used in the ordinary Kriging interpolation method is as follows:

$$\boldsymbol{Z(s_0)} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{N}} \boldsymbol{\lambda_i Z\ (s_i)} \quad \text{(Ozturk and Kilic, 2016)}$$

The input point data utilized for the spatial interpolation methodology spanned a twenty-year period from 2000 to 2020. The sample size varied by year, reflecting differences in data availability across the sampling campaigns. Specifically, the earliest dataset in 2000 comprised

132 sample points, which increased to 185 points in 2010. The final dataset collected in 2020 contained the largest number of observations, totalling 214 input points. Overall, the number of input sample points across the study years ranged from a minimum of 132 to a maximum of 214 locations, ensuring a robust and evolving coverage for the annual interpolation surfaces.

Statistical Analysis of GWD

Zonal Statistics as Table tools are used for the analysis of minimum, maximum and mean value of GWD for the year 2000, 2010 and 2020 for different Tehsils of Churu district.

Rainfall Analysis

Decadal annual average of rainfall has been calculated for the year 1991 to 2019. The mean of the rainfall for the 1991 to 2000, 2001 to 2010 and 2011-2019 are further calculated. Then the decadal changes in rainfall condition have been compared.

RESULT AND DISCUSSION

Since irrigated agricultural area for Rabi crop are having significant impact on Ground Water Depth (GWD), this study has been taken to assess and evaluate this impact using geospatial technique. Study is undertaken by using NDVI technique for crop extraction and Kriging interpolation for GWD. It shows sharp increase in irrigated agricultural area in some parts of the district specially in non-saline aquifer zones of the district and fluctuations in GWD. Most irrigated agricultural areas lies in alluvium aquifer where groundwater can be used for irrigation.

Change in irrigated Crop area

The estimation of the irrigated crop area is shown in Fig 4. The irrigated area for rabi crop for the year 2000 was 29642.9 ha, increased to 216709.34 ha in year 2020. There is phenomenal increase in irrigated crop area. This can also be viewed from the temporal maps generated (Fig 4). Table-1 shows temporal change in Rabi crop area in different tehsils of the district. Sardarshahar tehsil has recorded an increase from 1306.8 ha to 89779.1 ha between 2000 and 2020. Churu and Taranagar tehsils has also similar trends of increase in irrigated Rabi crop area. The irrigated Rabi crop area also increased in Rajgarh, Ratangarh and Sujangarh tehsils. This increasing trend of irrigated crop area is also represented by a graph in Fig 5.

Figure 04: Temporal change in Rabi crop area (ha)

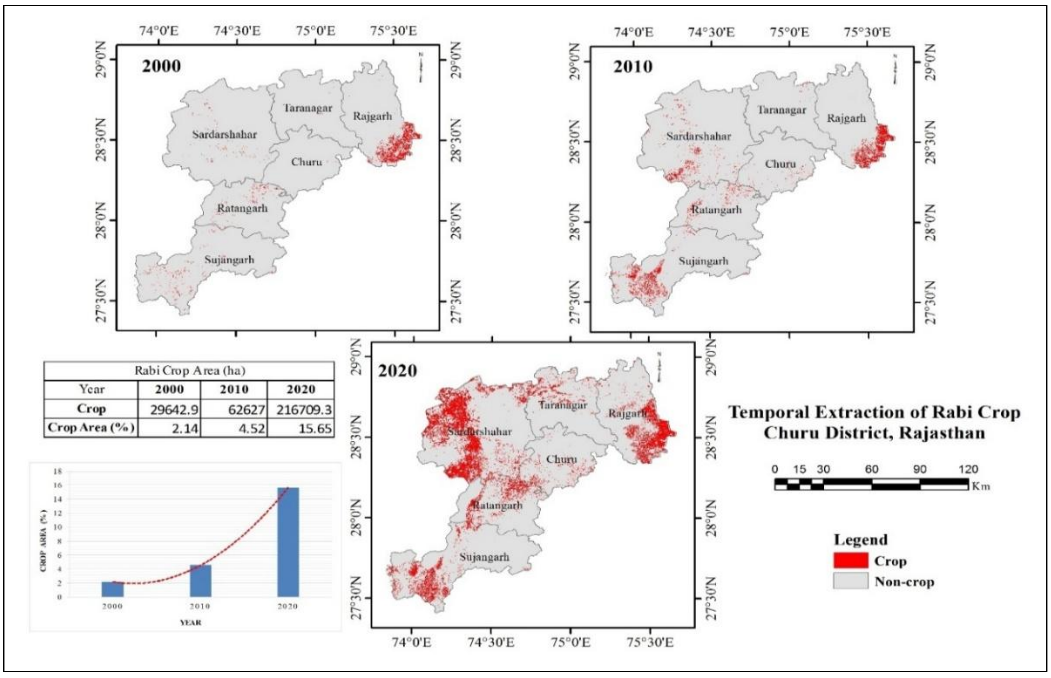
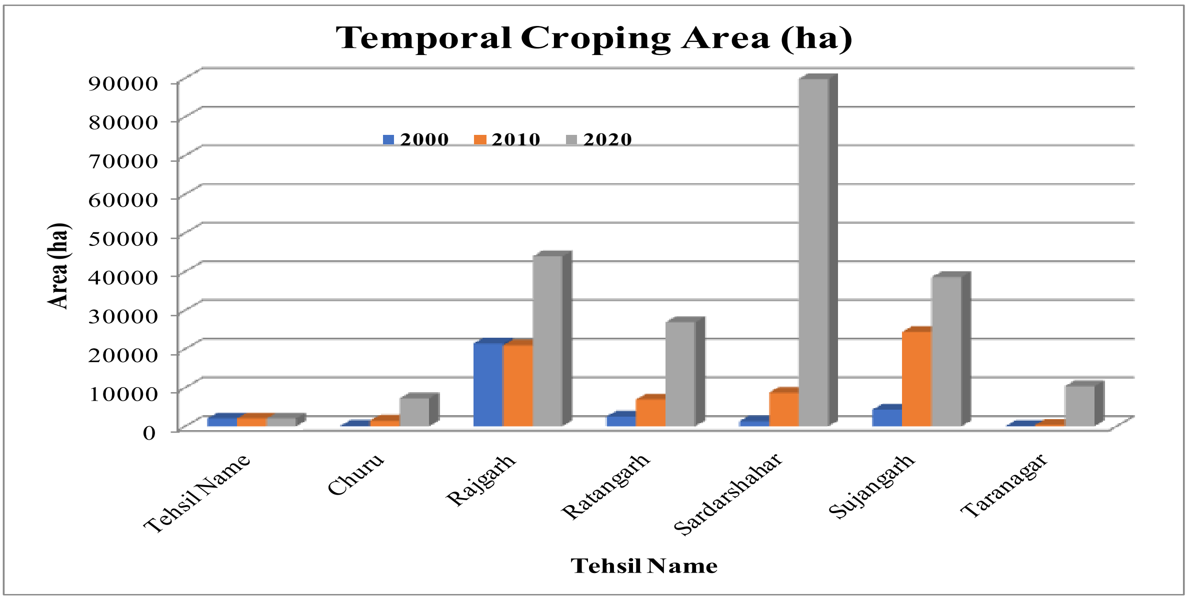


Table 01: Tehsil wise change in Rabi Crop Area

Tehsil Name	Year / Crop Area (ha)			Decadal Change		Total Increase
	2000 (A)	2010(B)	2020 (C)	B-A	C-B	C-A
Churu	111.42	1424.25	7211.34	1312.83	5787.09	**7099.92**
Rajgarh	21372	20923.5	43899.5	-448.50	22976.00	**22527.5**
Ratangarh	2514.06	6901.47	26885.2	4387.41	19983.73	**24371.14**
Sardarshahar	1306.8	8696.34	89779.1	7389.54	81082.76	**88472.3**
Sujangarh	4292.19	24353.3	38574.2	20061.11	14220.90	**34282.01**
Taranagar	46.44	328.14	10360	281.70	10031.86	**10313.56**

Figure 05: Trend of Temporal Change in Rabi Crop Area (ha.)



Groundwater Depth Analysis

Based on the table 2, the groundwater depth in the district exhibits a clear and continuous decreasing trend in groundwater level since 1999, which is observed as an increasing depth in meters. This pattern confirms that the groundwater reserves are being significantly depleted. For the pre-rabi season, the minimum groundwater depth deepened from 8.72meters in November 1999 to 11.58meters by November 2019. Similarly, the post-rabi season minimum depth increased from 11.92meters in May 2000 to 13.56meters in May 2020. This consistent increase in depth across two decades is a direct indicator that the water table has fallen substantially. The primary driver for this depletion is the continuous drafting of groundwater for irrigation across the district. This increased extraction pressure is particularly evident in specific areas. For instance, Sujangarh tehsil showed a dramatic increase in pre-rabi minimum depth, rising from 8.79meters in 2000 to 15.74 meters in 2020. Other regions, including Sardarshahar and Ratangarh tehsils, also report higher average mean depths, confirming continuous, concentrated water extraction in these irrigated zones. Overall, the data underscores a critical need for sustainable water management practices to halt the decline of the groundwater level.

Table 01: Average Minimum, Maximum and Mean Groundwater Depth in District (Meter)

	Nov,1999 (Pre M)	May, 2000 (Post M)	Nov,2009 (Pre M)	May, 2010 (Post M)	Nov,2019 (Pre M)	May, 2020 (Post M)	Change 2000	Change 2010	Change 2019
MIN	8.72	11.92	13.57	8.75	11.58	13.56	3.20	-4.83	1.98
MAX	62.61	56.36	57.12	60.86	53.77	50.64	-6.25	3.74	-3.12
MEAN	36.43	33.05	33.88	34.84	31.04	30.89	-3.38	0.96	-0.15

Figure 06: Irrigated Rabi Crop Area and Ground Water Depth (GWD), 2000

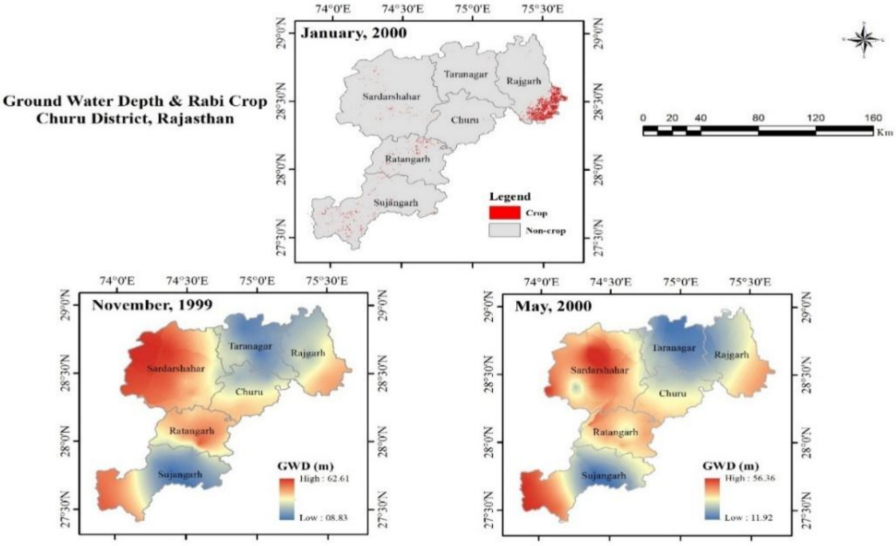


Figure 07: Irrigated Rabi Crop Area and Ground Water Depth (GWD), 2010

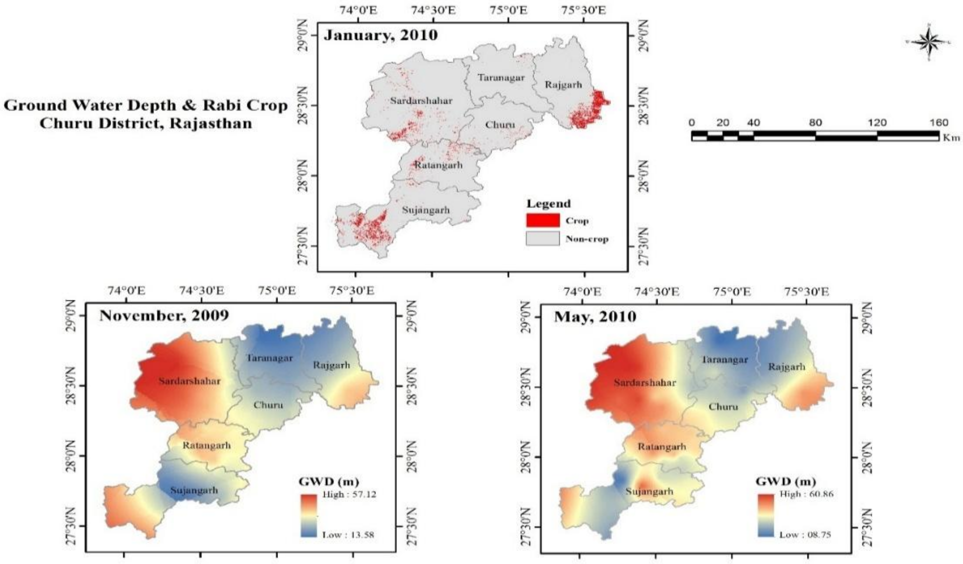
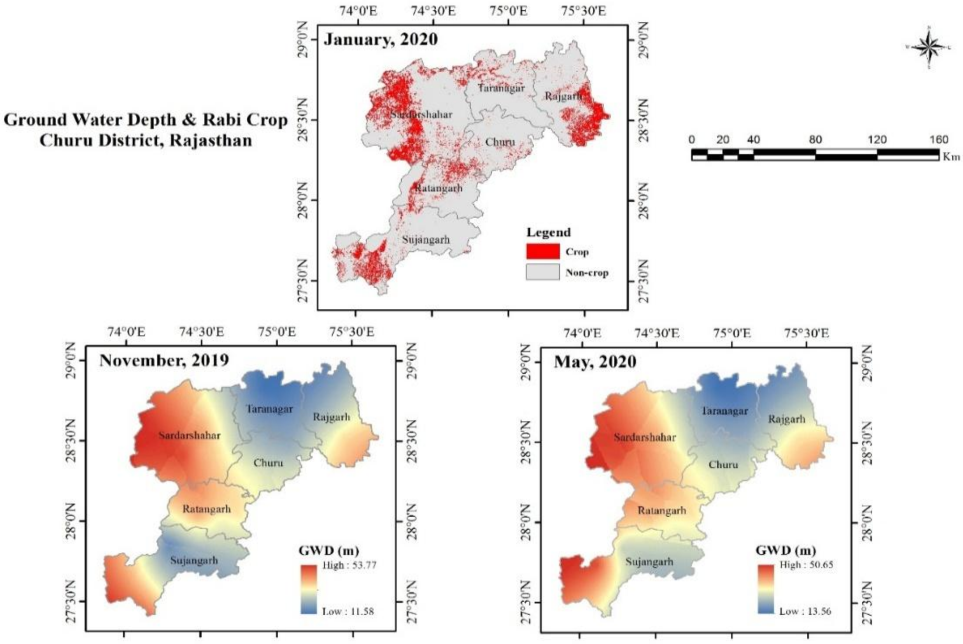


Figure 08: Irrigated Rabi Crop Area and Ground Water Depth (GWD), 2020

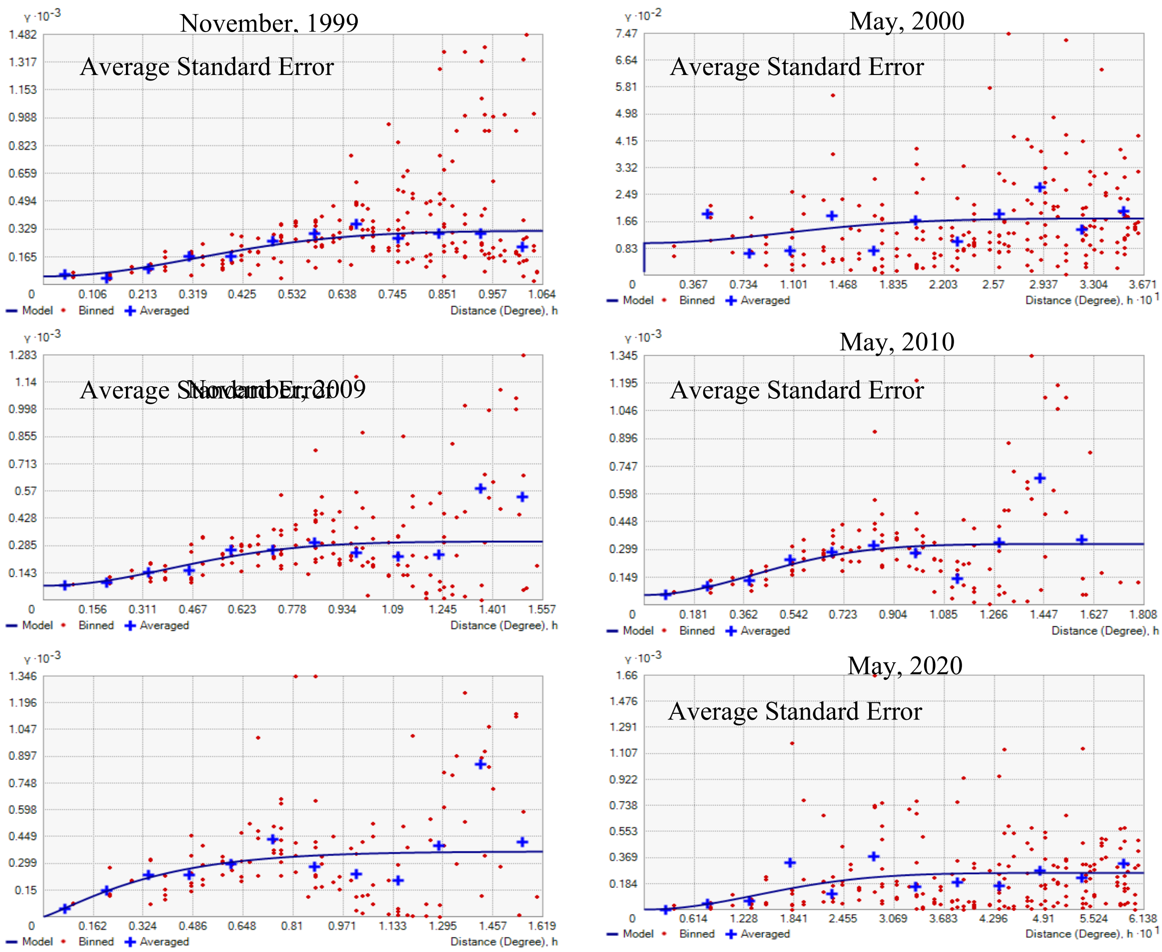


The analysis of the relationship between the irrigated agriculture area and groundwater level for the years 2000, 2010, and 2020 is presented in Figures 6, 7, and 8. As Rabi crops are typically grown from November to April, groundwater depth data for November and May were considered. Figure 5 provides information on the irrigated area under Rabi crops in 2000, indicating that only a few areas of the district were under this type of agriculture. Figures 7 and 8, conversely, show the increasing areas under irrigated Rabi crops for 2010 and 2020, with many areas across different tehsils now being cultivated with irrigated crops. The maps generally show a correlation between the increasing irrigated area and greater groundwater depth (i.e., lower water level). An exception is Taranagar tehsil, which, despite an increased irrigated area, shows a lesser impact on groundwater due to the availability of the Sahwa lift canal irrigation facility. Areas that have seen an expansion in irrigated agriculture have experienced a significant decrease in the groundwater level, indicating greater exploitation and overdraft. The study concludes that the continued increase in irrigated area will further deplete the groundwater level. Therefore, increasing irrigation efficiency, growing more water-resistant crops in the dry season, and widening the canal irrigation network are necessary measures to reduce pressure on groundwater resources.

Accuracy Assessment of Interpolation

Many studies on interpolation methods indicated that level of bias for estimation is lower in kriging as compared to other interpolation methods (Ikechukwu et al, 2017, Mazzella, 2013). It appears that if accuracy is taken as a prime concern, kriging interpolation is a preferable option for reliable estimation (Sompop and Nawinda, 2020). The average standard error is measured to assess the accuracy of the interpolation model. The average standard error calculated in the present study is within the limit, which shows more than 90 percent of accuracy.

Figure 08: Average Standard error



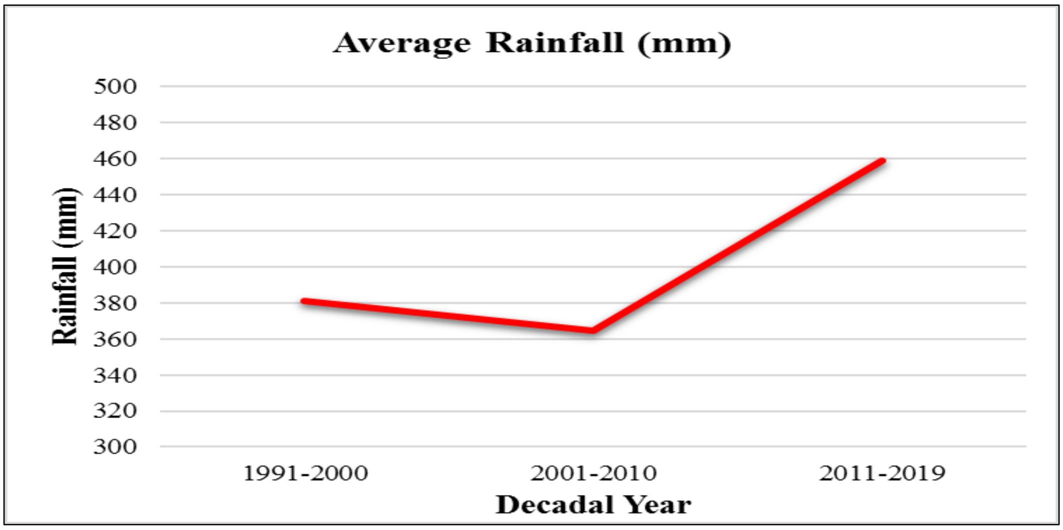
Rainfall Condition

The analysis of decadal average rainfall for the Churu district (Table 3) indicates a fluctuating trend in precipitation over the period from 1991 to 2019. During the first recorded decade (1991–2000), the average annual rainfall was 380.71mm. This figure saw a slight reduction in the following decade (2001–2010), dropping to 364.44mm, suggesting a period of drier conditions. However, the most recent period analysed (2011–2019) shows a substantial increase in precipitation, with the average rainfall climbing sharply to 458.74mm. This observed increase in average rainfall during the last decade is naturally favourable for the replenishment of groundwater reserves through recharge. Nevertheless, the study concludes that despite this positive trend in precipitation, the volume of recharge is not sufficient to reduce the existing stress on the groundwater system (Figure 9). This finding suggests that while climatic conditions are improving, the rate of water extraction, primarily for intensive irrigated agriculture, continues to outweigh the natural replenishment capacity, thereby perpetuating the problem of groundwater depletion in the region.

Table 03: Decadal Average Rainfall Condition in Study Region

Decadal Average Rainfall, Churu District			
Year	1991-2000	2001-2010	2011-2019
Average Rainfall (mm)	380.71	364.44	458.74

Figure 09: Decadal Average Rainfall Condition in Study Region



Conclusion

The rapid expansion of irrigated Rabi agriculture in the semi-arid district of Churu has significantly contributed to the continuous decline in groundwater levels over the past two decades. Geo-spatial analysis using NDVI-based crop mapping and kriging interpolation of groundwater depth reveals a strong spatial association between areas of intensive irrigation growth and zones experiencing pronounced water-table depletion. Tehsils such as Sardarshahar, Churu, Rajgarh, and Sujangarh show the largest increases in irrigated area and correspondingly the sharpest deepening of groundwater levels in both pre- and post-monsoon seasons, confirming sustained overexploitation. Although the last decade shows an improvement in rainfall, the natural recharge remains insufficient to offset the high groundwater abstraction driven by agricultural intensification. The findings underscore that groundwater depletion in the region is primarily anthropogenic and will continue unless demand is reduced. Ensuring long-term agricultural sustainability in this semi-arid environment will require improving irrigation efficiency, diversifying crops toward less water-intensive varieties, increasing artificial recharge measures, and expanding surface-water supply where feasible.

Overall, this research highlights the critical need for integrated groundwater management strategies informed by geo-spatial evidence to mitigate ongoing depletion and secure future water availability.

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