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Groundwater Prospects in Arid Zone of Rajasthan- Trends, Forecasts and Strategies for Sustainable Management: A Case Study of Jhunjhunun District

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Abstract: Groundwater is an important source of water for meeting the major water demands of the present time. Its ease of accessibility and reliable supply make it especially important. However, the precarious nature of groundwater, particularly in arid regions, demands serious analysis for future water management. More than 80% of total groundwater extraction is used for irrigation. Excessive use of groundwater has led to water scarcity in many areas. A study was conducted in the Jhunjhunun district of the western hot arid zone of Rajasthan, India, to examine long-term groundwater trends and forecast future groundwater scenarios for the years 2030, 2040 and 2050. Groundwater data from 8 blocks of each district, comprising of 200 monitoring wells, from the period 1984 to 2020 were used for the analysis. The Mann-Kendall (MK) test and Sen's slope were applied for statistical analysis, while the ARIMA model was used for modeling the time series data and forecasting. The results of the Mann-Kendall test indicated an overall declining trend in groundwater levels across all blocks, with the most most significant decrease observed in Buhana block (-42.44 m), followed by Surajgarh (-36.90 m), Udaipurwati (-32.8 m), Chirawa (-32.7 m), Khetri (-27.2 m), Nawalgarh (-26.3 m), Jhunjhunun (-18.2 m) m) and Alsisar (-5.8 m) block from the base year 1984 to the year 2020. The district overall reported a decline in the water table by 27.3 m from 1984 to 2020. The ARIMA (0,1,0) model forecasted groundwater table levels of 66.6 m, 74.3 m and 82.0 m for the years 2030, 2040 and 2050, respectively, compared to an average groundwater table of 50.76 m in 2020. The declining groundwater levels are attributed to the increasing cropped area and other water uses in the district. There is an urgent need to recharge groundwater in the district at appropriate locations and to adopt more water-efficient cropping practices for sustainable groundwater management.

Key words: Groundwater trend, Mann–Kendall, Sen's slope, ARIMA, Future groundwater scenario, Jhunjhunun, Rajasthan.

In arid areas, surface water is very limited. Under such conditions, groundwater resources assume prime importance. Although groundwater is a replenishable resource, excessive exploitation beyond the rate of dynamic recharge can result in irreversible damage to the groundwater reserves. The indiscriminate extraction of groundwater for irrigation and other uses has caused both decline in the groundwater table and deterioration in water quality beyond recovery (Goyal *et al*., 2021).

The climate change has resulted in an increase in hydrological extremes, such as droughts and floods and future projections suggest that these events will become more frequent (Ziervogel *et al.,* 2014; IPCC, 2014). Disasters related to climate change, especially those affecting water resources, are growing in scale and severity. Therefore, monitoring long-term changes in groundwater levels (GWLs) is crucial for enhancing adaptive capacity in the face of climate-related water resource disasters (Tladi *et al*., 2023).

In India, it is estimated that more than Rs. 6,000 crore is required annually to lift water from an additional depth of 1 meter. This highlights the need for close monitoring of groundwater exploitation. Approximately 68% of India's total net sown area (140 mha) is under rainfed agriculture, which plays a significant role in the Indian economy. A policy of "safe mining" of groundwater may be acceptable, provided it is coupled with positive measures such as artificial recharge or the conjunctive use of groundwater and surface water. However, long-term over-exploitation of groundwater at rates exceeding the hydrological safe yield is undesirable (Goyal and Gaur, 2020; 2021).

The objective of this study is to emphasise the critical importance of groundwater resources in arid regions, particularly in light of limited surface water availability and the adverse effects of climate change. We aim to analyze the consequences of groundwater over-exploitation and the need for sustainable management practices, while promoting the necessity of long-term monitoring to enhance adaptive capacity. By focusing on the Jhunjhunun district in Rajasthan, this study seeks to assess long-term groundwater trends essential for effective resource management in a region heavily reliant on rainfed agriculture.

Materials and Methods

***Study Area*:** Jhunjhunun district is located in the state of Rajasthan, India, situated between 27°38′ and 28°31′ North latitudes and 75°02′ and 76°06′ East longitudes. The district covers a geographical area of 5,915 km^2. It is bordered by Churu district to the northwest, to the northeast by the Hisar and Mahendragarh districts of Haryana and to the west, south and southeast by Sikar district, all within Rajasthan. Jhunjhunun is part of the Jaipur division and is administratively divided into eight blocks: (1) Alsisar, (2) Buhana, (3) Chirawa, (4) Jhunjhunu, (5) Khetri, (6) Nawalgarh, (7) Surajgarh and (8) Udaipurwati (Fig. 1).

The climate of Jhunjhunun district is predominantly dry and arid, characterized by a hot summer season. The average annual rainfall at the district headquarters is 444.5 mm, with the region experiencing approximately 27 rainy days yr^{-1}. Sandstorms are a typical feature during the summer months. The temperatures in the district can vary widely, with recorded minimum temperatures as low as 1.0°C and maximum temperatures reaching up to 45.0°C.

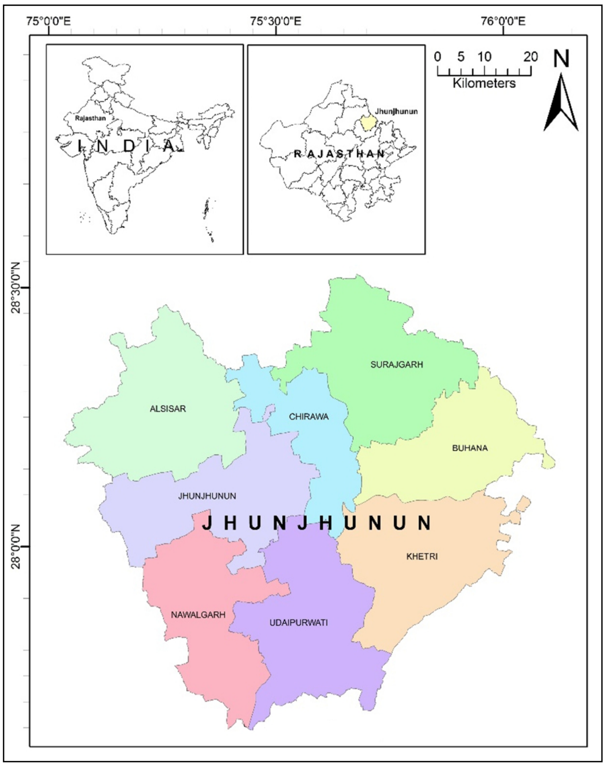


Fig. 1. Location of study area

The mean annual temperature is 23.0°C, reflecting the district's generally hot climate.

Land Use Land Cover: Land use and land cover mapping in Jhunjhunun district was carried out using remote sensing data (Sentinel-2A), GIS tools and field surveys for understanding the spatial distribution of various human activities and natural resources. It provided valuable insights into the land utilization for agricultural, residential, industrial and other purposes. This information is crucial for effective resource management, environmental monitoring and sustainable development planning. Unsupervised classification, was applied to categorize the land use/cover into distinct classes.

The majority of district's land is under agriculture (51.7% of total geographical area of 5927.84 km^2)). Crop land includes areas used for growing cereals like wheat, barley and millet, as well as pulses, oilseeds and cotton. The district's agriculture is primarily rainfed, although groundwater plays a vital role in irrigating crops, especially during dry seasons. Irrigated land is relatively limited in comparison to rainfed land. The district has limited forest cover (7.19%), consisting mostly of scrub and thorny vegetation typical of arid and semi-arid regions. The district has small to medium-sized urban settlements with the district headquarters, Jhunjhunun town, being the most significant urban center. Urbanization is gradually increasing due to population growth and infrastructural development and occupied an area of 3.06%. Water bodies, including seasonal ponds, lakes and irrigation reservoirs (0.5%), are scattered across the district (Fig. 2). These are crucial for water storage and flood control, although their number is limited due to the arid climate. A significant portion of the land is barren or categorized as wasteland (7.66%) due to poor soil quality, lack of water, or unsuitable terrain for cultivation. Fallow land occupied an area of 1730.97 km^2 (29.2%). Some areas in Jhunjhunun have salt-affected soils, especially in the dry regions, making them unfit for cultivation without special management. Pastureland used for grazing by livestock, primarily cattle, sheep and goats. Pastureland and grazing lands are important for the local economy, which relies heavily on animal husbandry.

Data collection: A detailed hydro-geological survey of the entire Jhunjhunun district was conducted between 2015 and 2020 to assess the groundwater resources. Long-term groundwater level data from a total of 200 groundwater monitoring wells were collected from the Central Groundwater Board (CGWB), Jodhpur, covering the period from 1984 to 2020.

In addition to groundwater data, information related to rainfall, cropping patterns and other relevant factors were collected from secondary sources, such as government reports, meteorological data and agricultural statistics. These data were essential for understanding the broader hydro-geological context and for analyzing the factors influencing groundwater trends in the district.

Trend analysis: The Mann-Kendall test (Mann, 1945; Kendall, 1975; Gilbert, 1987) is a commonly used non-parametric statistical test for detecting monotonic trends in environmental, climatic, or hydrological data. The null hypothesis of this test assumes that

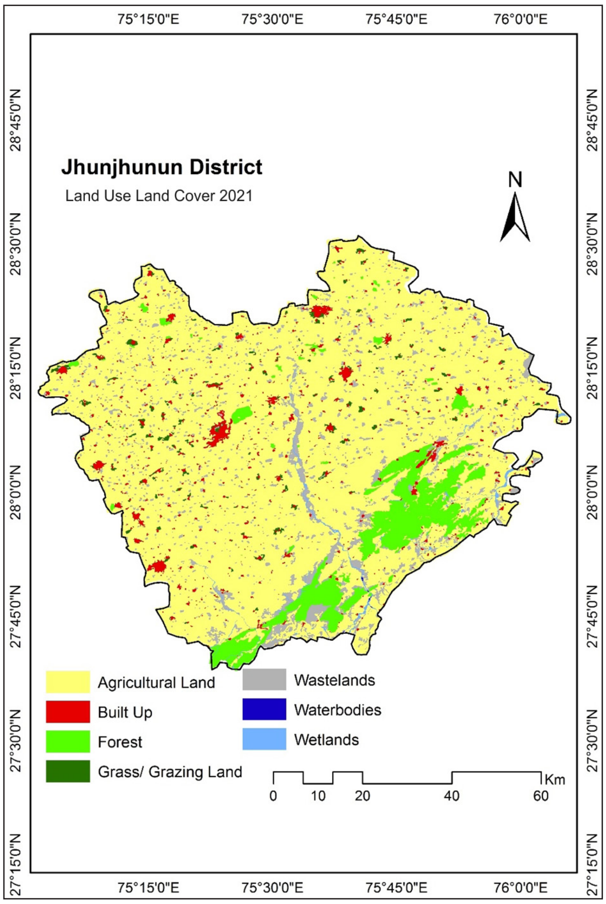


Fig. 2. Land Use Land Cover of Jhunjhunun district.

Table 1. Statistical patameters of Mann-Kendall trend test

Parameter	Blocks							
	Alsisar	Buhana	Chirawa	Jhunjhunun	Khetri	Nawalgarh	Surajgarh	Udaipurwati
Corrected Zc	4.03	3.17	5.13	5.45	4.28	3.61	5.78	3.62
Original Z	4.80	5.47	7.62	7.18	5.92	6.55	8.02	6.97
Tau	0.55	0.63	0.87	0.83	0.75	0.75	0.92	0.80
Sen's slope	0.11	1.41	0.89	0.53	0.65	0.65	1.17	0.77

the data come from a population where the observations are independently and identically distributed (*i.i.d.*). The alternative hypothesis posits that the data exhibit a monotonic trend. A statistically significant trend is determined based on the test statistic, denoted as Z. A positive value of Z indicates an upward (increasing) trend, while a negative value of Z indicates a downward (decreasing) trend.

For groundwater table analysis, levels are measured relative to the ground surface. Therefore, an increase in the depth to the groundwater table indicates a declining water table, while a decrease in depth suggests an increasing groundwater levels.

The Mann-Kendall trend test and the Sen's Slope estimator were calculated and plotted using the R statistical software program, utilizing the "trendchange" and "trend" packages (R Core Team, 2013).

Results and Discussion

Due to uneven topography, the no. of observation wells varied widely across all blocks of study area. The density of observation wells varies from the highest of 2,204 ha well^{-1} in Udaipurwati block to the lowest of 4,132 ha well^{-1} in Surajgarh block, with an overall average of 2,953 ha well^{-1}. Trend analysis of groundwater levels was conducted to investigate the presence of any significant trends. The non-parametric Mann-Kendall test and Sen's slope estimator (Sen, 1968) is widely used in climate and hydrological time series analysis and these two methods have been employed in the present study to analyze trends in groundwater levels.

The detailed statistical parameters for all blocks in the Jhunjhunun district are presented in Table 1.

The table presents the detailed results of the Modified Mann-Kendall trend test (Hamed and Rao, 1990) for groundwater levels across the eight blocks of Jhunjhunun district, used for trend analysis. Both the Mann-Kendall trend test and Sen's Slope analysis indicate a positive trend in the water level data for all blocks, confirming a general decline in groundwater levels over the study period. The Sen's Slope values range from 0.11 to 1.41, further supporting the conclusion of a declining groundwater table between 1984 and 2020. These values are also associated with high *Tau values*, indicating a strong and statistically significant correlation between time and groundwater levels.

The highest Sen's Slope of 1.41, observed in the Buhana block, indicates a rapid depletion of the groundwater table, suggesting that this area has experienced the most significant decline. In contrast, the minimum slope of 0.11 in the Alsisar block suggests a more gradual decline in groundwater levels, indicating slower depletion in that region.

The trend graph visually confirms this general declining trend, with a noticeable decrease in water levels over the years (Fig. 3). These findings are indicative of significant downward trends in groundwater levels across all blocks, with strong statistical confidence and correlation, which suggests that regional factors are contributing to the rapid decline in groundwater levels in certain areas.

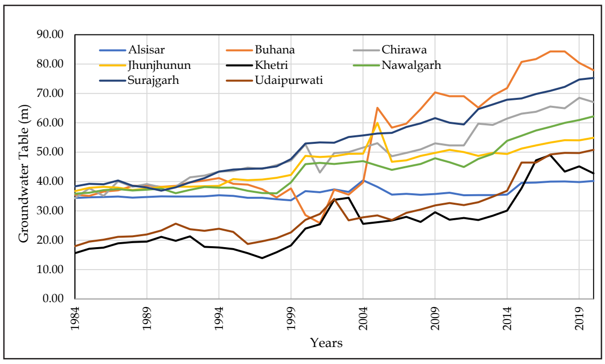


Fig. 3. Groundwater Table of different tehsils of Jhunjhunun district (1984-2020).

Such insights are critical for the sustainable management of water resources in the region. Understanding these trends will help inform appropriate strategies for groundwater recharge, conservation and management to ensure long-term water availability for agricultural and domestic use.

Innovative Trend Analysis (ITA): The Innovative Trend Analysis (ITA) plot is a useful tool for detecting trends in hydrological time series data. In an ITA plot, each data point represents a paired value of the variable of interest, taken from the first half and the second half of the time series. The solid line in the plot represents the 'No Trend' line, which indicates where data points would lie if there were no trend in the time series. The dotted lines represent the confidence interval, typically the ±5 percentile lines, which provide a range where we can be 95% confident that the data points would fall in the absence of a trend (Şen, 2012).

In Fig. 4, the data points are predominantly positioned above the 'No Trend' line, suggesting

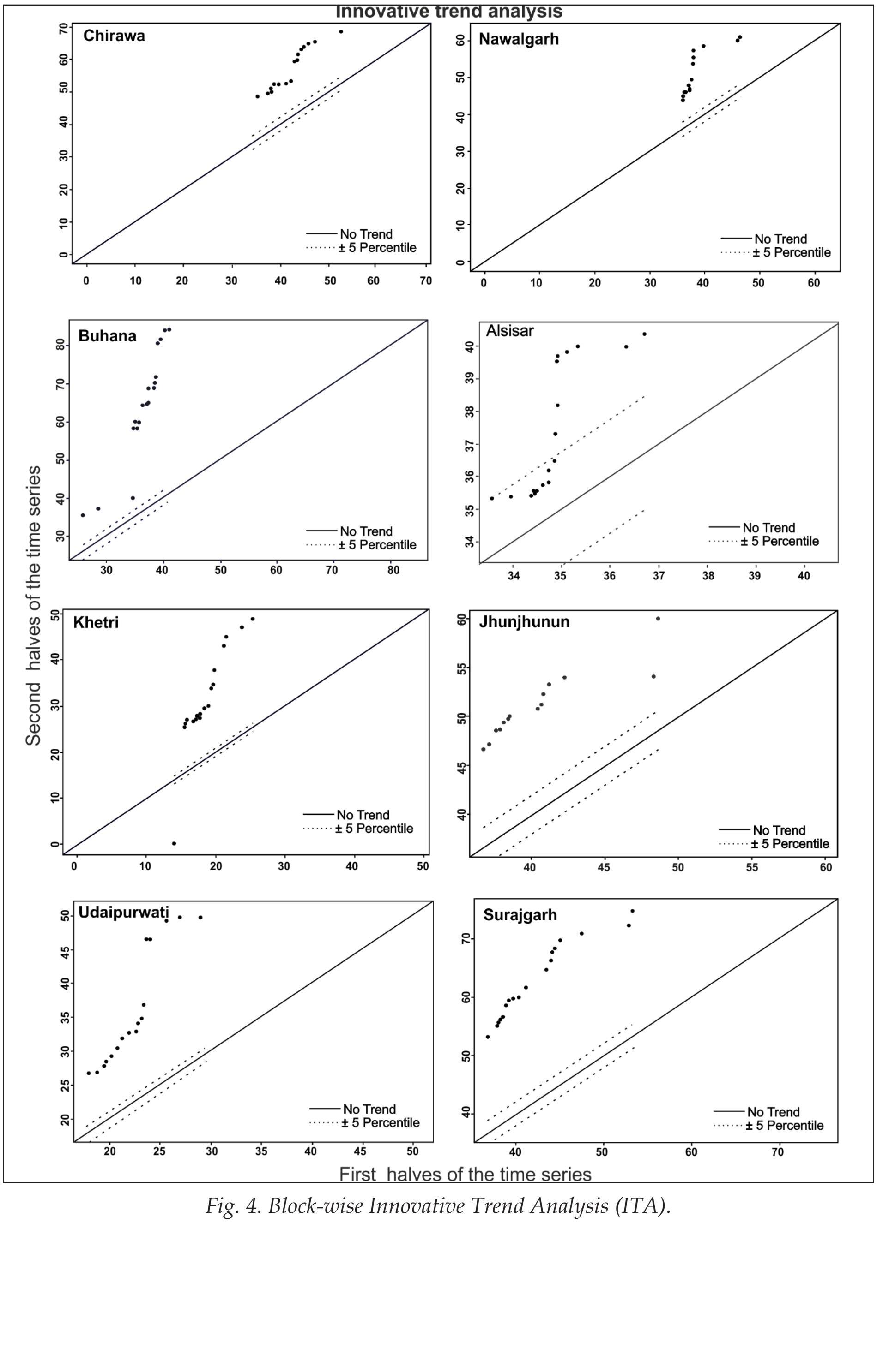


Fig. 4. Block-wise Innovative Trend Analysis (ITA).

a clear declining trend in groundwater levels over the observed period. The plot shows a distinct trend, with the majority of data points residing above the no-trend line, which serves as a reference for detecting shifts in the median of the dataset. The absence of any data points below this line, coupled with the clear positioning of all points outside the lower 5th percentile confidence boundary, robustly establishes the presence of a downward trend in groundwater levels.

The intensity of this declining trend is further emphasized by the substantial deviation of the data points from the 'No Trend' line, which visually reinforces the direction and magnitude of the change. This declining groundwater trend (shown as an upward shift in the ITA plot) could be attributed to several factors, such as the expansion of cropped areas, increased extraction of groundwater for new uses, or changes in recharge rates due to climate variability.

The implications of this observed trend are significant, as a consistent decline in groundwater levels can have far-reaching consequences for water resource management. A declining groundwater table could threaten the availability of water for irrigation, drinking and other uses, potentially impacting agricultural productivity and ecological sustainability. Moreover, this trend may also be a response to the effectiveness of implemented water conservation policies or lack thereof. Addressing this trend is crucial for ensuring long-term water security in the region and it highlights the need for adaptive management strategies to mitigate the impact of declining groundwater levels.

Overall Groundwater Scenario of Jhunjhunun District: Jhunjhunun district consists of eight administrative blocks, each with distinct geological characteristics and landforms, which result in significant variations in groundwater levels across the region. The depth to the groundwater table varies considerably, with the deepest groundwater table observed in Buhana block at 77.9 meters, while Alsisar tehsil has the shallowest groundwater table at 40.2 meters. The difference in groundwater table depth is also attributed to the local land forms and quality of water itself.

Given that all eight blocks exhibit a declining trend in groundwater levels, the average groundwater conditions for the entire district were forecasted by calculating the yearly average groundwater levels from all blocks. This approach allows for a consolidated representation of the overall groundwater scenario in Jhunjhunun district for district level planning. The average groundwater levels over the study period are presented in **Fig. 5.**

The trend line for the average groundwater level shows a clear and consistent decline, with a high correlation coefficient (R = 0.91), indicating a strong and statistically significant downward trend in groundwater levels across the district. This confirmed and distinct decline in groundwater levels highlights the pressing need for sustainable water management practices in the region, particularly given the variability in groundwater availability across different blocks.

***Future Scenario of Groundwater in the district*:** One of the major future challenges will be to ensure the short- and long-term availability of groundwater to meet

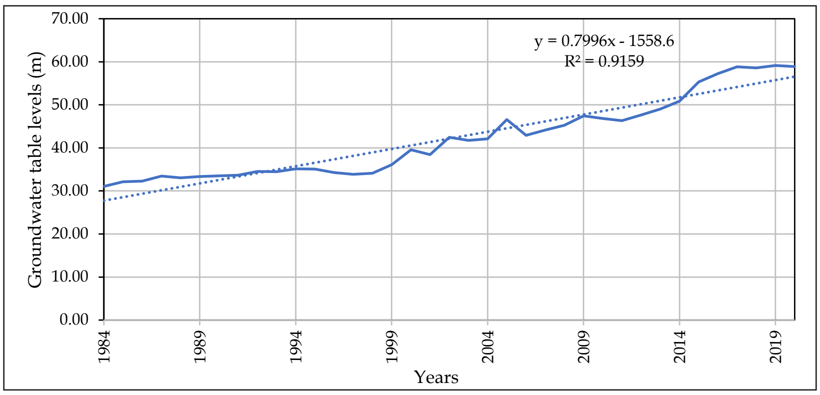


Fig. 5. Trend of groundwater levels of Jhunjhunun district (1984 to 2020).

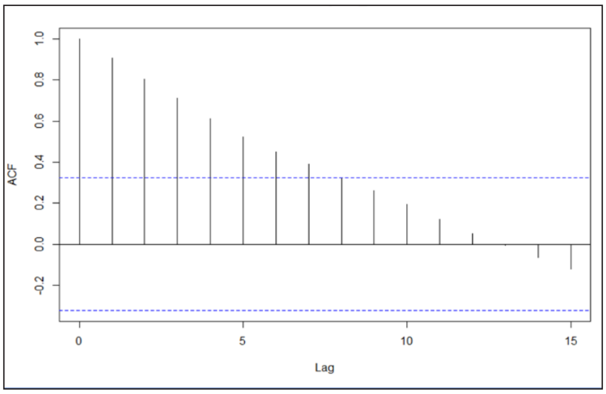
the needs of present uses and of the fast-growing human population. Therefore, future scenario of groundwater is very important for long term planning as well reallocation of water for various sectors. In the present study, the future scenario of groundwater is forecasted considering only past trends of the groundwater table without considering changes in human and livestock populations and other new uses of groundwater. For generation of future scenario, the ARIMA (Auto Regressive Integrated Moving Average) model has been used. The ARIMA model is one of the most widely used tools for time series data modeling and forecasting (Box and Jenkins, 1976). The ARIMA model consists of three key components: autoregressive (AR), integrated (I) and moving average (MA) parts, which are expressed as ARIMA (*p, d, q*). In this expression, *p* represents the autoregressive part, *d* is the integrated part (the number of differences required to make the series stationary) and *q* is the moving average part. The methodology involves four key steps: model identification, parameter estimation, diagnostic checking and forecasting. Through these systematic steps, the Box-Jenkins method provides a robust framework for time series analysis and forecasting, allowing for more accurate predictions and informed decision-making based on future trends and patterns.

To assess the stationarity of the groundwater table depth data, we first applied the Augmented Dickey-Fuller (ADF) test. The ADF test yielded a Dickey-Fuller statistic of -2.059, with a lag order of 3 and a corresponding *p-value* of 0.55. Since this *p-value* exceeds the commonly used significance level of 0.05, we fail to reject the null hypothesis at the 5% significance level. This result suggests that the groundwater table depth data is non-stationary, meaning that its statistical properties, such as the mean and variance, may vary over time.

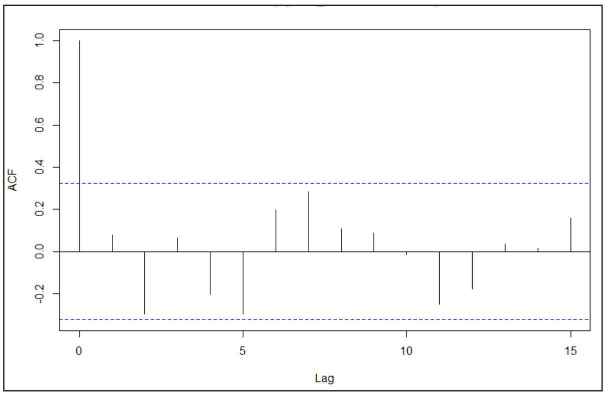
Next, we examined the autocorrelation function (ACF) plot without differencing. The plot revealed eight significant spikes, which exceeded the confidence limits at lags 1 through 8 (Fig. 6a). These spikes indicate substantial autocorrelation at these lags, further supporting the conclusion that the original groundwater data is non-stationary. After applying first-order differencing, however, no significant spikes extended beyond the confidence limits (Fig. 6b), indicating that differencing successfully removed the autocorrelation present in the original series and made the data stationary.

Similarly, the partial autocorrelation function (PACF) plot before differencing (Fig. 6b) displayed a significant spike at lag 1, indicating partial autocorrelation at that lag. Following differencing, the PACF plot no longer showed significant spikes, reinforcing the conclusion that the data had become stationary.

For the ARIMA model selection, the "auto. arima" function in R was used to evaluate various combinations of autoregressive, differencing and moving average terms. The output from this model selection process revealed several candidate ARIMA models, each with different combinations of parameters. Among these, the ARIMA (0, 1, 0) model with a drift term emerged as the best-fitting model, based on commonly used information criteria such as AIC (Akaike Information Criterion), AICc (corrected AIC) and BIC (Bayesian Information Criterion). This model suggests

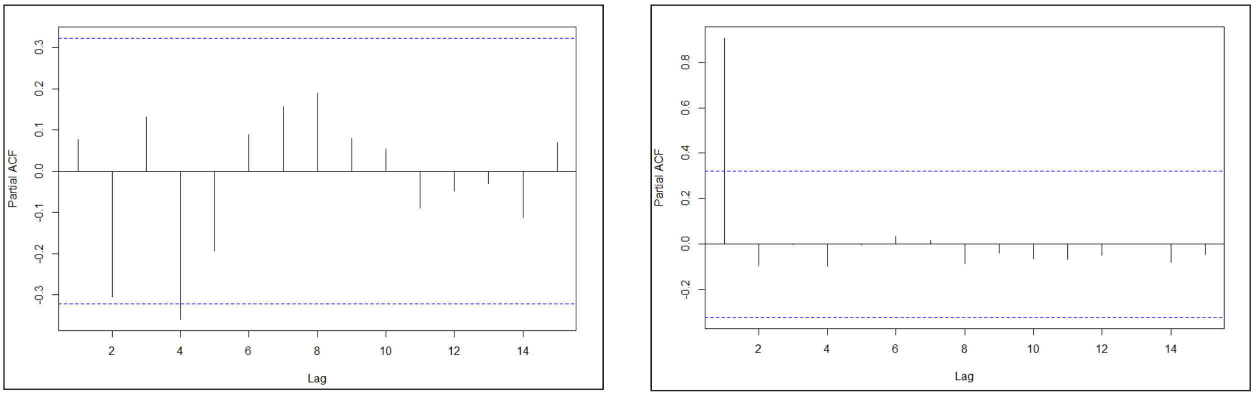


(a) ACF plot (without differencing)



(b) PACF plot (without differencing)

Fig. 6. Plot of the autocorrelation function and partial autocorrelation function without differencing.



(a) ACF plot of residuals *(b) PACF plot of residuals*

Fig. 7. Plot of ACF and PACF of residuals for the selected ARIMA(0,1,0) model.

that the groundwater table depth data exhibits a first-order differencing (d = 1) and a constant trend over time, represented by the drift term.

The estimated coefficient for the drift term is 0.7725, with a standard error of 0.3140, indicating a positive trend in the groundwater table over time. To ensure that the selected model adequately captured the temporal patterns in the data, we also examined the residuals using ACF and PACF plots (Figures 7a and 7b). These plots help identify any remaining autocorrelation or partial autocorrelation in the residuals. Both the ACF and PACF plots of the residuals were within the confidence limits, indicating that no significant autocorrelation remained and the model had adequately captured the dynamics of the groundwater table depth data. Thus, the ARIMA (0, 1, 0) model was deemed appropriate for forecasting future groundwater table depths.

The forecasted values for the groundwater table depth from 2021 to 2050, along with their corresponding 95% prediction intervals, are presented in **Fig. 8** and **Table 2**. The "Point Forecast" column represents the estimated groundwater table depths for each year, while the "Lower_95" and "Upper_95" columns indicate the lower and upper bounds of the 95% prediction intervals, respectively. These prediction intervals provide a range within which the actual groundwater table depth is expected to fall, with a 95% level of confidence.

According to the forecast, the groundwater table depth is projected to continue its gradual decline throughout the forecast period. Specifically, the estimated groundwater table depth is expected to decrease from 59.65 m below the ground level in 2021 to 82.05 meters below ground level by 2050. This trend suggests a sustained reduction in groundwater availability, which could have

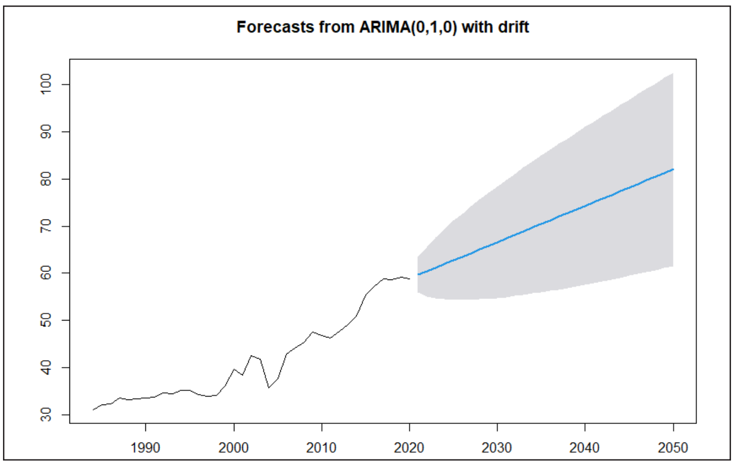


Fig. 8. Forecast of groundwater level using ARIMA (0, 1, 0) model. The grey-shaded areas show the 95% prediction intervals, respectively.

Table 2. Forecast of groundwater level (2021-2050) using ARIMA (0, 1, 0) model

Years	Point Forecast	Lower_95	Upper_95
2021	59.653	55.908	63.397
2022	60.425	55.129	65.721
2023	61.198	54.711	67.684
2024	61.970	54.481	69.459
2025	**62.743**	**54.369**	**71.116**
2026	63.515	54.342	72.688
2027	64.288	54.380	74.195
2028	65.060	54.468	75.652
2029	65.833	54.598	77.067
2030	**66.605**	**54.763**	**78.447**
2031	67.378	54.958	79.797
2032	68.150	55.178	81.122
2033	68.923	55.421	82.424
2034	69.695	55.684	83.706
2035	**70.468**	**55.964**	**84.971**
2036	71.240	56.261	86.219
2037	72.013	56.573	87.452
2038	72.785	56.898	88.672
2039	73.558	57.235	89.880
2040	**74.330**	**57.583**	**91.077**
2041	75.103	57.942	92.263
2042	75.875	58.311	93.439
2043	76.648	58.689	94.606
2044	77.420	59.075	95.765
2045	**78.193**	**59.469**	**96.916**
2046	78.965	59.871	98.059
2047	79.738	60.279	99.196
2048	80.510	60.695	100.325
2049	81.283	61.117	101.448
2050	**82.055**	61.544	102.566

significant implications for water resource management, agricultural practices and the overall sustainability of groundwater resources in the region. The prediction intervals reflect the uncertainty inherent in the forecasting process, with the actual depth likely to fall within the specified range, depending on various factors influencing groundwater recharge and extraction.

The Box-Ljung test was conducted, to further assess the adequacy of the ARIMA (0, 1, 0) model, on the residuals of the forecasted groundwater level data. The Box-Ljung test is used to check for the presence of significant autocorrelations in the residuals, which are the differences between the observed values and the values predicted by the model. The test generates a test statistic (Chi-squared) and its associated *p-value*, which help determine whether any autocorrelation remains in the residuals after model fitting.

The null hypothesis of the Box-Ljung test is that there is no autocorrelation present in the residuals, meaning the residuals are independent of one another. If the *p-value* is greater than a predefined significance level (typically 0.05), the null hypothesis is not rejected, indicating that the residuals do not exhibit significant autocorrelation and are likely random. In this case, the *p-value* of the Box-Ljung test was found to be 0.0788, which is greater than the 0.05 significance level. As a result, we fail to reject the null hypothesis, suggesting that there is no significant autocorrelation in the residuals.

This outcome supports the conclusion that the selected ARIMA (0, 1, 0) model adequately captures the underlying autocorrelation structure in the groundwater table data. In other words, the residuals appear to be independent, further validating the model's suitability for forecasting the future groundwater levels. The absence of significant autocorrelation in the residuals suggests that the model has appropriately accounted for the temporal dependencies in the data, making it a reliable tool for forecasting future trends.

The results of the Mann-Kendall test indicated a clear and consistent declining (negative) trend in groundwater levels across all blocks in the district. Specifically, the groundwater table in the district declined from 31.07 meters below ground level in 1984 to 58.88 meters in 2020, with an average decline of 0.75 meters per year. These findings are consistent with similar studies, such as the work of Patle *et al.* (2015) in the Karnal district of Haryana, India, where a comparable decline in groundwater levels was observed. This decline in groundwater levels is a cause for concern, as it signals a depletion of the resource that may eventually threaten water availability for agricultural and other uses.

Furthermore, the ARIMA (0, 1, 0) model, used for time series forecasting, projected that the groundwater table will continue to decline in the coming decades. Specifically, the forecasted groundwater table depths are 66.6 m by 2030, 74.3 m by 2040 and 82.0 m by 2050, compared to an average groundwater level of 50.76 m in 2020. These projections highlight the ongoing depletion of groundwater resources, which could have significant implications for water availability, agricultural productivity and overall resource management in the region.

Strategies for Sustainable Groundwater Management: The declining groundwater levels in Jhunjhunu district highlight the urgent need for effective and sustainable water management strategies to safeguard this crucial resource. Given the district's reliance on groundwater for irrigation in a predominantly arid climate, proactive measures are essential to ensure long-term water security for agriculture, domestic use and livestock (Goyal and Gaur, 2021). Several strategies can be adopted to address the groundwater depletion issue and promote sustainable water use (Goyal and Gaur, 2016).

One of the most critical strategies is rainwater harvesting. Since the district receives low and erratic rainfall (average annual precipitation of 444.5 mm), capturing and storing rainwater during the monsoon season can significantly recharge groundwater reserves. Promoting the construction of small-scale rainwater harvesting structures, such as ponds, check dams and rooftop rainwater collection systems, can help supplement groundwater recharge, especially in rural areas where agricultural demand is high (Goyal, 2004). These structures not only store water but also mitigate the effects of floods and soil erosion, improving both water availability and agricultural productivity (Goyal *et al.,* 2019).

Another important approach is the *recharge of groundwater through artificial recharge techniques*. Techniques such as *recharge pits, recharge wells* and *infiltration galleries* can help direct surface water into the ground, promoting groundwater replenishment (Narain & Goyal, 2005; Goyal *et al.,* 2007). This is particularly relevant in areas where the natural recharge rate is insufficient to meet the demands of increasing groundwater extraction. The use of *constructed wetlands* for wastewater treatment and subsequent use for recharge is also gaining attention as a sustainable method for both water purification and replenishment (Goyal *et al.,* 2016).

The *conjunctive use of surface water and groundwater* is another key strategy for sustainable management. In Jhunjhunun, where irrigation largely depends on groundwater, integrating surface water from existing water bodies like ponds, tanks and seasonal reservoirs can reduce the pressure on aquifers. The optimal combination of surface and groundwater use not only helps prevent over-extraction but also ensures that agricultural practices remain resilient in the face of climate variability. Efficient irrigation systems, such as *drip irrigation* and *sprinkler systems*, should be promoted to reduce water wastage and increase crop water-use efficiency.

Furthermore, improving *water use efficiency* at the farm level is essential. Farmers should be encouraged to adopt water-saving technologies, such as *precision irrigation*, *mulching* and *soil moisture management techniques*. Educating farmers on the importance of water conservation and efficient irrigation practices is crucial, as it can reduce the dependency on groundwater for crop irrigation, especially during dry spells. Financial support in the form of subsidies or low-interest loans for purchasing water-efficient equipment could help accelerate this transition.

Community participation is a cornerstone of sustainable groundwater management. Engaging local communities, farmers and stakeholders in the planning and decision-making process fosters a sense of ownership and responsibility for the water resources. Local water user associations can play an active role in monitoring groundwater levels, promoting water-saving practices and ensuring equitable distribution of water resources. Community-driven initiatives like *water budgeting* and *aquifer management plans* can help regulate water use and prevent over-exploitation.

Finally, *policy reforms and government intervention* are necessary to address the long-term sustainability of groundwater resources. The implementation of *groundwater governance* frameworks, which regulate the extraction and use of groundwater, can be instrumental in curbing over-exploitation. This could include setting up *water pricing mechanisms* to reflect the true cost of water, incentivizing the use of renewable sources like solar-powered pumps and regulating the drilling of deep borewells. Additionally, promoting policies that focus on the *conservation of soil moisture* and *afforestation* can help mitigate the impact of land degradation and reduce water loss from evaporation.

Thus, a multi-pronged approach that includes technological interventions, community participation, policy reforms and environmental conservation will be essential for ensuring the sustainability of groundwater resources in Jhunjhunun district. By adopting these strategies, the district can strike a balance between meeting the growing demands for water and maintaining the health of its aquifers, ensuring a stable and resilient water supply for future generations.

Conclusions

Groundwater is the most important natural resource on earth but its excessive use has led to water scarcity in many areas. In the present study long term groundwater data (1984-2020) of Jhunjhunu districts were analyzed for trend and future scenario. The Mann-Kendall (MK) test and Sen's slope were applied for statistical analysis, while the ARIMA model was used for modeling the time series data and forecasting. The results indicate significant declining trends of groundwater in all blocks of study area. The district overall reported a decline in the water table by 27.3 m from 1984 to 2020. The declining groundwater levels are attributed to the increasing cropped area and other water uses in the district. There is an urgent need to recharge groundwater in the district at appropriate locations and to adopt more water-efficient cropping practices for sustainable groundwater management.

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