The variation in groundwater level and groundwater recharge based on the rainfall received in four semi-arid districts of West Bengal, India

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ABSTRACT

This article investigates the fluctuations in groundwater level (GWL) and groundwater recharge in response to rainfall variability using 2001–2021 rainfall data from four districts in West Bengal, India: Purulia, Bankura, West Midnapore, and East Midnapore. Purulia and Bankura have a tropical semi-arid to sub-humid type of climate, while West Midnapore and East Midnapore have a tropical wet-dry monsoon climate. The GWL analysis was performed using the Mann-Kendall Test (M-K Test) and Sen's Slope Estimator, while groundwater recharge was estimated using empirical expressions, including the Chaturvedi and Modified Chaturvedi formulas, and the Maxey-Eakin and Krishna Rao methods. We used pre-monsoon and post-monsoon GWL data for the GWL trend analysis and monthly rainfall data for groundwater recharge estimation. To assess the impact of climate change on GWL variation for the 2022–2050 period, the global climatic model (GCM) CanESM5-SSP126 rainfall data was used. The trend analysis of groundwater level at East Midnapore and West Midnapore shows a higher rate of decline (GWL beyond 15 m bgl) compared to Purulia and Bankura during both the pre- and post-monsoon periods. Groundwater recharge estimates increased linearly with rainfall and the results show the Modified Chaturvedi formula as the most suitable in the selected districts. Additionally, new empirical expressions developed between rainfall and groundwater levels showed a better fit for Bankura and Purulia stations. These expressions suggest that rainfall will increase in Purulia toward 2050, leading to a subsequent rise in groundwater levels.

KEYWORDS

groundwater level; recharge; Mann-Kendall; climatic model; Chaturvedi Formula; West Benga; India

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1. Introduction

Groundwater (GW) represents approximately 30% of the global freshwater supply and serves as a crucial resource for over two billion people across the world (Ajami 2021). The growing population, multiple environmental issues, extended periods of drought, and ineffective water system management pose significant challenges on a global scale. These concerns necessitate immediate intervention from authorities overseeing groundwater resources. Jasechko et al. (2024) highlights that unsustainable pumping and reduced precipitation are the key drivers of depletion, leading to risks like land subsidence, streamflow loss, and wells running dry. Groundwater plays a vital role in ensuring both food and freshwater security, especially in water-scarce countries like India (Yazdian et al. 2021). In India, groundwater supports over 60% of irrigation needs and provides nearly 80% of the drinking water supply. Similar to many other water-stressed areas worldwide, India has also seen immense groundwater depletion in the recent years (Asoka et al. 2017; Wada et al. 2010). The pronounced decline in groundwater reserves has been predominantly attributed to unsustainable extraction practices for irrigation and alterations in the spatiotemporal distribution of monsoonal precipitation (Asoka et al. 2017). A substantial body of literature has documented with marked reductions in groundwater storage and water levels, primarily linking these trends to intensive groundwater withdrawal for irrigation purposes (Macdonald et al. 2016; Shah 2017; Mukherjee et al. 2015). Despite this, the influence of precipitation dynamics on groundwater recharge is a critical component for assessing long-term groundwater sustainability and that remains insufficiently explored in the Indian context. Over recent decades, notable changes have occurred in both the intensity and structural attributes of the Indian southwest monsoon rainfall (Mishra et al. 2016; Singh et al. 2014). A notable hydrological shift identified in recent decades is the decline in monsoonal precipitation over the Indo-Gangetic Plain (Mishra et al. 2016; Roxy et al. 2017). As a result, ensuring sustained groundwater recharge has become critical for maintaining long-term water security. The eastern segment of the Indian subcontinent, which embodies these geoclimatic constraints, offers a unique context for investigating the multifaceted drivers of groundwater recharge.

The fluctuation of groundwater levels is governed by a range of factors, including precipitation patterns, recharge rates, subsurface flow dynamics, soil characteristics, and groundwater extraction capacities, among other variables (Maliva 2020; Osborn and Hardy 1999; Stempvoort et al. 1993). Beyond these hydrogeological and anthropogenic parameters, climate variability serves as a critical determinant influencing groundwater systems. Studies have demonstrated that climate change exerts direct effects on soil properties, land cover, and hydrological processes, primarily through increased temperatures, altered precipitation regimes, shifts in evapotranspiration, and a heightened frequency of extreme weather events such as cyclones, floods, and droughts (Hamed et al. 2018; Mokadem et al. 2018).

This study presents an investigation into the variations of groundwater level and groundwater recharge in the districts of Purulia, Bankura, East Midnapore, and West Midnapore of West Bengal. This work also projected the groundwater levels for changing climatic scenarios in future period using CanESM5 model for SSP-126 scenario. The groundwater hydrology of the selected regions transit from hard rock terrain to coastal alluvial plains. By examining the relationship between rainfall patterns and groundwater level fluctuations, the study captures the heterogeneity in recharge potential influenced by rainfall variability. Unlike previous localized studies, this research offers a comparative regional analysis that integrates historical groundwater and rainfall data to identify recharge trends and stress zones. By establishing empirical correlations and recharge response patterns across physiographical distinct districts, the study addresses a critical data and knowledge gap in regional aquifer behavior, particularly under the stress of seasonal rainfall variability and increasing extraction pressures. The findings have significant implications for sustainable groundwater management, especially in areas facing agricultural water stress, and contribute to bridging the gap between climate variability and groundwater resource planning in eastern India.

2. Study area and data collection

The study area encompasses four major districts of West Bengal, namely Purulia, Bankura, West Midnapore and East Midnapore (Bhattacharya et al. 2020), which span an area of 9,658 km^2 (Fig. 1). All the four selected districts is a part of Kangsabati river basin, in which the aquifer system of the entire basin is more of diversified characteristic. This aquifer has arranged of upper and lower aquifers under unconfined and confined condition, where upper aquifer has 40 m bgl water level depth under unconfined condition whereas lower aquifer has <50 m water depth under confined condition (Bhattacharya et al. 2020). In this study, all selected wells are tapping the upper aquifer. Within the four districts of the study area, Purulia and Bankura have tropical semi-arid to sub-humid (dry type) of climate (Goswami et al. 2022) while West Midnapore and East Midnapore have tropical wet-dry monsoon climate (Ghosh et al. 2015; CGWB 2022). Block wise (administrative sub-district) 2 data sets per year i.e pre-monsoon and post-monsoon depth to groundwater level (GWL) of the four districts of the study area Purulia, Bankura, West and East Midnapore from Government of West Bengal collected for a period of 21 years (from 2001 to 2021) has been used for the analysis. This data was collected from 5 stations of East Midnapore, 8 stations of West Midnapore, 8 stations of Bankura and 13 stations of Purulia district and is marked in Fig. 1. In this, only one well data is considered as the representative well among each district, as the variation of data is minimum and hence it is used for further groundwater level analysis (Bharti et al. 2024). Henceforth, the analysis of the selected representative well represents the entire district in this study. Monthly rainfall data was collected for each district from the India Meteorological Department (IMD), during the period 2001 to 2021. The climatic model data for the future period (2022–2050) is downloaded for CanESM5-SSP126 climatic model from WCRP CMIP6. Compared to CMIP5, the latest CMIP6 modelling framework incorporates updated specifications for greenhouse gas concentrations, emissions trajectories, and land-use change, along with a revised baseline year for future scenario simulations. A key advancement in CMIP6 is the integration of Shared Socioeconomic Pathways (SSPs) with the Representative Concentration Pathways (RCPs) previously used in CMIP5. The SSP framework comprises five distinct socioeconomic narratives that describe alternative global development patterns (Riahi et al. 2017): sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil fuel-driven development (SSP5). Detailed descriptions of the SSPs are available in O'Neill et al. (2016). In the present study, only one emission scenario SSP1-2.6 from the CanESM5 global climate model, which was found to most appropriate for this region in the previous literature (Chakraborty and Roshni 2025), is applied for projection of the groundwater levels under changing climate. SSP1-2.6 represents a low-emission, sustainability-oriented pathway characterized by reduced greenhouse gas emissions, improved resource efficiency, and strong environmental stewardship.

The selected districts form a major part of the Kangsabati river basin. The Kangsabati river flows generally in the south easterly direction and after traversing through the district of Purulia, it flows through Bankura and Midnapore for the remaining course before it falls into the river Hooghly. It originates from Jabarbund (641 m altitude) in the hilly areas of Chotanagpur Plateau in Jharkhand, which gradually flows down the lateritic/old alluvium areas of Purulia, Bankura and Midnapur districts and then extends to the interfluvial region between the Rupnarayan and Kheliaghai basins in the lower Gangetic Plain of West Bengal (Chakraborty and Roshni

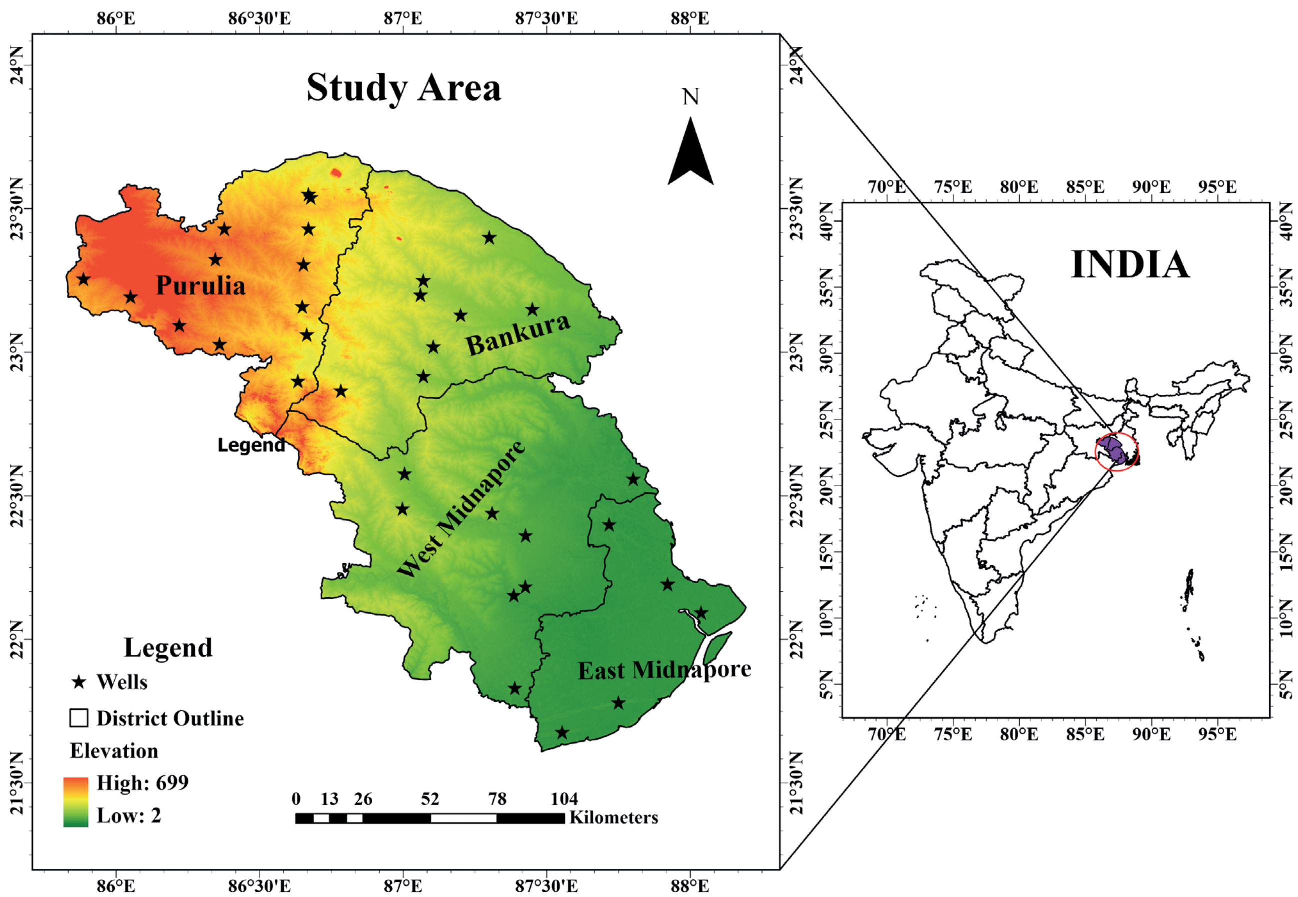

Fig. 1 Location of study area in semi-arid region of eastern India.

2025). River Kangsabati, is tropically rain-fed (Ghosh et al. 2022) and remains almost dry for most parts of the year, except the monsoon season. During the rainy season, sometimes this catchment area experiences heavy rainfall, and the river carries too much water in a short period of time with a high velocity, which frequently results in sudden and violent floods heavily loaded with rolling sand and suspended silt (Chakraborty et al. 2022).

The hydro-meteorological characteristics of this study area exhibit a predominantly subtropical humid climate. However, the majority of rainfall is concentrated during the monsoon season, ranging between 2360mm/year to 1170 mm/year. The data has been collected from India Meteorological Department, Pune, India. The diverse geological formations of the study area influence its aquifer zones which primarily consist of granite, granite gneiss, and mica schist in the upper reaches, laterite and metavolcanic rocks in the middle sections, and alluvial deposits in the lower regions. Weathered and fractured aquifers in the upper reaches, having limited storage capacity due to the hard rock terrain. The middle regions of the study area with geomorphic units offer moderate groundwater potential while extensive alluvial plains and floodplains with unconsolidated sediments are seen in the lower basin, making it for groundwater extraction (Ghosh et al. 2022).

The study area encompasses a wide range of stratigraphic formations, extending from the Precambrian Archean basement – characterized by fractured crystalline hard rock – to the more recent Tertiary-Quaternary sequences, which include both the older porous alluvium and younger alluvial plains (Mukhopadhyay 1992). During the pre-monsoon season, the depth to the water table in shallow phreatic aquifers typically ranges from 4 to 10 meters below ground level (m bgl), primarily influence by the presence of substantial layers of sand, silt, and clay in the upland lateritic terrain. In contrast, the deeper aquifer systems, which occur beneath semi-confined to confined conditions, exhibit water table and piezometric surface levels between 5 and 9 m bgl.

The Purulia district is geologically characterized by a Precambrian and Archean lithological framework that includes granite, gneiss, calgranulite, ultrabasic, and other metamorphic rocks. Groundwater is predominantly confined to the weathered zone within a depth of 10 meters below ground level. The water table fluctuates, with pre-monsoon levels ranging between 3.63 and 9.76 meters below ground level, and post-monsoon levels ranging from 1.32 to 7.3 meters below ground level (Shah 2017). Bankura is predominantly composed of crystalline rock, with groundwater residing in a weathered mantle whose thickness ranges between 6 and 15 meters. In the eastern alluvial region, groundwater is confined beneath a clay layer approximately 10 meters thick. Seasonal variations include a water table decline of about 2.5 to 3 meters during peak summer, followed by a rise of around 1 meter in the post-monsoon period. (Chatterjee 2018).

In West Midnapore, the phreatic aquifer is encountered at depths ranging from 12 to 30 m bgl. During the summer season, the water table fluctuates between 2 and 21 m bgl, whereas in the post-monsoon period it ranges from 1.5 to 9 m bgl. Overall, the groundwater level exhibits a fluctuation of 6 to 19 m, which is consistent with the reported findings (Bhunia et al. 2012). In East Midnapore, hydrological data from Public Health Engineering Department (PHED), West Bengal indicate that the groundwater level generally remains 15–20 meters below the surface throughout most of the year. However, coastal regions such as Contai, Egra, and Digha are experiencing saltwater intrusion, which complicates the water quality and reduces the volume of usable water.

Furthermore, reduced precipitation in the East Medinipur (Midnapore) in recent years has resulted in significant saline contamination of surface water, leading to groundwater extraction rates that exceed natural recharge (Chakraborty et al. 2020).

3. Methodology

Mann-Kendall (M-K) test for GWL and rainfall trend detection was used in this study. The MK test (Mann 1945; Kendall 1955) has been frequently employed in water resources and climatic research to measure the trend in a time series of data (Patle et al. 2015, Himayoun and Roshni 2019). Monotonic trends in a given time series can be identified using the Mann-Kendall (M-K) test (Mann 1945; Kendall 1975). This is a statistical method, which involves in comparing the Groundwater data. This in turn leads to the formulation of two hypotheses:

a) Null hypothesis (H_0): It shows that the data is independent and shows no trend.
b) Alternative hypothesis (H_a): It shows that the data has the possible existence of a monotonic trend over time.

3.1 The M-K statistic

The Mann-Kendall test is a non-parametric statistical test used to detect monotonic trends in time-series data (like rainfall, temperature, groundwater levels, etc).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i)$$

where n is the number of data points, x_i is the rank for i_{th} observations ($i = 1,2 \ldots n - 1$), x_j is the rank for j_{th} observations ($j = i + 1,2 \ldots n$).

The variance σ^2 for the S-statistic is defined by:

$$\sigma^2 = \frac{[n(n-1)(2n+5)]}{18}$$

The standard test statistic Z_S is calculated as follows:

$$Z_S = \begin{cases} \frac{S-1}{\sigma}; \text{ for } S > 0 \\ 0\,; \text{ for } S = 0 \\ \frac{S+1}{\sigma}; \text{ for } S < 0 \end{cases}$$

If |Z| >Zα/2, reject null hypothesis (no trend), Z > 0 → increasing trend, Z < 0 → decreasing trend.

- ☐ In the Mann-Kendall (M-K) test, the p-value is the probability of observing the test statistic (or a more extreme value) if the null hypothesis is true. If p < α (commonly α = 0.05), reject null hypothesis → there is a significant trend.
- ☐ If p ≥ α, fail to reject null hypothesis → no significant trend.

Utilizing the computed values of S and σ, the standard test statistic (Z_8) is derived and subsequently employed to calculate the p-value. The null hypothesis is rejected when the absolute value $|Z_8|$ exceeds the critical value Z(α/2), with α denoting the significance level, thereby indicating a significant trend. A lower p-value provides compelling evidence against the null hypothesis, confirming the statistical significance of the observed trend. Specifically, a p-value below 0.05 signifies the presence of a monotonic trend.

3.2 Sen's Slope test

Sen's Slope represents the magnitude and direction of the trend, where a positive value indicates an increasing trend and a negative value indicates a decreasing trend (Sen 1968). The equation for Sen's slope is expressed as follows:

$$\text{Sen's slope} = \text{median}\left[\frac{Y_i - Y_j}{(i - j)}\right]; j < i\,,$$

where Y_i and Y_j are the rainfall data values at time periods i and j.

3.3 Empirical formula for groundwater recharge estimation

For effective groundwater modeling, development, and sustainability, accurate estimation of the recharge rate is very important. A fraction of the precipitation reaching the surface does not contribute to groundwater recharge, as portions are lost via evaporation, transpiration, and surface runoff. The infiltrated rainwater mitigates soil moisture deficits and percolates to recharge aquifers. Quantitative assessments of rainfall-induced recharge were conducted using several empirical correlations between recharge and precipitation, developed from regions with comparable climatic conditions (i.e., similar rainfall and temperature profiles) and is shown in Tab. 1.

Maxey and Eakin (1949) developed the empirical relationship between mean annual precipitation of the subbasin and Recharge from precipitation by considering evapotranspiration, surface water runoff, and recharge coefficient values between 0–25%. Chaturvedi formulated an empirical model that quantifies recharge as a function of annual precipitation, based on observed fluctuations in water levels and recorded rainfall in the Ganga-Yamuna doab (Chaturvedi 1973). Later, this formula was modified at the UP-Irrigation Research Institute, Roorkee as Modified Chaturvedi Formula. The Chaturvedi formula is extensively employed for the initial estimation of groundwater recharge resulting from rainfall. It is important to note that there exists a rainfall threshold below which no recharge occurs. This lower rainfall limit within the formula likely incorporates losses attributable to runoff, soil moisture deficits, interception, and evaporation. Krishna Rao developed an empirical relationship to determine the groundwater recharge in a limited climatological homogeneous area (Chaturvedi 1973). The factors of each of the above specified empirical correlations are inherently site-specific; therefore, a single generalized formula may not be applicable to all alluvial regions.

3.4 Rainfall variation within the study area

Fluctuations in groundwater levels are directly influenced by rainfall, which serves as the primary source of recharge for aquifers. The response of groundwater levels to rainfall events is governed by the hydrogeological characteristics of the region. The Fig. 2 depicts the annual rainfall variability (2001–2021) across four districts of West Bengal: East Midnapore, West Midnapore, Bankura, and Purulia. Rainfall fluctuated between ~1,000–2,500 mm, with coastal districts (East and West Midnapore) consistently receiving higher precipitation compared to the drought-prone districts of Bankura and Purulia. Distinct peaks are observed in 2005, 2007, 2013, 2017, and 2021,

Tab. 1 Empirical correlations for recharge estimation from rainfall.

Sl. No.	Formula name	Equation(s)	Definition of parameter and coefficient value range
1	The Maxey-Eakin (1949) method	R = P*a	P = Yearly rainfall, a–20%, R = Net Recharge (mm)
2	Chaturvedi Formula (Chaturvedi 1973)	$R = 2.0(P-15)^{0.4}$	P = Yearly rainfall (inch), R = Net Recharge (inch)
3	Modified Chaturvedi Formula (Kumar and Seethapathi 2002)	$R = 1.35(P-14)^{0.5}$	P = Yearly rainfall (inch), R = Net Recharge (inch)
4	Relationship of Krishna Rao (Krishna Rao 1970)	R = 0.30(P−500)	P = Yearly rainfall (mm), R = Net Recharge (mm)

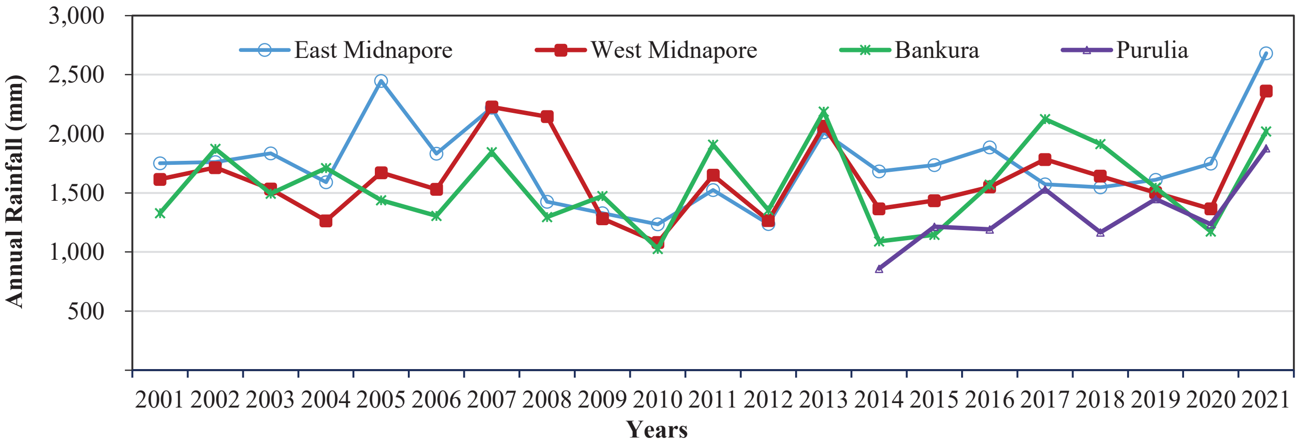

Fig. 2 District-wise annual rainfall plots during the period 2001 to 2021.

with 2021 recording exceptionally high rainfall (>2,800 mm in East Midnapore). Post-2016 rainfall shows a rising tendency, culminating in a sharp increase in 2021, likely linked to anomalous monsoonal activity and cyclonic events. Overall, the data reflect the spatial heterogeneity and temporal fluctuations of monsoonal rainfall in the Red and Lateritic Zone, with coastal districts being wetter and western plateau districts experiencing greater variability (Ghosh et al. 2015; Das et al. 2015). Similar finding has been observed in the study of Roy et al. 2024, in which the authors have analysed rainfall trends in eastern India, covering 23 districts of West Bengal, based on data from 1993 to 2022, reveals a significant increase of nearly 34% in post-monsoon rainfall and an overall 3% rise in annual rainfall.

4. Results and discussion

4.1 Groundwater level trend analysis

Tab. 2 shows the outcomes of the Mann-Kendall (M-K) trend test and Sen's Slope for groundwater levels across different locations of the study area. The primary parameter here is the p-value, which indicates the significance of the trend. East and west Midnapore, demonstrates a significant downward trend, implying reduced groundwater recharge as well as excessive groundwater pumping for agriculture, industry or domestic use. Bankura and Purulia shows insignificant trends, suggesting that GWL changes are not consistent enough to establish a clear pattern. With the study area experiencing very hot and dry to humid summers, erratic monsoon to heavy monsoons with cyclones and storms, combined with over-extraction of groundwater, geological factors for reduced retention capacity and human interventions, the groundwater level is declining. This decline was quantified using Sen's slope estimator, which reveals that most locations are undergoing a significant reduction in groundwater levels with East Midnapore exhibiting the highest negative values with Sen's slope of 0.50873 m/year in the pre-monsoon season and 0.50742 m/year in the post-monsoon season, as shown in Table 2.

4.2 Groundwater level variations of pre-monsoon and post-monsoon period

Based on the collected data, preliminary GW analysis (Bharti et al. 2024) has been carried out for pre-monsoon and post monsoon period for the study area i.e. four selected districts of West Bengal. In regions

Tab. 2 District-wise GWL trend analysis by using M-K and Sen's slope estimation during pre-monsoon and post-monsoon (2001–2021).

Location	Period	p-value	Sen's slope	Test interpretation
East Midnapore	pre-monsoon	0.0005	−0.509	significant decreasing trend
	post-monsoon	0.00001	−0.507	significant decreasing trend
West Midnapore	pre-monsoon	0.043	−0.181	significant decreasing trend
	post-monsoon	0.003	−0.201	significant decreasing trend
Bankura	pre-monsoon	0.608	0.019	no trend
	post-monsoon	0.194	−0.040	no trend
Purulia	pre-monsoon	0.415	0.020	no trend
	post-monsoon	0.880	0.004	no trend

influenced by monsoonal rainfall, groundwater levels exhibit seasonal fluctuations. During the pre-monsoon period, the groundwater table is situated at greater depths, whereas in the post-monsoon phase, the water table rises to shallower depths due to enhanced rainwater infiltration during the monsoon season. The GW level data for pre- and post-monsoon from 2001 to 2021 for the four districts has been analysed from total 34 (East Midnapur-5, West Midnapore-8, Bankura-8, Purulia-13) monitoring wells (as obtained from State Water Investigation Directorate, Government of West Bengal, India).

Variation of GWL from <5m to >15m below ground level has been studied for a period of 20 years from a number of monitoring wells within the study area. Data shows that the GWL varies from a minimum of 1.96m to a maximum level of 20.39m. The percentage (%) of the wells (monitoring wells) lying within this ranges have been categorized into 4 divisions below ground level, such as i) <5m, ii) >=5 to <10m, iii) 10 to 15m and iv) >15m depth.

In East Midnapore, the GWL in 100% of the wells were found to be at a depth >15m since 2015 in the pre-monsoon period while in the post-monsoon period, the GWL was between 10–15m depth in most of the region. West Midnapore showed a major percentage of the wells within >=5m to <10m and 10m-15m range while in the post-monsoon period, this GWL

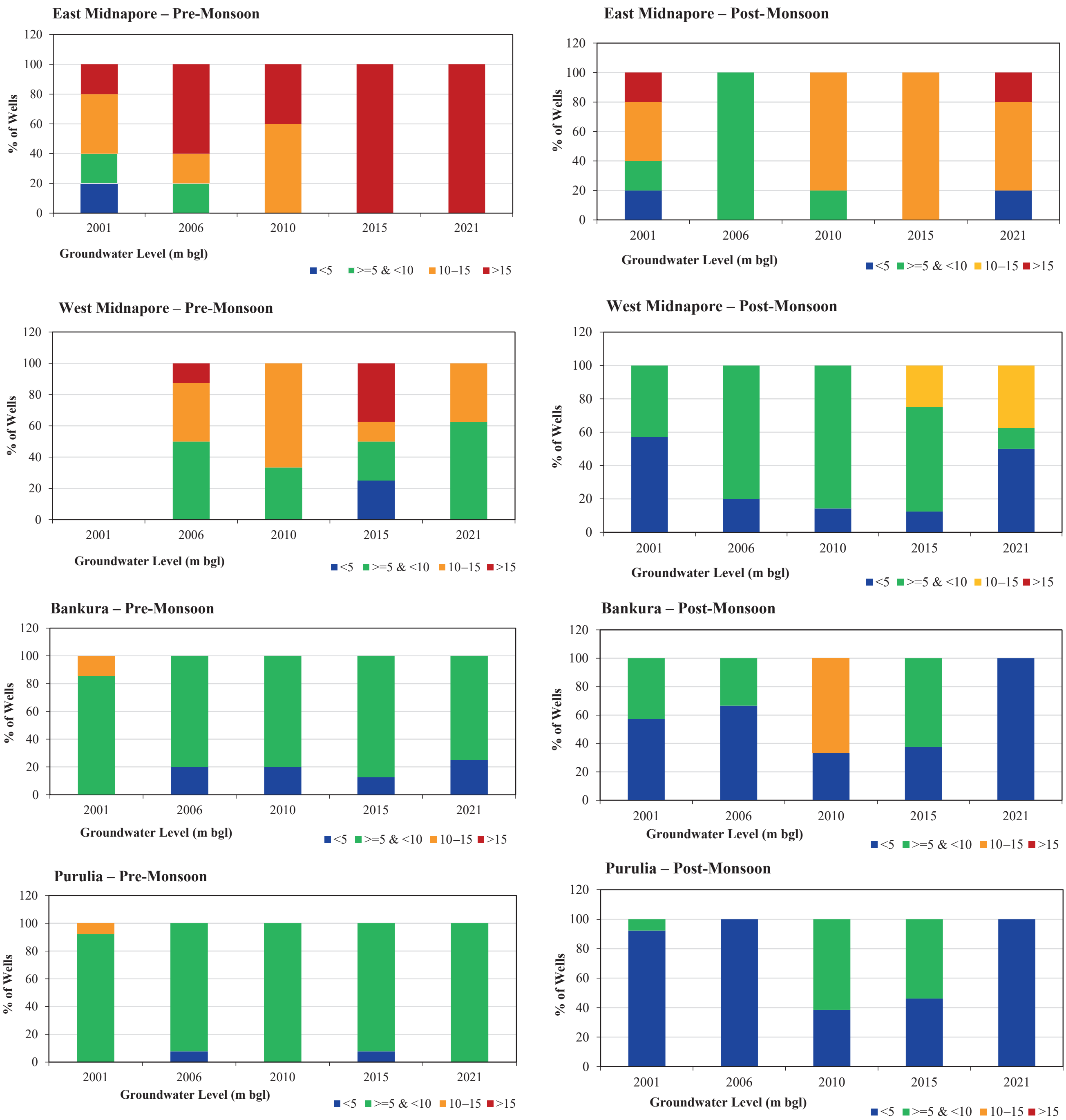

Fig. 3 District-wise plots for groundwater level (m bgl) data with % of wells (2001–2021).

increased to 5 to 10m in most of the wells. In Bankura more than 80% of the wells were found with a GWL <10m depth in pre-monsoon which increased to <5m depth in the post-monsoon period. In Purulia, GWL in 90–100% of the wells were within >=5 to <10m depth in pre-monsoon while <5m in post monsoon period. On an average it can be stated that, there is a difference of more or less 5m between the pre- and post-monsoon GWL within the study area.

The pre-monsoon period of East Midnapore shows 100% of the wells to have the GWL more than 15m since 2015 while post-monsoon shows a rise of at least 5m in the GWL. In case of West Midnapore, pre-monsoon period shows a major % of the wells to have a GWL within 10–15m throughout the period with few variations while post monsoon shows a rise of at least 5m in the GWL. In Bankura and Purulia, 80 to 90% of the wells showed the GWL to be within 5–10m range in pre-monsoon which later had a rise of at least 5m in the post-monsoon period. Overall, it can be stated that, there is a difference of more or less 5m between the pre- and post-monsoon GWL within the study area (DSR 2022; Bhattacharya et al. 2020).

4.3 Plot of GWL variation in pre-monsoon and post-monsoon period

GWL variation plotted for pre-monsoon and post-monsoon data from 2001 to 2021, for the four districts are shown in Fig. 3 and Fig. 4. From Fig. 3, it is evident that pre-monsoon GWL is decreasing from 2001 to 2021(Bera et al. 2022). The rate of decline in Bankura and Purulia is much less than East and West Midnapore. In Bankura and Purulia, there is no significant fluctuation throughout the study period except one or two instances.

The pre-monsoon groundwater level trends across the four districts of the western part of West Bengal (East Midnapore, West Midnapore, Bankura, and Purulia) were analyzed using linear regression (Fig. 4). The regression equations and coefficients of determination (R^2) reveal significant spatial differences in groundwater dynamics.

In East Midnapore, the regression slope is positive ($y = 0.3973x - 784.76$, $R^2 = 0.4886$), indicating a clear groundwater decline before monsoon, with a moderately strong trend. The trend reflects a clear long-term declining nature in pre-monsoon groundwater availability, likely due to intensive pumping and increased anthropogenic demand. West Midnapore, (equation: $y = 0.0543x - 98.986$, $R^2 = 0.0266$) shows a very small positive slope which implies a slight groundwater decline and the R^2 value indicates an extremely weak fit i.e. No strong trend; year-to-year variations dominate. In contrast, Bankura and Purulia, exhibit very low R^2 values (<0.05) and slightly negative slopes implies a marginal rise in the water table. These changes are statistically insignificant due to the extremely weak fit of the regression models. Similarly, West Midnapore shows a marginal decline, but the trend is unreliable given the negligible R^2.

Overall, the regression analysis highlights East Midnapore as the only district with a statistically meaningful declining trend in pre-monsoon groundwater levels, whereas the other districts show no significant temporal trends, with fluctuations likely driven by short-term hydroclimatic variability and localized pumping stresses rather than long-term depletion.

Post-monsoon groundwater levels in East Midnapore, West Midnapore, Bankura, and Purulia show distinct spatial variability (Fig. 5). The post-monsoon groundwater levels across four districts of West Bengal display spatial variability in depletion trends. East Midnapore exhibits the steepest decline, indicating severe groundwater depletion (~12–20 m bgl over time). With a regression slope of 0.4977 m/year

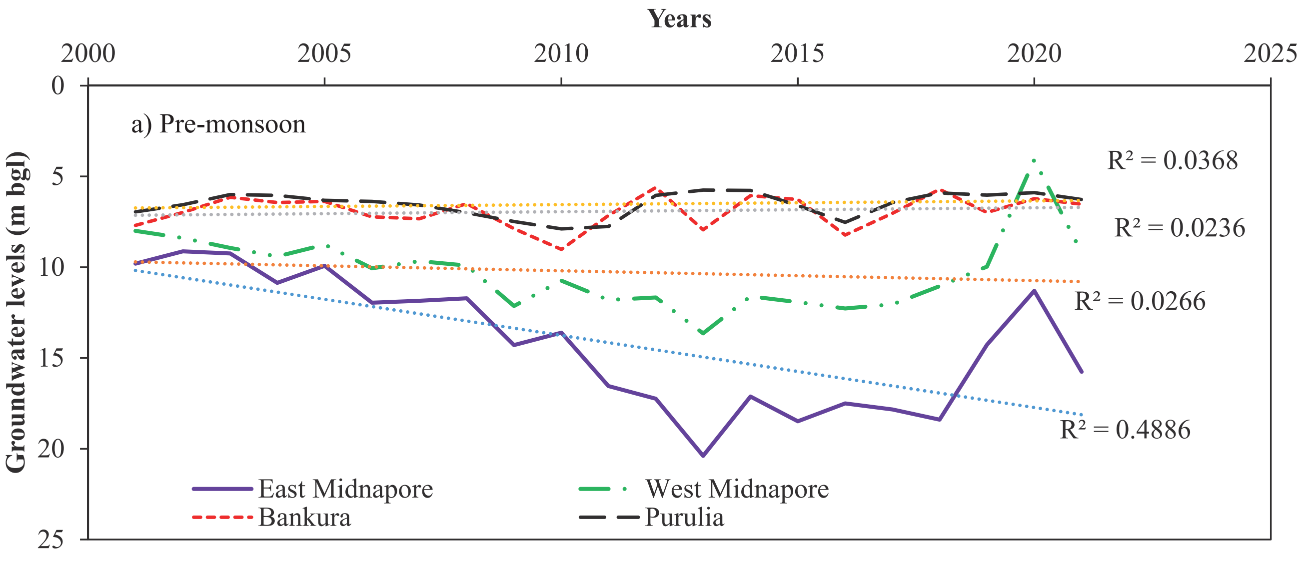

Fig. 4 District-wise temporal groundwater levels (2001–2021) plot for pre-monsoon season in the study regions of West Bengal.

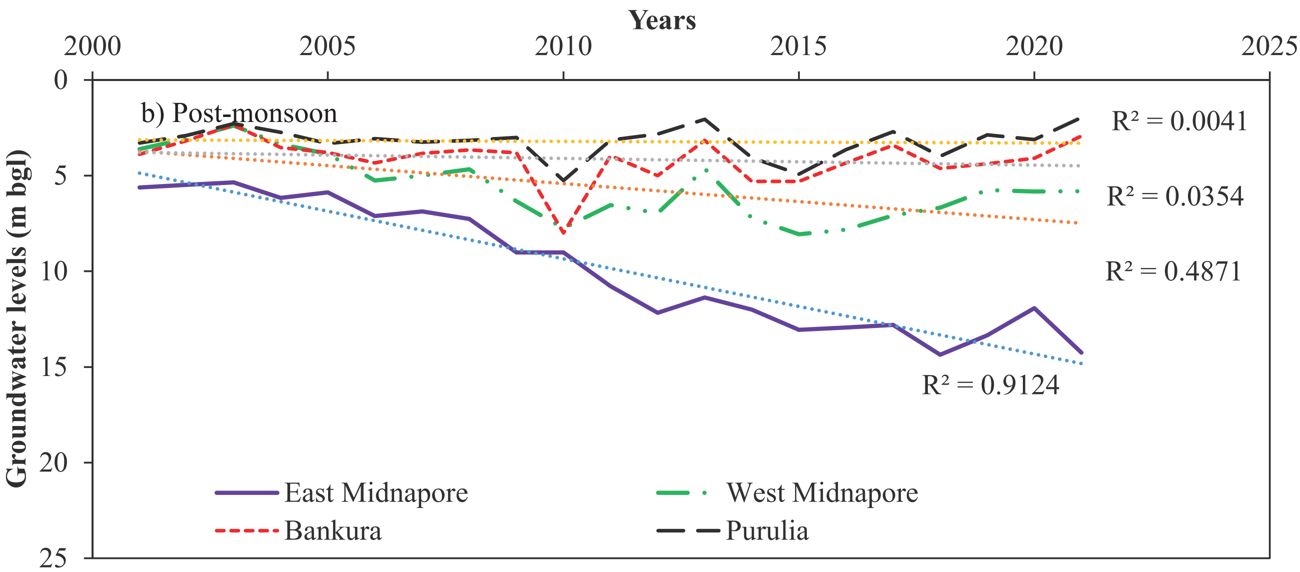

Fig. 5 District-wise temporal groundwater levels (2001–2021) plot for post-monsoon season in the study regions of West Bengal.

(R^2 = 0.9124), indicating a consistent and significant groundwater depletion over the study period. West Midnapore shows a moderate declining trend (0.1882 m/year, R^2 = 0.4871), suggesting localized stress. In contrast, Bankura (0.0351 m/year, R^2 = 0.0354) and Purulia (0.0084 m/year, R^2 = 0.0041) exhibit negligible long-term trends, with very low coefficients of determination, implying largely stable groundwater conditions.

In East and West Midnapore, according to groundwater bulletins by the Central Ground Water Board (CGWB 2022), parts of West and East Midnapore have experienced a post-monsoon water level fall of less than 2 m, reflecting moderate depletion trends in these regions. Further, district-level water management reports indicate that East Midnapore has substantial groundwater reserves (71,090.4 ha-m), of which irrigation accounts for 17,103.2 ha-m and domestic use for 4,751.4 ha-m highlighting intense extraction pressures, especially for agriculture. Bankura and Purulia show negligible long-term trends; however, both experience episodic recharge limitations and drought-induced stress in hard-rock aquifers especially Purulia, where deep aquifers show low resilience and groundwater levels during lean periods can reach upto 8–10 m bgl (Bera et al. 2022).

4.4 Groundwater recharge estimation with different empirical methods

Groundwater recharge was estimated using the four empirical methods namely, the Chaturvedi method, the Modified Chaturvedi method, Krishna Rao method and the Maxey and Eakin method, and is shown in Fig. 6. These methods were applied to the same study area, to evaluate their respective estimates and understand the variability introduced by methodological differences. The recharge estimates (in inch/year), primarily based on rainfall, when plotted against the post monsoon groundwater level, for the period 2000 to 2021, shows a similar trend in all the four districts of the study area (Fig. 6).

Recharge estimates in East Midnapore, range between ~5–25 mm/year, with major peaks in 2006–2008 and 2021. Groundwater levels, however, show a steady decline from ~6–8 m bgl in the early 2000s to ~12–15 m bgl after 2010, despite high recharge events. This mismatch suggests that over-extraction outweighs natural replenishment, consistent with coastal aquifer stress (Ghosh et al. 2022).

In West Midnapore, recharge varied from ~8–20 mm/year, with peaks in 2004–2007, 2011–2013 and 2021. Groundwater levels declined sharply from ~2–3 m bgl in 2000 to ~8 m bgl in 2014–2015, before partially recovering (~5–6 m bgl) post-2016. The data suggest initial shallow aquifers subjected to progressive depletion but with partial resilience during high rainfall years. Recharge estimates in Bankura fluctuates between ~8–18 mm/year, with episodic peaks above 20 mm/year (2004, 2012, 2016, 2019). Groundwater levels showed high sensitivity to recharge fluctuations, ranging from ~2 m bgl (shallow, wet years) to ~9 m bgl (2010 drought year). This indicates a direct climate-driven recharge–storage linkage in Bankura, where rainfall variability governs aquifer conditions more strongly than extraction.

While Recharge estimates (2014–2021) remained comparatively low, with recharge values (8.21–10.36 mm/year), lowest among the four districts. These results confirm Purulia's semi-arid, water-stressed environment, where limited rainfall and low-yielding lateritic aquifers restrict recharge capacity.

The suitability of the groundwater recharge estimation methods for different types of soil is detailed

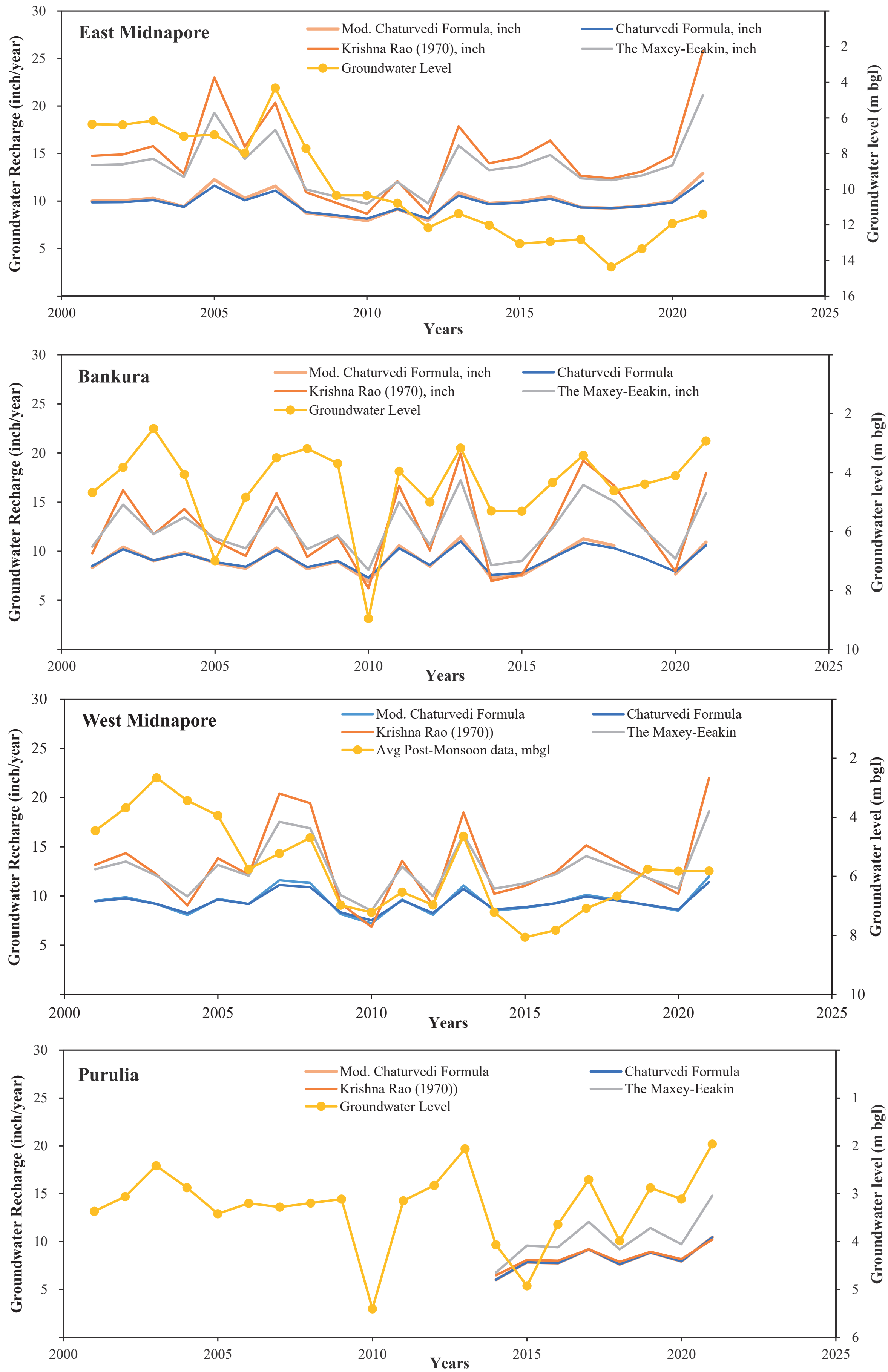

Fig. 6 Districtwise plot of groundwater recharge estimates using four empirical methods against post monsoon groundwater level for the period 2000 to 2021.

Tab. 3 Suitability of Empirical recharge estimation methods in the Red and Lateritic Zone of West Bengal.

East Midnapore	Coastal alluvial aquifers, high abstraction	Chaturvedi method (1936) / Modified Chaturvedi	Better suited to alluvial systems; Modified Chaturvedi can supplement.
West Midnapore	Lateritic uplands, semi-humid	Krishna Rao (1970) / Modified Chaturvedi	Krishna Rao captures variability; Modified Chaturvedi provides stable conservative values.
Bankura	lateritic, hard-rock terrain	Krishna Rao (1970)	Captures monsoon-driven recharge; aligns with hard-rock aquifers.
Purulia	low-rainfall, lateritic hard-rock	Krishna Rao (1970)	Best reflects episodic recharge in fractured aquifers

in Tab. 3. It is evident from the Table that the most appropriate empirical formula that can be applied consistently across Bankura, Purulia, West Midnapore, and East Midnapore, is the Modified Chaturvedi formula because, it is widely used across India for both alluvial and hard-rock settings and provides realistic, conservative estimates that avoid overestimation (Barik and Ghosh 2024).

4.5 Correlation between groundwater level and groundwater recharge by modified Chaturvedi formula

The correlation analysis between groundwater recharge (estimated using the Modified Chaturvedi formula) and groundwater levels (Fig. 7) reveals marked spatial contrasts across the four districts. Purulia shows a moderately strong positive correlation which indicates that groundwater levels in Purulia are relatively sensitive to recharge variations. This may be due to its shallow, fractured lateritic aquifers and semi-arid climate (Chakraborty and Roshni 2025). Bankura represents a moderate correlation. Groundwater levels respond to rainfall-driven recharge, but the relationship is partly obscured by abstraction for irrigation. Aquifers are slightly more buffered than in Purulia, hence weaker correlation. By contrast, East Midnapore (R^2 = 0.0076) and West Midnapore (R^2 = 0.0113) display very weak correlations, reflecting the dominance of anthropogenic abstraction and aquifer storage effects over natural recharge in coastal and lateritic upland settings (Ghosh et al. 2022). These results underscore that while the Modified Chaturvedi formula provides a consistent basis for recharge estimation across diverse hydrogeological contexts, the degree of correlation with observed groundwater levels is strongly mediated by local aquifer characteristics and abstraction pressures.

4.6 Correlation between rainfall and groundwater level

The regression analysis (Fig. 8) provides insights into the spatial variability of GWL in four districts of West Bengal against the variability in average annual rainfall. Purulia exhibits the strongest correlation (R^2 = 0.6392), suggesting that groundwater levels here are highly sensitive to rainfall variability. This is expected in, lateritic hard-rock aquifers with limited storage, where recharge events directly translate into water-level fluctuations (Chakraborty and Roshni 2025). Bankura displays a moderate correlation (R^2 = 0.3295), reflecting that there is some dependence of groundwater levels on rainfall recharge. These findings also suggest that rainfall contributes to recharge processes, but it is not the sole or dominant driver of groundwater fluctuations in these areas. Instead, the

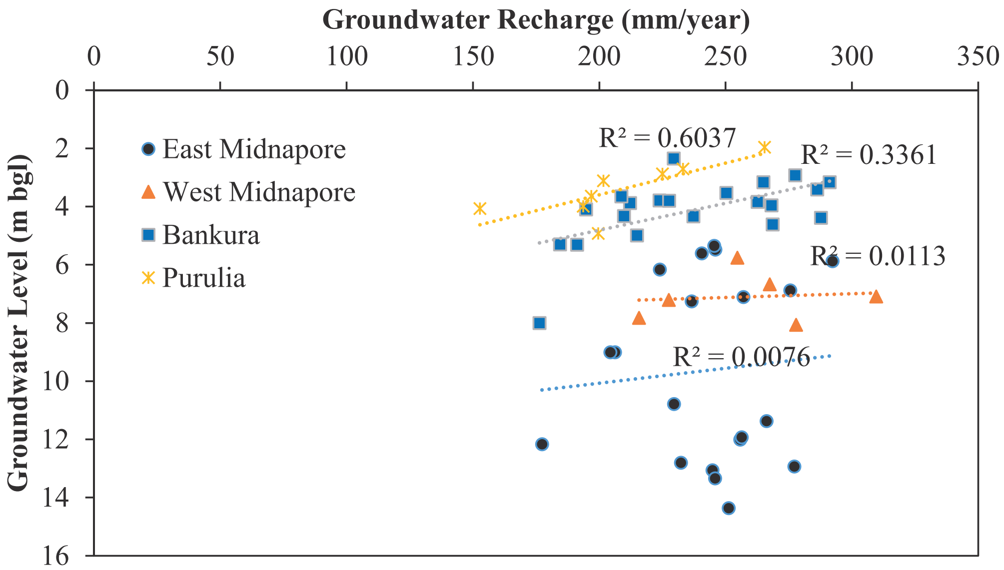

Fig. 7 Groundwater level (2001–2021) plot in relation with groundwater recharge in the study area.

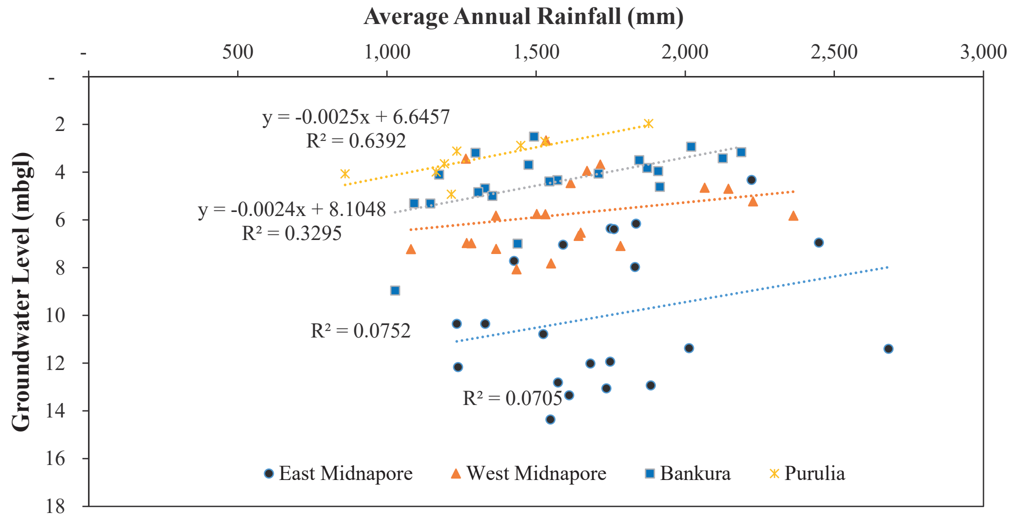

Fig. 8 Groundwater level (2001–2021) plot in relation with average annual rainfall in the study area.

moderate correlations indicate the presence of additional controlling factors. East and West Midnapore show a weak correlation indicating that groundwater levels are only marginally influenced by rainfall. Persistent abstraction and larger aquifer storage reduce the observable rainfall and GWL linkage (Ghosh et al. 2022) and intensive pumping for agriculture and domestic water supply outweighs the contribution of rainfall recharge. Hence, an in-depth study related to surface water-groundwater interaction is required in this study area to find the additional controlling factors affecting groundwater fluctuations. Hence, for projection of groundwater level in future time periods, only the relation for Purulia and Bankura has been considered.

4.7 Projection of groundwater levels under changing climate

Based on the previous literature (Chakraborty and Roshni 2025), the rainfall data from CanESM5 climatic model with SSP-126 scenario (Fig. 9a) is highly suitable for the present study area. Hence, the rainfall data of this climatic model (Fig. 9a) has been utilized for the projection of groundwater levels in the selected study region. With the empirical expressions developed for the observation period (Fig. 8) for the stations Bankura ($y = -0.0024x + 8.1048$) and Purulia ($y = -0.0025x + 6.6457$), the future groundwater levels have been projected and are shown in Fig. 9 (b). It is observed from the figure (Fig. 9a) that there appears to be a slight increase in the annual rainfall for the time period 2022–2050. As average annual rainfall increases, groundwater levels tend to become shallower across all districts. This is reflected in the negative slopes of all regression lines, i.e. higher rainfall generally enhances groundwater recharge, allowing the water table to rise closer to the surface. However, the strength of this trend differs significantly between districts. Areas like Purulia show a strong and clear response of groundwater levels to variations in rainfall ($R^2 \approx 0.64$), which implies as rainfall increases, groundwater levels become shallower.

5. Conclusions

This study examined the variability of groundwater levels and recharge in four semi-arid to sub-humid districts of West Bengal (Purulia, Bankura, West Midnapore, and East Midnapore) using long-term rainfall records, groundwater observations, empirical recharge models, and future climate projections.

The Mann-Kendall and Sen's slope analyses revealed a significant declining trend in groundwater levels in East and West Midnapore, while Bankura and Purulia exhibited insignificant trends, consistent with their comparatively lower abstraction pressures and hard-rock aquifer buffering.

Recharge estimation demonstrated that rainfall-driven variability is primary in Bankura and Purulia, where correlations between rainfall/recharge and groundwater levels were moderate to strong ($R^2 = 0.3295$–0.6392), reflecting the limited storage and direct rainfall dependency of lateritic aquifers. In contrast, East and West Midnapore displayed very weak correlations, emphasizing the dominance of anthropogenic abstraction and aquifer storage effects in alluvial and coastal settings.

Recharge assessments indicate that rainfall-driven variability is the dominant control in Purulia, where rainfall/recharge–groundwater level relationships exhibit moderate coefficients of determination in Bankura. Conversely, East and West Midnapore show very weak correlations, suggesting that groundwater dynamics in these alluvial and coastal aquifers are governed primarily by pumping stresses and subsurface storage characteristics rather than direct rainfall inputs.

Among the Empirical recharge estimation methods, Krishna Rao's formulation was most compatible

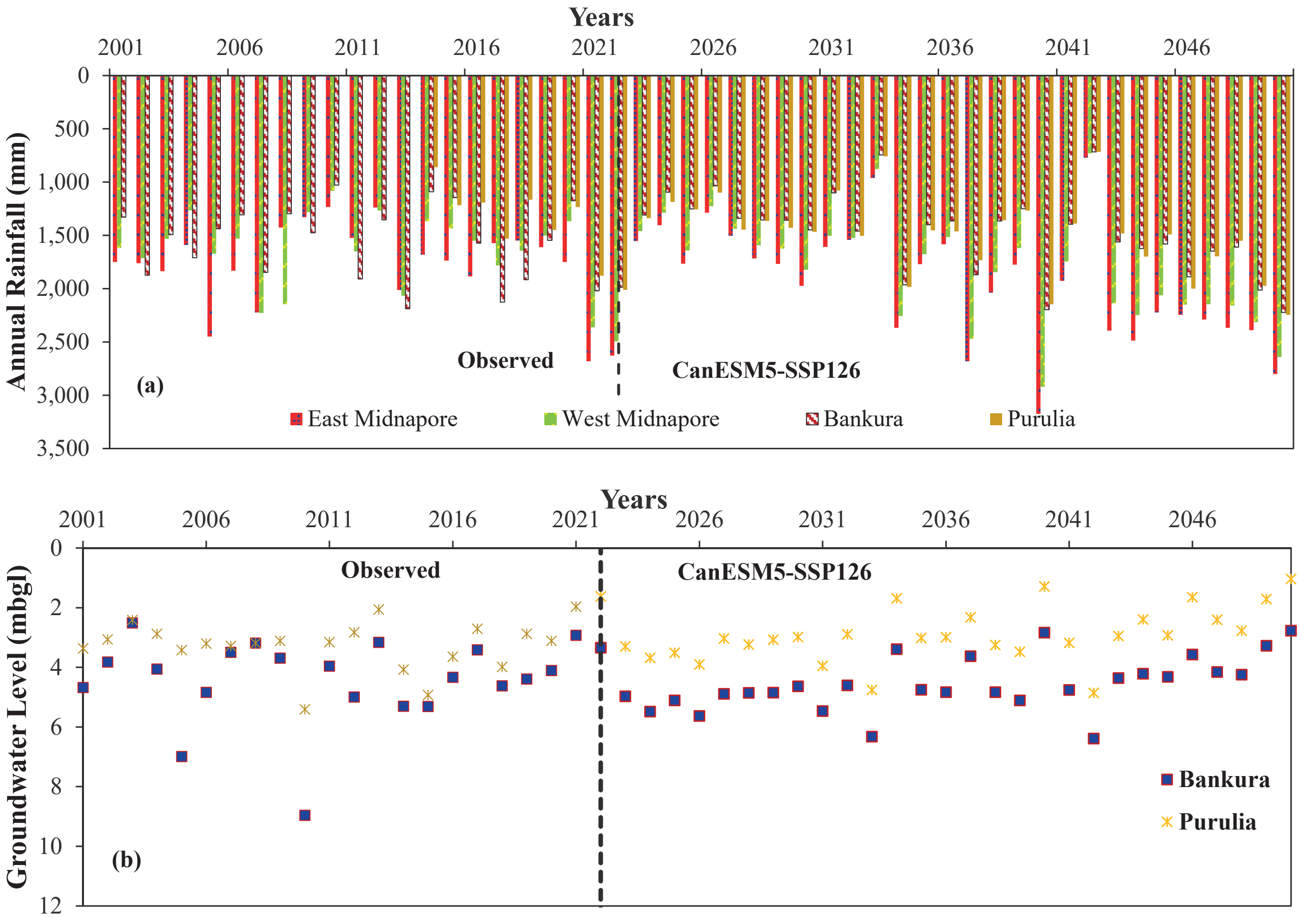

Fig. 9 Temporal variation. (a) Rainfall data of selected districts for the observed time period and the projected time period. (b) Observed groundwater levels (2001–2021) and the projected groundwater levels for the time period (2022–2050).

with hard-rock settings, whereas the Chaturvedi method showed better agreement with recharge behaviour in alluvial aquifers. Nevertheless, the Modified Chaturvedi equation provided the most robust and consistent performance across all four districts, owing to its applicability in both hard-rock and alluvial terrains and its conservative recharge estimates that minimize the risk of overestimation.

Future projections using the CanESM5 GCM under the SSP1-2.6 scenario indicated marginal increases in rainfall through 2050. The results suggest that even if rainfall increases, it will not be enough to balance the heavy stress caused by groundwater extraction, which is also a major cause of groundwater decline across India.

Future simulations based on the CanESM5 GCM under the SSP1–2.6 pathway indicate only marginal increases in rainfall by 2050. Correspondingly, groundwater levels are expected to remain broadly stable in Bankura and Purulia. However, the projections also underscore that any rainfall-induced recharge increases are unlikely to offset the substantial groundwater stress imposed by sustained extraction – an established driver of groundwater depletion across India.

The correlation of groundwater level and rainfall in East and West Midnapore is very poor. Hence, further in-depth analysis may be required for finding other potential factors for groundwater level decline. Overall, the study emphasizes the urgent need for sustainable groundwater governance, particularly in East and West Midnapore where declining trends are acute. Incorporating climate variability into water resource planning, adopting efficient irrigation practices, and strengthening aquifer recharge interventions are critical to ensure long-term water security in the Red and Lateritic Zone of West Bengal.

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