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Assessment of the Effect of Climatic Change on the Water Balance and Groundwater Recharge in Al-Teeb District, Southern Iraq

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ABSTRACT

Groundwater resources in arid and semi-arid regions are highly sensitive to climate variability, and assessing future water balance conditions is essential for sustainable management. This study evaluates the effect of climate change on the water balance of the Al-Teeb district in southern Iraq under both historical (1993–2023) and future (2031–2050) climate conditions. The analysis was performed with the Thornthwaite-Lerner method, combined with statistically downscaled climate projections produced through Long Ashton Research Station Weather Generator (LARS-WG, v8) that was driven by HadGEM3-GC31-LL GCM for the SSP2-4. 5 scenarios. During the reference period, mean annual precipitation amounted to 178.9 mm/yr, and corrected potential evapotranspiration (PETc) was 2535 mm/yr, resulting in a large annual water deficit (2414 mm/yr) and indicating arid conditions in this region. Future simulations indicate a rise in precipitation (258.4 mm/yr), but a sharper increase in PETc to 4011 mm/yr, resulting in a larger deficit (3853 mm/yr) while the region remains arid. Groundwater recharge, estimated using the coefficient approach, was 8.9 mm/yr in the baseline and 12.9 mm/yr in the future scenario. Although rainfall is projected to increase, the strong evaporative demand severely restricts recharge opportunities. These findings highlight the urgent need for adaptive groundwater management strategies to mitigate intensifying aridity and secure long-term water availability in the Al-Teeb district.

Keywords: Climate change, Groundwater, Water balance, Thornthwaite, LARS-WG.

1. INTRODUCTION

Groundwater constitutes a vital component of global freshwater resources, particularly in arid and semi-arid regions where surface water is scarce, seasonal, or unreliable. Globally, it accounts for more than 30% of total freshwater withdrawals, sustaining billions of people for domestic, agricultural, and industrial purposes **(Todd and Mays, 1980; WWAP, 2015)**. However, increasing climate variability, population growth, and unsustainable water practices have intensified reliance on groundwater, exposing aquifer systems to severe risks

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of overexploitation and deterioration in quality **(Hem, 1985; IPCC, 2021; FAO, 2022)**. This is a global issue that is particularly salient for Iraq, a riparian country in this ecologically sensitive belt that suffers from chronic water stress due to reduced availability of transboundary river inflows and increases in the frequency of drought episodes **(Saleh et al., 2024)**. In the southern governorates, especially in Maysan, groundwater abstractions are rapidly increasing due to dwindling surface water resources and rising agricultural requirements. In Al-Teeb, groundwater is the main source of drinking and irrigation, mostly pumped from shallow unconfined aquifers **(Al-Gharabi, 2016; Al-Salih, 2016; Atiaa et al., 2020)**. Local studies have continued to express concern regarding over-extraction of groundwater in the area, which is exacerbated by low and highly variable rainfall combined with high evapotranspiration rates, making groundwater resources particularly sensitive to climatic fluctuations.

Previous research emphasized serious problems concerning the groundwater amount, such as aquifer exhaustion and over-abstraction effects **(Hussein and Abed, 2019; Zwain and Abed, 2023a; 2023b; Ali and Oleiwi, 2015; Mustafa et al., 2017; Hussein et al., 2020)**. In addition, studies on groundwater quality have indicated some common constraints such as high salinity and poor chemical characteristics, mainly regarding hydrochemical classification of the aquifer **(Aderemi et al., 2014; Abed and Hussain, 2020; Al-Waeli et al., 2021; Al-Kubaisi and Al-Salih, 2016; Zwain and Abed, 2023c)**. While these efforts provide valuable insights into current groundwater dynamics and quality status, they have generally neglected the temporal dynamics of the resource, particularly the combined and inherently stochastic effects of climate variability on groundwater recharge. The Climatic Water Balance (CWB) method has been successfully used in Iraq to account for the water resource limitation **(Al-Dabbas and Abdul Razzaq, 2017; Al-Kubaisi and Al-Kubaisi, 2018; Al-Kubaisi et al., 2019; Al-Dabbas and Abdulla, 2019)**, and the LARS-WG model is applicable to generate site-specific projections of future climate **(Osman et al., 2014; Mohammed and Hassan, 2022; Abdulsahib et al., 2024)**.

More recently, data-based methods (e.g., ANNs) have also started to be widely used for hydrological modeling and rainfall-runoff prediction in the case of arid Iraqi basins **(Al-Juhaishi et al., 2024)**, indicating that computational intelligence approaches are becoming common for water resources research purposes. However, to our knowledge, no such study has so far combined LARS-WG with CWB analysis toward assessing groundwater recharge potential in the future in the Al-Teeb district or even the Maysan region. This critical gap in integrated, future-oriented assessment reflects the absence of quantitative evaluations addressing how projected climate change may alter the climatic water balance and groundwater recharge processes in the Al-Teeb district.

The Al-Teeb district relies heavily on its shallow aquifer system despite its vulnerability to climatic shifts. Therefore, the primary objective of this study is to evaluate the climatic water balance of the Al-Teeb district under both historical (1993–2023) and projected (2031–2050) climate conditions. This will be achieved by utilizing the Thornthwaite–Lerner method combined with statistically downscaled projections from the LARS-WG model, providing new, integrated insights to support sustainable water-resource management in this arid environment.

2. LOCATION AND GEOLOGICAL CONDITIONS OF THE STUDY AREA

The Al-Teeb district is located in the northeast of Maysan Governorate, southern Iraq, and lies between latitudes 32°15′00″–32°30′00″N and longitudes 46°55′00″–47°25′00″E with a total area of around 1,191 km^2 **(Al-Kubaisi and Al-Salih, 2016)**, as shown in **Fig. 1**.

The subsurface geology of the Al-Teeb area is dominated by Quaternary alluvial and floodplain deposits that overlie the Bai-Hassan and Muqdadiyah formations of Late Miocene–Pliocene age, as shown in **Fig. 2**.

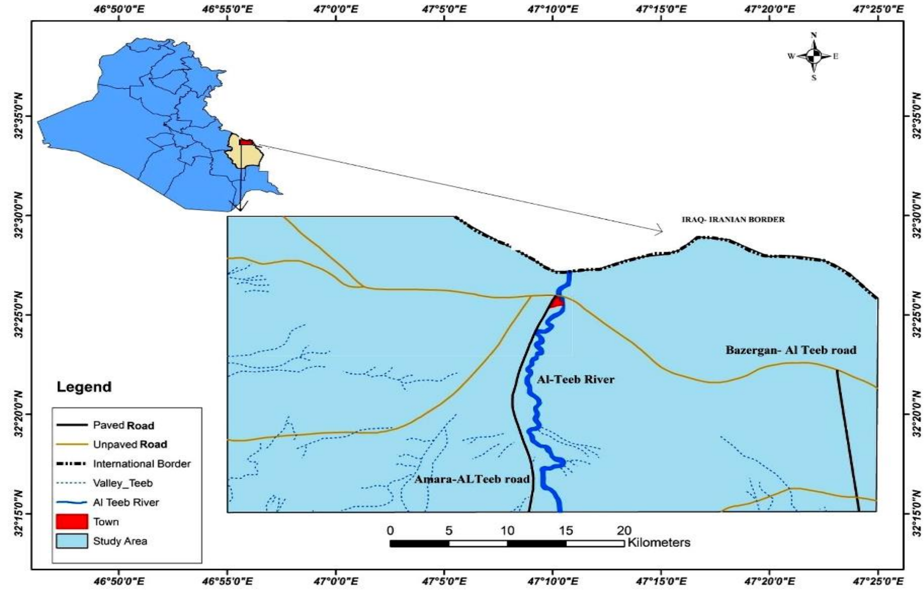

Figure 1. Location map of the Al-Teeb district in Maysan Governorate **(Al-Salih, 2016)**.

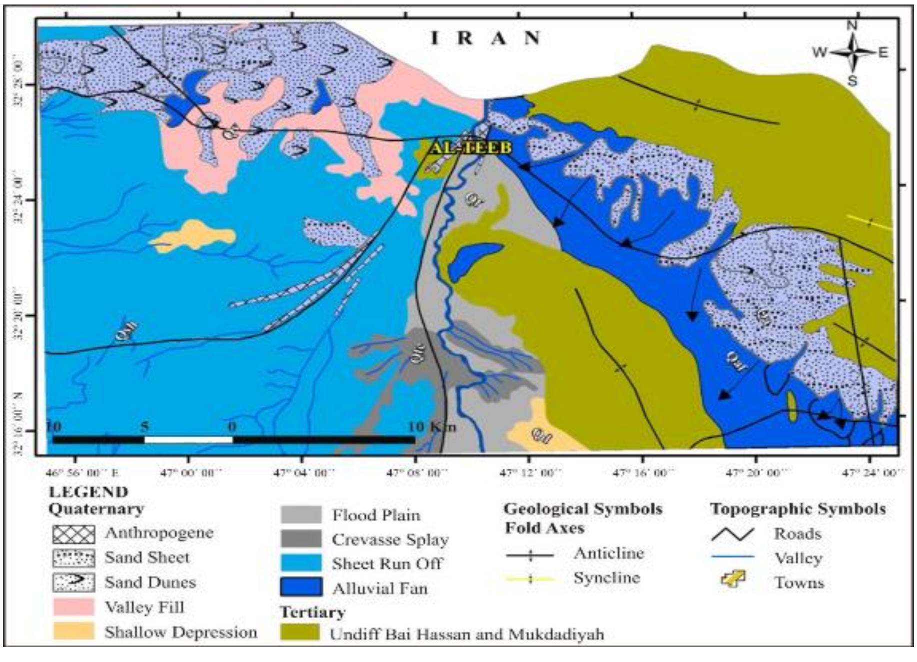

Figure 2. Simplified geological and hydrogeological map of the Al-Teeb district **(Barwary, 1992)**.

These formations consist of alternating sandstone, siltstone, and claystone layers, with variable thickness and lateral facies changes, forming the principal aquifer system of the region. Groundwater storage occurs mainly within the sand and gravel beds of the Bai-Hassan and Muqdadiyah units, where it is present under unconfined to semi-confined conditions **(Al-Salih, 2016)**. Recharge is naturally limited due to the arid climate, occurring primarily during winter through rainfall infiltration and, occasionally, ephemeral streamflow **(Al-Dabbas and Hussain, 2018)**.

3. MATERIALS AND METHODS

3.1 Data Collection

Meteorological data used in this study were obtained from the Iraqi Meteorological and Seismology Organization **(IMSO, 2024)** for the Al-Amarah station, which represents the nearest and most climatically relevant station to the Al-Teeb district. The Al-Amarah meteorological station shares similar physiographic and topographic conditions with the Al-Teeb district, as both are located within a low-relief alluvial plain, making the station representative for regional-scale climatic water balance analysis. The dataset spans a continuous thirty-one period during the period 1993–2023, and the climatic data includes: monthly precipitation mm, maximum, minimum, and mean temperatures °C, relative humidity (%), wind speed (m/sec), Evaporation mm, and sunrise (hr/day). Future climate projections were derived from statistically downscaled CMIP6 outputs using the LARS-WG model. The projected data were generated at a daily temporal resolution and aggregated into monthly values for climatic water balance analysis after basic quality control.

3.2 Climate Water Balance Estimation

The climatic water balance of the Al-Teeb district was evaluated to quantify the relationship between Rainfall (P), potential evapotranspiration (PET), and the resulting water surplus (WS) or deficit (WD). The analysis follows the classical **(Thornthwaite, 1948)** method for estimating monthly PET using mean monthly air temperature as the primary input, with standard astronomical corrections for month length and day length. The Thornthwaite method was adopted in this study as it is well suited for climatic water balance analysis and has been widely applied in arid and semi-arid regions of Iraq, allowing direct comparison with previous regional studies. The monthly temperature index j is computed as:

$$j = \left(\frac{T}{5}\right)^{1,514} \quad (1)$$

where T is the mean monthly air temperature (°C). The annual heat index J is the sum of monthly j values, and the empirical coefficient a is obtained from J as:

$$a = 0.49239 + J(1.797 \times 10^{-2}) - J^2(7.71 \times 10^{-5}) + J^3(6.75 \times 10^{-7}) \quad (2)$$

The uncorrected monthly potential evapotranspiration PET is computed as:

$$PET = 16\left(\frac{10.T}{J}\right)^a \quad (3)$$

To account for variations in month length (D, days) and astronomical day length (N, hours), the corrected PET is:

$$PET_c = PET \times \frac{D}{30} \times \frac{N}{12} \quad (4)$$

Corrected potential evapotranspiration (PETc) was calculated following **(Thornthwaite, 1948)** using standard day-length corrections for the station latitude. The corrected PET values were then used to estimate actual evapotranspiration (AET), water surplus (WS), and water deficit (WD) following the bookkeeping of **(Lerner, 1990)**:

$if\ P \geq PET_c \rightarrow AET = PET_c\ and,$
$WS = P - PET_c$,(WD=0) (5)
$if\ PET_c > P \rightarrow AET = P\ and,$
$WS = PET_c - P$,(WS=0) (6)

3.3 Climate classification

By applying the **(Mather, 1974)** to classify the climatic conditions of the Al-Teeb district for the period (1993–2023). This approach defines climatic types based on the moisture index (Im), which is computed from the long-term climatic water balance components, including precipitation (P), potential evapotranspiration (PETc), water surplus (WS), and water deficit (WD). For climatic classification, the Thornthwaite Moisture Index (Im) **(Mather, 1974)** was calculated as:

$$I_m = \frac{P - PET_c}{PET_c} \times 100 \quad (7)$$

where P is the mean annual precipitation (mm) and PET_c is the mean annual potential evapotranspiration (mm), all calculations were performed monthly, and Im % ranges between 0-100 % as shown in **Table 1**.

Table 1. Climatic classification according to **(Mather, 1974).**

Range of Im (%)	Climate Type
0.0 to –33.3	Dry-sub humid
–33.3 to –66.7	Semi-arid
–66.7 to –100	Arid

3.4 Future Climate Projection Using LARS-WG

The future climatic changes in Al-Teeb district were carefully estimated by the Long Ashton Research Station Weather Generator (LARS-WG, V. 8). The first step of this approach was to calibrate and validate the LARS-WG model using observed daily meteorological records during the baseline period (1993–2023) at Al-Amarah station. The reference input data used in this procedure consisted of daily precipitation, maximum and minimum air temperature, and other climate variables available. This stringent validation procedure was executed to ensure that the stochastically generated series accurately replicates the long-term monthly means and the inherent statistical distribution of observed wet and dry spells. The validation results indicated a strong agreement between observed and generated data, with close correspondence in monthly means, low bias, and satisfactory reproduction of seasonal precipitation and temperature patterns over the 1993–2023 period. Bias correction was inherently accounted for through the calibration and validation procedures of the LARS-WG model, ensuring consistency between observed and generated climatic variables and supporting the reliability of the model for future climate projections.

Upon successful validation, downscaled future climate data were produced using the CMIP6 Global Climate Model HadGEM3-GC31-LL via the SSP2–4.5 emissions scenario. This model was selected as it is one of the CMIP6 global climate models supported within the LARS-WG framework and is commonly applied in climate impact assessments using statistical downscaling approaches, particularly in arid and semi-arid regions. This particular pathway was deliberately chosen because it can be considered as a defendable intermediate, "middle of the road" trajectory consistent with existing global climate policies and socio-economic developments outlined in the IPCC Sixth Assessment Report **(IPCC, 2021)**. A 20-year stochastic dataset was then generated for the projection interval of 2031–2050. This period was selected based on the standardized time slices available within the LARS-WG model and the CMIP6 framework, which are widely used to represent near- to mid-term future climate conditions and to ensure consistency with global climate model outputs. The outputs generated are daily records of the key variables such as precipitation, maximum and minimum temperatures, and solar radiation. The generated data were then aggregated into monthly means and totals to serve as inputs for the subsequent climatic water balance analysis, mirroring the exact Thornthwaite–Lerner procedure applied to the historical record.

3.5 Recharge Quantification (R)

Groundwater recharge was calculated using the coefficient approach (R = Cr × P) for two assessment periods (1993–2023 and 2031–2050). A regionally representative recharge coefficient of 5% of annual precipitation (Cr = 0.05) was adopted, as recommended by previous hydrogeological investigations conducted in the southern Iraqi alluvial plain, where similar climatic and geological conditions prevail **(Ali, 2007; Hussen, 2019; Zwain and Abed, 2023b)**. To ensure methodological consistency between historical and future assessments, the same recharge coefficient was applied to both periods, allowing the relative influence of projected climatic changes on groundwater recharge to be evaluated under identical assumptions.

4. RESULTS AND DISCUSSION

4.1 Climatic Conditions

Based on long-term observations at the Al-Amarah meteorological station (1993–2023), the mean annual rainfall is approximately 178.8 mm, concentrated between November and April, while summer months are almost completely dry. The mean annual temperature is about 25.6 °C, ranging from 11–18 °C in winter to over 37 °C in July and August, as illustrated in **Fig. 3 and Table 2**. Mean relative humidity ranges from 22% in summer up to 66% in winter, with mean sunshine duration levels of about 6.5 h/day and prevailing wind speeds of 2.5–5 m/s. Total annual evaporation reaches as much as an estimated 2899 mm, well surpassing precipitation events, leading to chronic macroclimatic water deficit conditions. These conditions are indicative of the dry hydroclimatic regime in the region and illuminate the heavy reliance on groundwater as a source of water supply.

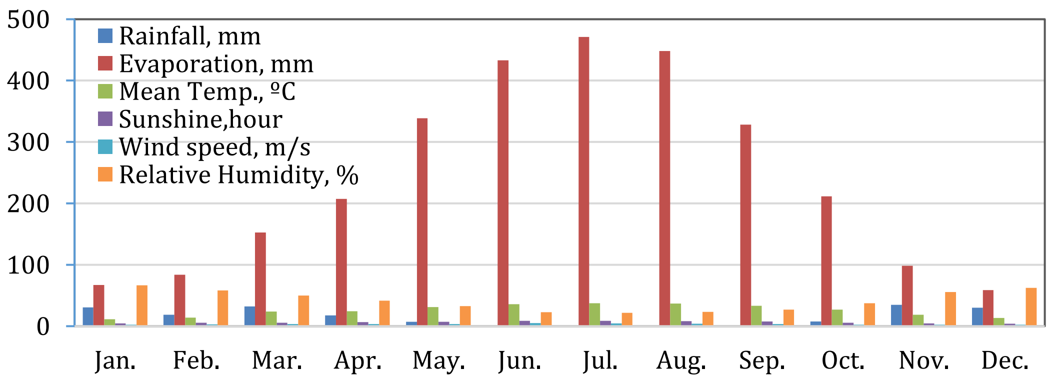

Figure 3. The relationship between the climatic parameters (1993–2023).

Table 2. Climatic data of Al-Amarah Meteorological Station (1993–2023) **(IMSO, 2024).**

Month	Rainfall, mm	Evaporation, mm	Mean Temp. °C			Sunshine, hr/day	Wind speed, m/sec	Relative Humidity, %
			Min	Max	Ave.			
Jan.	30.7	67.2	6.5	16.2	11.2	4.5	2.5	66.6
Feb.	18.5	83.9	8.6	19.3	14	5.4	3	58.1
Mar.	32.23	152.5	12.2	26.2	23.8	5.7	3.5	49.8
Apr.	17.5	207.2	17.3	30	24.5	6.4	3.5	41.6
May.	7.4	338.5	23.7	37.9	31	7.4	3.7	32.6
Jun.	0.01	433.1	27.4	43	35.6	8.9	5.1	22.6
Jul.	0.009	471.2	29.1	44.9	37.4	8.7	4.7	21.5
Aug.	0.0033	448.4	28.4	42	37.1	8.3	4.2	23.1
Sep.	0.025	328.3	24.6	41.4	33.1	7.7	3.6	26.9
Oct.	7.5	211.5	19.4	34.7	27.1	5.8	2.7	37.5
Nov.	34.9	98.5	12.7	24.8	18.6	4.8	2.6	55.7
Dec.	30.1	58.7	8.7	19.2	13.4	3.9	2.4	62.2
Average			18.22	31.63	25.57	6.5	3.46	41.52
Total	178.8	2899						

As shown in **Table 3,** Analysis of long-term hydroclimatic records for the Al-Teeb district (1993–2023) demonstrates a progressive decline in annual rainfall and notable variability in potential evaporation and temperature.

Table 3. Analysis of Long-Term Climatic Trends in Al-Amarah Station, Grouped by Time Period (1993–2023).

Time (Years)	Rainfall, mm	Evaporation, mm	Mean Temp. °C
1993-2003	222.40	3282.82	25.41
2004-2014	191.42	2972.80	27.11
2015-2023	172.24	2968.44	26.89

For 1993–2003, the average annual precipitation was around 222.4 mm along with a potential evaporation of 3282.8 mm and mean air temperature of 25.41°C; followed by an reduction rainfall amounting to 191.4 mm during intermediate years (2004–2014) while slightly lower was the rate of evaporation that declined to about 2972.8 mm and rise in temperature up to reach at an average level of nearly 27.11°C then recent decade (2015–2023) as shown in **Figs. 4A–C**.

These hydroclimatic changes indicate an overall depletion in atmospheric water supply combined with a persistent high evaporative demand, leading to the exacerbation of moisture stress and an increase in aridity across the region. This pattern of change suggests ongoing desiccation of the local hydrological regime, manifested as decreases in effective rainfall, soil moisture storage, and groundwater recharge potential over time. Thus, the Al-Teeb district becomes more susceptible to hydrological droughts in that surface water supplies are intermittent and aquifer recharge is mainly controlled by rare winter rainfalls.

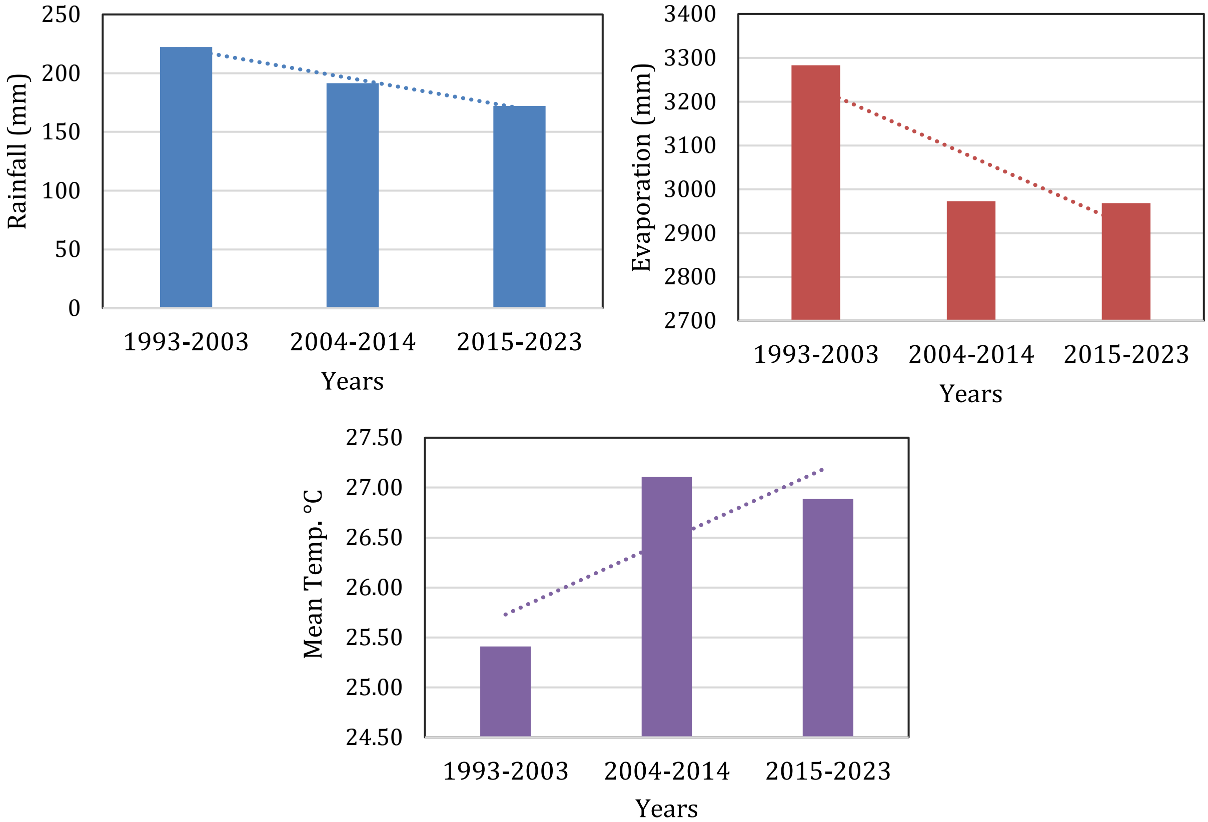

Figure 4. Comparative analysis of climatic parameters across three historical periods (1993–2003, 2004–2014, and 2015–2023) at the Al-Amarah meteorological station. (A) Mean annual rainfall, mm, (B) Annual evaporation, mm, and (C) Mean annual temperature ^{0}C

4.2 Water Balance for the Period (1993-2023)

The results of water balance during 1993–2023 in the Al-Teeb district are presented in **Table 4**. Using the Thornthwaite method, the corrected potential evapotranspiration (PETc) was calculated to reach approximately 2535 mm/year, whereas the mean annual precipitation (P) was only 178.9 mm. This large imbalance results in an annual water deficit (WD) of nearly 2414 mm/year, a limited actual evapotranspiration (AET) by about 121 mm/year, and a minor cumulative winter-water surplus (WS) of as low as 57.9 mm/year. This conclusion implies an arid climate, where PETc exceeds precipitation by over one order of magnitude. All calculated water-balance components follow the Thornthwaite framework, with actual evapotranspiration (AET) not exceeding corrected potential evapotranspiration (PETc) for all months. The majority of rain in the Al-Teeb District occurs during winter (December – February), and further rainfalls take place in November and March. The PETc increases rapidly starting from early spring, because of the rise in temperature and solar radiation values and reaches highest values above 450 mm /month during June–July when precipitation is nearly absent as shown in **Fig. 5**. During the peak summer months (July–August), the monthly water deficit exceeds 500 mm, indicating extreme evaporative demand and very limited moisture availability.
The monthly variation of WS and WD is illustrated in **Fig. 6**, showing that water surplus occurs only during a brief winter period, while deficit conditions dominate most of the year. The climatic classification of the Al-Teeb district was determined using the **(Mather, 1974)** moisture index (Im), which expresses the degree of aridity or humidity based on the

relationship between mean annual precipitation (P) and corrected potential evapotranspiration (PETc). The computed Im value for the study period (1993–2023) was –92.9 %, indicating that the Al-Teeb district falls within the arid climatic zone.

Table 4. Results of the water balance for Al-Amarah station (1993–2023).

Month	P (mm)	PETc (mm)	AET (mm)	WS (mm)	WD (mm)
Jan.	30.7	4.84	4.84	25.85	0
Feb.	18.5	11.07	11.07	7.42	0
Mar.	32.23	91.14	32.23	0	58.91
Apr.	17.5	106.38	17.5	0	88.88
May.	7.4	279.25	7.4	0	271.85
Jun.	0.01	464.28	0.01	0	464.27
Jul.	0.009	567.81	0.009	0	567.80
Aug.	0.0033	522.64	0.0033	0	522.64
Sep.	0.025	307.79	0.025	0	307.77
Oct.	7.5	139.67	7.5	0	132.17
Nov.	34.9	31.17	31.17	3.72	0
Dec.	30.1	9.22	9.22	20.87	0
Annual	178.87	2535.32	121	57.87	2414.32

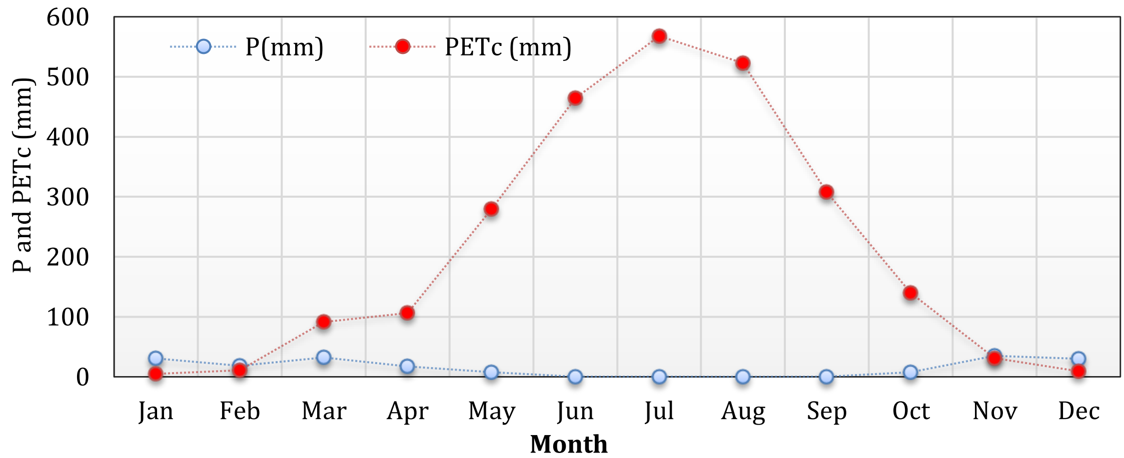

Figure 5. Monthly precipitation (P) and corrected potential evapotranspiration (PETc) for the period (1993–2023)

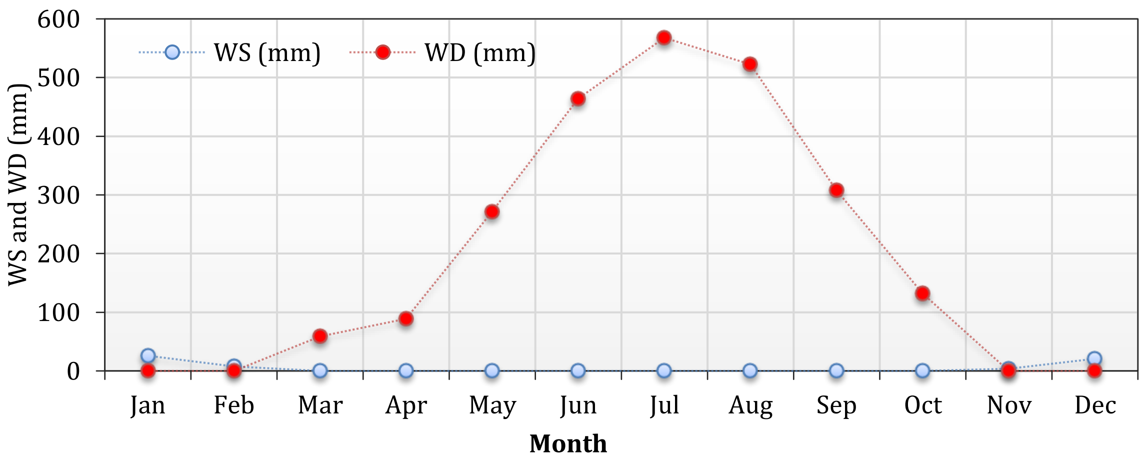

Figure 6. Monthly water surplus (WS) and water deficit (WD) for the period 1993–2023.

4.3 Projected Climatic Data and Water Balance through the Period (2031–2050)

Future hydroclimatic conditions for 2031–2050, projected using LARS-WG under the SSP2–4.5 scenario, indicate that annual P will increase to 258.42 mm. This increase reflects a projected climatic trend derived from stochastic model simulations, while PETc rises sharply to 4010.94 mm/year, resulting in a WD of 3853.11 mm/year. AET and WS are projected at 157.82 mm/year and 100.6 mm/year, respectively, mainly during winter, as shown in **Table 5**. Despite increased rainfall, extreme summer PETc values (>950–1000 mm/month) will intensify aridity, limiting groundwater recharge to short winter periods.

Table 5. Projected water balance components for Al-Amarah station (2031–2050).

Month	P (mm)	PETc (mm)	AET (mm)	WS (mm)	WD (mm)
Jan	32.34	4.367	4.36	27.97	0
Feb	18.83	9.27	9.27	9.55	0
Mar	24.87	39.89	24.87	0	15.02
Apr	31.79	128.59	31.79	0	96.8
May	14.85	384.19	14.85	0	369.34
Jun	0	690.75	0	0	690.75
Jul	1.07	997.11	1.07	0	996.04
Aug	2.14	945.49	2.14	0	943.35
Sep	3.93	531.28	3.93	0	527.35
Oct	10.81	225.24	10.81	0	214.43
Nov	54.47	45.1	45.1	9.36	0
Dec	63.32	9.61	9.619	53.7	0
Annual	258.42	4010.94	157.82	100.6	3853.11

Compared with the historical period (1993–2023), precipitation is projected to increase by about 44.5%, while PETc rises by 58.2%, causing the annual water deficit to expand by nearly 60%. Although the winter surplus may grow from 57.87 mm to 100.6 mm, this remains insufficient to offset the high evaporative demand. Applying the same **(Mather, 1974)** approach used for the baseline period, the Moisture Index (Im) for the projected period (2031–2050) was recalculated based on the simulated climatic water-balance components. The resulting Im value of −93.6 % indicates that the Al-Teeb district will remain within the arid climatic zone, with slightly intensified dryness. This finding demonstrates that, although rainfall is projected to increase, the stronger evaporative demand will continue to dominate the regional water balance and constrain effective groundwater recharge. The dominance of potential evapotranspiration over precipitation observed in the Al-Teeb district is consistent with findings reported for other arid and semi-arid regions of Iraq, where projected increases in evaporative demand outweigh potential gains in rainfall, leading to intensified water deficits and limited groundwater recharge **(Al-Dabbas and Abdul Razzaq, 2017; Al-Kubaisi et al., 2019; Hassan et al., 2023)**.

4.4 Impact of Climate Change on Groundwater Recharge (Coefficient Approach)

In arid and semi-arid environments, only a minor portion of annual rainfall contributes to groundwater recharge, as most precipitation is lost through evapotranspiration or short-lived surface runoff. Under such data-limited conditions, the coefficient approach provides a practical first-order estimation of recharge (R) as a fraction of annual precipitation (P) **(Lerner et al., 1990)**.

Based on the rainfall data for the period 1993-2023, the rainfall was178.9 mm, which estimated the recharge of 8.9 mm/yr, as shown in **Fig. 7 and Table 6**. While for the projected future period (2031–2050), rainfall increases to 258.4 mm/yr, resulting in a recharge of 12.9 mm/yr, as illustrated in **Fig. 8 and Table 7**. Although the total recharge slightly increases in absolute terms, its proportion relative to precipitation remains small compared with the significant rise in PETc. Consequently, effective groundwater replenishment will continue to be restricted to short winter periods, offering minimal relief to the persistent water deficit. Previous local investigations in comparable hydrogeological settings have indicated that recharge typically represents about 5% of rainfall in low-relief alluvial plains underlain by Quaternary sediments **(Ali, 2007; Hussen, 2019)**.
Considering the nearly flat topography, shallow unconfined aquifer, and moderately permeable alluvial soils in the Al-Teeb district, a representative coefficient of Cr = 5% was adopted for the current estimation.

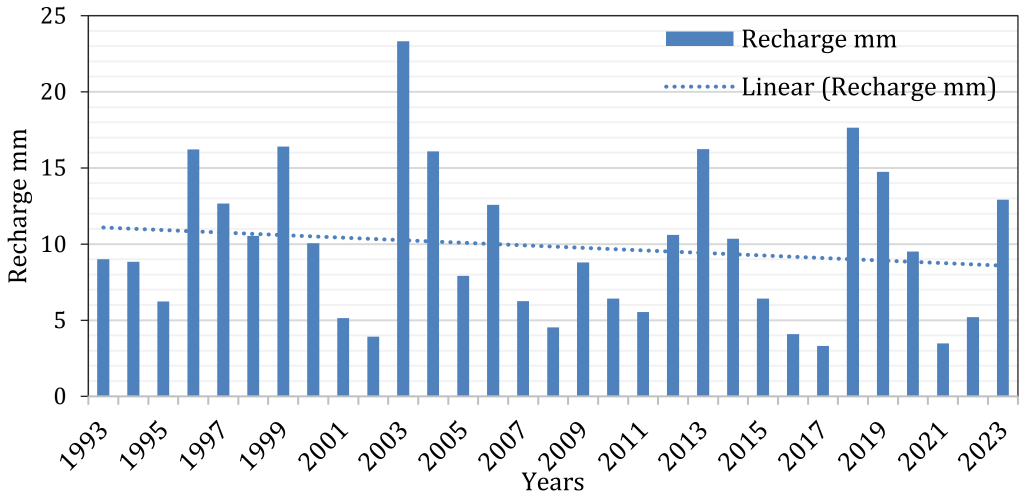

Figure 7. Variation of Groundwater Recharge based on historical rainfall data used during (1993-2023).

Table 6. Estimated Groundwater Recharge for historical rainfall data used during (1993-2023) using the Coefficient Approach.

Year	Recharge mm	Year	Recharge mm	Year	Recharge mm
1993	9.015	2004	16.0851	2014	10.35
1994	8.84	2005	7.91	2015	6.42505
1995	6.2401	2006	12.57	2016	4.08
1996	16.2051	2007	6.255	2017	3.3
1997	12.6551	2008	4.5301	2018	17.645
1998	10.5401	2009	8.7951	2019	14.745
1999	16.4101	2010	6.41505	2020	9.505
2000	10.06	2011	5.5351	2021	3.47505
2001	5.13005	2012	10.6055	2022	5.2
2002	3.91005	2013	16.2301	2023	12.9201
2003	23.314				

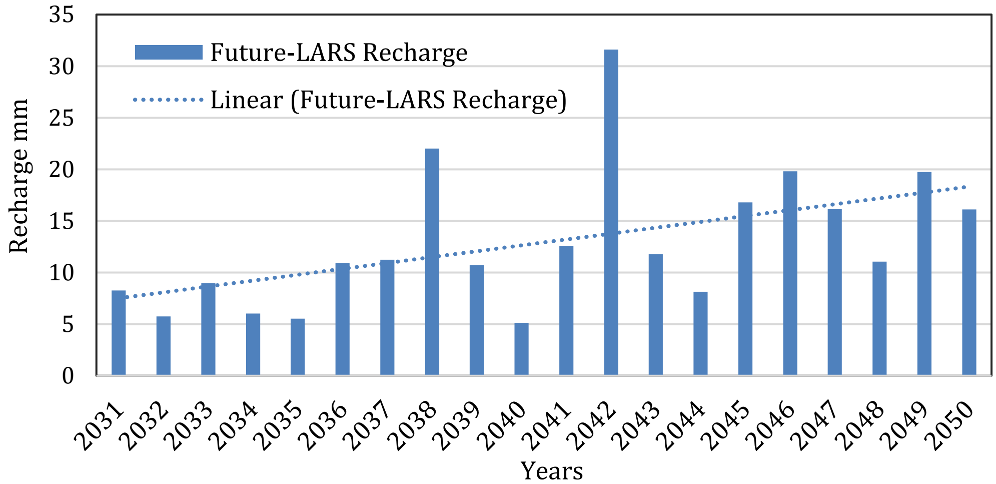

Figure 8. Variation of Groundwater Recharge based on historical rainfall data used during (2031-2050).

Table 7. Estimated Groundwater Recharge for historical rainfall data during Projected Periods using the Coefficient Approach.

Year	Recharge	Year	Recharge
2031	8.25	2041	12.585
2032	5.755	2042	31.6
2033	8.98	2043	11.76
2034	6.03	2044	8.15
2035	5.545	2045	16.815
2036	10.945	2046	19.805
2037	11.245	2047	16.16
2038	22.02	2048	11.055
2039	10.72	2049	19.74
2040	5.125	2050	16.12

5. CONCLUSIONS

This study concludes that the Al-Teeb district is characterized by persistently arid hydroclimatic conditions, both in the historical (1993–2023) and projected (2031–2050) periods. Although mean annual precipitation is expected to increase by approximately 44%, this improvement is counterbalanced by a pronounced rise in potential evapotranspiration, which intensifies the annual water deficit and maintains the arid climatic classification of the region. The values of the Thornthwaite Moisture Index (Im) found in this study, −92.9 and 93.6 % for historical and future periods, respectively, reveal continued aridification in the area and its further increase due to climate change. Increases in temperature and PETc imply that effective recharge to the groundwater will still be restricted to short winter periods. Predictions from the coefficient approach suggest that, although recharge may be marginally higher in the future as a result of increased precipitation, it remains relatively small when compared to the magnitude of the projected water deficit and increased evaporative demand. Collectively, these findings indicate the responsiveness of the Al-Teeb catchment system to progressive climate change and encourage action towards sustainable strategies of adaptive measures that ensure efficient water resources management. Actions, including managed abstraction, artificial recharge, and integrated surface–sub-surface water planning, are required to mitigate the effects of increasing aridity and safeguard long-term water security for southern Iraq's alluvial plain.

NOMENCLATURE

Symbol	Description	Symbol	Description
P	Precipitation (mm)	j	Monthly Heat Index
PET	Potential Evapotranspiration (mm)	J	Annual Heat Index
PETc	Corrected Potential evapotranspiration (mm)	a	Empirical coefficient
AET	Actual evapotranspiration (mm)	Im	Thornthwaite moisture index (%)
WS	Water Surplus (mm)	N	Length of day
WD	Water Deficit (mm)	D	Number of days in a month

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Credit Authorship Contribution Statement

Abrar M. Abd Al-Ali, Basim Sh. Abed and Alyaa Shakir Oleiwi: Writing – review and editing, Writing – original draft, Validation, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تقييم تأثير التغيّر المناخي على الموازنة المائية وإعادة تغذية المياه الجوفية في قضاء الطيب، جنوبي العراق

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الخلاصة

تُقيّم هذه الدراسة الموازنة المائية المناخية لمنطقة الطيب في جنوب العراق تحت الظروف المناخية الحالية (1993–2023) والمستقبلية (2031–2050). تم إجراء التحليل باستخدام طريقة ثورنثويت وليرنر، بالاعتماد على بيانات مناخية مستقبلية مولّدة إحصائيًا بواسطة برنامج التوليد المناخي الذي يستند إلى نموذج المناخ العالميHadGEM3-GC31-LL وفق السيناريو المتوسط للانبعاثات (السيناريو 2-4.5). خلال الفترة الحالية، بلغ المعدل السنوي للأمطار 178.9 ملم، في حين بلغت قيمة البخر–النتح الكامن المصحح 2535 ملم سنويًا، مما أدى إلى عجز مائي كبير قدره 2414 ملم سنويًا، وصُنفت المنطقة بأنها قاحلة. أما في الفترة المستقبلية، فتشير النتائج إلى زيادة في معدل الأمطار إلى 258.4 ملم سنويًا، إلا أن الزيادة الأكبر في قيم البخر–النتح إلى 4011 ملم سنويًا أدت إلى عجز مائي أعلى بلغ 3853 ملم سنويًا، مع استمرار تصنيف المنطقة بأنها قاحلة. بلغت كمية التغذية الجوفية المقدّرة بطريقة المعامل 8.9 ملم سنويًا في الفترة الحالية و12.9 ملم سنويًا في المستقبل. وعلى الرغم من الزيادة المتوقعة في كمية الأمطار، إلا أن الارتفاع الكبير في معدلات التبخر يحدّ بشكل كبير من فرص تغذية المياه الجوفية. تُظهر هذه النتائج الحاجة الماسة إلى اعتماد استراتيجيات تكيف فعّالة لإدارة المياه الجوفية، بهدف الحد من تفاقم الجفاف وضمان استدامة الموارد المائية في منطقة الطيب على المدى الطويل.

الكلمات المفتاحية: التغير المناخي؛ الموازنة المائية؛ ثورنثويت؛ المياه الجوفية؛ LARS-WG