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ORGINAL ARTICLE

Impact of surface irrigation practices on groundwater level and water quality in North West Amhara Region, Ethiopia

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ABSTRACT

Natural resources are degraded continuously due to rapid population, global climate change, poor management, and misunderstanding of the nature of resources. Changes in groundwater level and water quality caused by irrigation practices (overwater application and use of high chemical fertilizers) are currently observed problems. This study focused on investigating the impact of surface irrigation practices on groundwater level and water quality. To investigate the impact, 72 groundwater samples were collected from 6 wells positioned inside and outside the irrigated fields for 12 months, and groundwater levels were recorded at monthly intervals. The concentration of nitrate (NO^{-} ^{3}), phosphate (PO_4), and potassium (K) were analyzed in the laboratory following the standard procedures of photometer methods. One-way ANOVA was used to analyze the data. The result showed that a huge amount of chemical nutrients was deposited in the groundwater wells located in the irrigated area as compared to wells located outside the command area. Similarly, the water levels rose in the irrigated area and the water levels decline outside the irrigated area. This indicates that overwater use and high chemical dose application had a significant effect on groundwater water level changes and nutrient concentrations. For all nutrients, the peak value occurred in April and July for irrigated and non-irrigated areas, respectively, due to the effect of groundwater recharge long-term events. In conclusion, poor surface irrigation management, an overdose of nutrient application, and unforeseen biological activities aggravate the degradation of groundwater quality and water level changes in irrigated agriculture.

Keywords: *Groundwater, Koga, nutrient concentration, surface irrigation*

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1. Introduction

Natural resources are degraded continuously due to rapid population; global climate change, poor management, and misunderstanding of the nature of resources resulted from a lack of coordination and integrated approaches. Among all, water is the prime natural resource that is basic for the healthful functioning of any ecosystem. The impacts of irrigation on groundwater level changes and nutrient concentration are both direct and indirect. For example, the practice of irrigation increases the overall demand for water in an area, and when water abstraction for irrigation exceeds the natural recharge rate of the aquifer, it can lead to a decline in the groundwater level and result in groundwater depletion. Two areas that have had the greatest impact on the quality and quantity of groundwater were the use of irrigation practices and the application of chemicals. In Sub-Saharan Africa, groundwater use is relatively high in absolute and percentage terms, driven by a supportive policy regime. Ethiopia is a country having great potential for both surface and groundwater resources and results have given its name to the country as the water tower of East Africa [1]. The main source of water in the country is rainfall which results in many transboundary rivers, which have different water volumes in different seasons [2].

In Ethiopia, there is a significant gap in considering the impacts of surface irrigation practices on groundwater. Currently, many users apply irrigation and nutrients without taking into account changes in groundwater levels and water quality. Groundwater levels can fluctuate due to various factors, including natural phenomena and human activities [3]. Ethiopia has both confined and unconfined aquifers, with some shallow unconfined aquifers being susceptible to surface activities while deeper confined aquifers remain isolated from surface or shallow subsurface influences. The composition of aquifers ranges from competent bedrock units to unconsolidated sediments. Water levels in aquifers can be influenced by factors such as water demand, usage patterns, and geological characteristics [4]. Additionally, elevated concentrations of dissolved salts and nutrients are common in groundwater due to the extensive approaches of evaporated plant minerals. Poor management of irrigation water also can contribute to high salinity and nutrient erosion issues. This study aims to assess the influence of irrigation on groundwater level changes and variations in nutrient content. The analysis focuses on groundwater wells located within and outside the irrigation scheme.

In general, this research delves into the profound influence of surface irrigation on groundwater levels and water quality, particularly under dry conditions. The primary objective of this study is to comprehensively, elucidate the dynamics of groundwater level changes and meticulously investigate the concentrations of macronutrients within and beyond the irrigated area. By doing so, this paper seeks to provide a robust understanding of the intricate relationship between surface irrigation practices and the consequential effects on groundwater resources and nutrient distribution.

2. Materials and methods

2.1 Study area description

The Koga watershed is one of the subbasins in the Tana basin and is found in the Amhara region, North Mecha district. The Koga subbasin that covers the 250 km^2 watershed is a tributary of the Gilgel Abay River in the headwaters of the Blue Nile basin which flows into Lake Tana [3]. The watershed is subject to the inter-tropical convergence zone and a single rainy season that begins in June and lasts through September resulting in contributing 70 % of the river flow (Figure 1). The Koga irrigation scheme and watershed management project are located south of Lake Tana in the Upper Blue Nile Basin of Ethiopia (Latitude 11° 10′N–11° 25′N, longitude 37° 02′E–37° 17′E). With an elevation between 1900 and 3200 m. The watershed had a unimodal form of rainfall and dominant clay soil texture. The climate and the soil properties of the irrigation scheme are expressed below (Table 1).

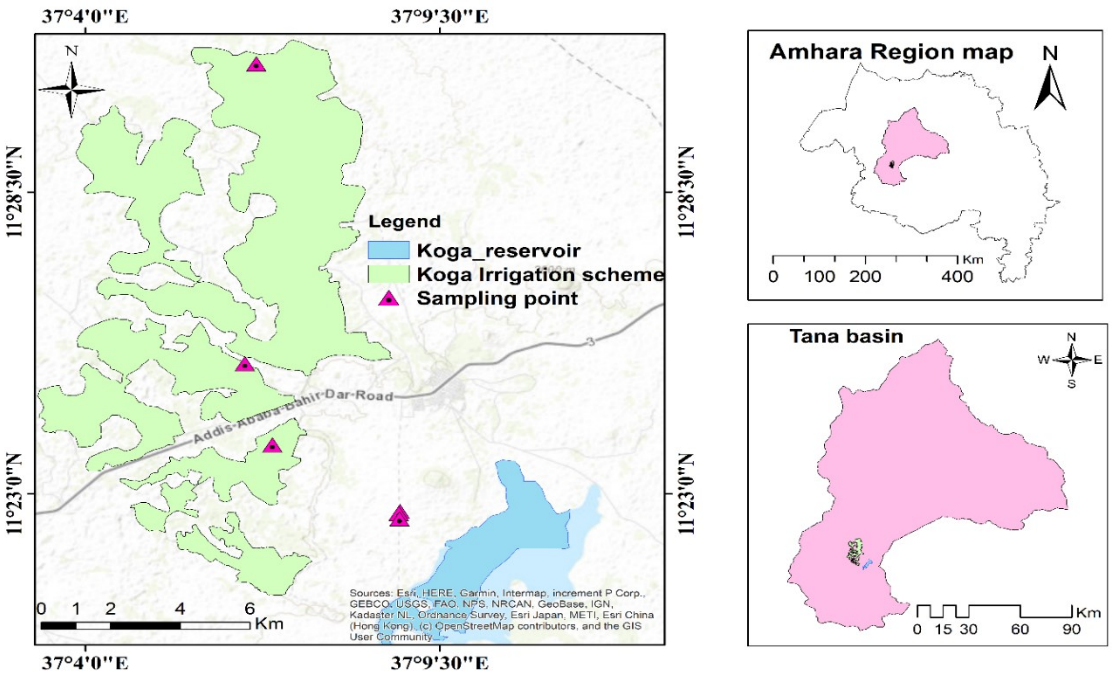

Figure 1 Location map of the study area and groundwater sampling points (wells located in and outside the irrigated area), Source:

The irrigation project had designed to irrigate 7004 ha of land and it has 12 irrigation blocks and eleven-night storage. The night storages or reservoirs of the irrigation scheme are constructed on the main canal and the water is distributed using smaller unlined tertiary channels to the individual fields. The main canal with a length of 42 km, and secondary canals are constructed from concrete, enables to prevent water loss through seepage. The dam is constructed as an earth fill dam in the Koga River and the dam distributes water to the three different areas by a main channel. Along the main canals, secondary channels are also lined with concrete to prevent erosion and percolation.

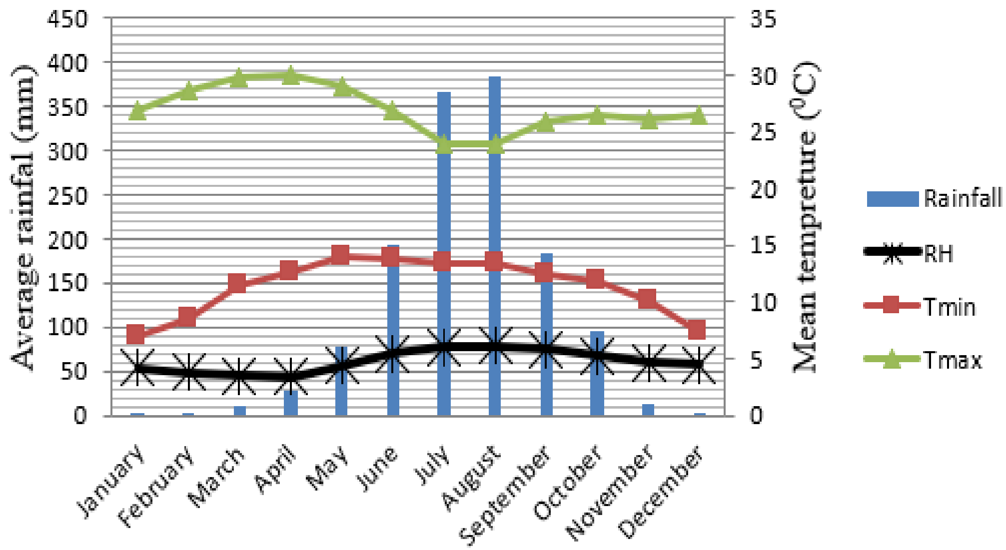

Figure 2 Climatic characteristics of the study area during the study period.

Table 1 some of the physical and chemical soil properties of the Koga irrigation command area

Physical parameters	values	Chemical parameters	values
FC (%)	34.1	PH (%)	4.6
PWP (%)	22.6	EC (mS/cm)	0.18
BD (gcm^{-3})	1.12	CEC (%)	22.2
Sand (%)	24.1	OM (%)	3.18
Clay (%)	67.3	N (%)	0.20
Silt (%)	30.6	Av. P (ppm)	8.72
Texture	Clay	Fe (ppm)	16.5

Note: FC is field capacity, PWP is the permanent wilting point, BD denotes bulk density, CEC is cation exchange capacity, and OM stands for organic matter, Av. P is available phosphorus, N is nitrogen, Fe is iron, and EC is electrical conductivity.

2.2 Water sampling

For the collection of the groundwater samples, a systematic sampling technique was used and the sampling wells were selected based on different reaches (upper, middle, and lower reaches) in the study area to take representative samples. Therefore, three of the wells with depth (8 to 15m) are located in the irrigated area at the upper, middle, and tail portions of the scheme whereas the other three wells with depth ranges 15 to 30 m are positioned in the upper stream of the dam. The sampling materials used include a plastic bottle, icebox, plaster, and parker for labeling. The sampling device (plastic bottles) was cleaned very well before use by the water to be sampled to prevent mixing up of water that remained in the bottle before sampling and to remove other unwanted ordinary materials. The samples were collected using clear plastic bottles with screw caps and put in the icebox then transported to the lab within 24 hours for analysis of the concentration of nitrogen, phosphorus, and potassium in groundwater. The total number of (N = 72) water samples were taken from groundwater sources (36 samples from deep wells and 36 samples from shallow wells) started from December 2018 to December 2019 for one year. The depth of wells varied from 8 m to 30 m with a diameter of 1 m (Table 2). The depth of the wells was measured using a tape meter, and samples were collected at monthly intervals. Before groundwater samples were collected, wells were purged for at least 20 minutes until the climatic condition of the area is stable. Groundwater samples were collected once a month in the morning time from irrigated areas and non-irrigated areas to identify the effect of irrigation practices on groundwater level change and its nutrient concentration.

Table 2 Groundwater depth and the geographical location of wells take into consideration for this investigation

	Wells code	Depth of well (m)	Geographical location		
			Longitude (◦)	Latitude (◦)	Elevation (m)
Wells located in the irrigated area	GW1	15.0	37.11501	11.39822	1993
	GW2	8.00	37.10788	11.42292	1991
	GW3	8.00	37.11085	11.51395	1878
Wells located in the non-irrigated area	GW4	30.0	37.14799	11.37799	2049
	GW5	30.0	37.14767	11.37745	2025
	GW6	30.0	37.14789	11.37576	2000

Note: GW represents groundwater well and the numbers indicate the identification code

2.3 Laboratory analysis

Six groundwater samples per month were gathered from six wells for one year to analysis the concentration of nitrogen, phosphorus, and potassium in groundwater. All collected water samples were analyzed in the laboratory to determine the availability of macronutrients in groundwater and the analysis was conducted at Amhara Design and Supervision Works Enterprise (ADSWE). The water samples were mixed with reagents before measuring the total nitrogen, phosphorus, and potassium, and after a while using the photometer the concentration of nitrogen (N), phosphorus (P), and potassium (K) in the sample was quantified and recorded. The photometer method [4] (https://www.manualslib.com/manual/1307422/Palintest-Photometer-7100.html) using standard procedures is used for the analysis of the collected samples in the lab.

2.4 Statistical analysis

One-way ANOVA was used to analyze the acquired data, and the mean differences between irrigated and non-irrigated fields were calculated. Finally, the analytic result was expressed using descriptive statistics.

3. Result and discussion

3.1 Effect of Irrigation on nutrient concentration

The most common macronutrients evaluated were nitrate (NO_3), phosphate (PO_4), and potassium (K). Overall, the highest mean concentration of NO_3 (2.45 ppm) and K (1.56 ppm) was found in the irrigated area (Table 3) and the result of nitrate concentration is higher than the other research findings conducted by [5] for both dry and wet season. This result was due to 40 % of agricultural chemicals in groundwater collected beneath irrigated fields and the irrigators have been applying a high amount of fertilizer dose. Several processes' probability contributes to the flow and season-dependent fluctuations in nitrate concentrations and exports. The nitrate accumulates in the dry period as a result of the mineralization of soil organic matter and the input of other biological activities such as nitrogen fixation, decomposition of organic matter, and microbial activity leads to the breakdown of under and above-ground biomass leads to elevate the concentration of nitrate in agricultural fields.

The high concentration also increased the number of macronutrients and micronutrients in the groundwater because agricultural practices in the irrigated area were carried out there more frequently than in the non-irrigated area. The maximum average concentration of PO_4 (1.86 ppm) is found in the non-irrigated field (Table 3). Based on the research performed by [6], for shallow and deep wells the values of phosphate did not exceed the permissible level (>2 ppm) in both irrigated and non-irrigated fields. This is due to the slow movement of phosphorus in the soil. In this study, the concentration of nitrate is lower than the other research findings for wells located in the agricultural field and higher than for wells used for water supply purposes [7]. The concentration of phosphate for both irrigated and non-irrigated fields was greater than the findings of [8] conducted at the Koga irrigation scheme. This shows the impact of agricultural practices on groundwater quality increases and may degrade the quality over the period. According to Tewabe, Dessie [9], the concentration of potassium is lower for wells positioned in irrigated and non-irrigated agricultural fields.

Table 3 The descriptive statistics of nutrient concentration in groundwater (in ppm) for irrigated and non-irrigated fields.

Parameters	Irrigated field			Non-irrigated field			WHO and FAO limits
	Min.	Mean	Max.	Min.	Mean	Max.	
NO3	0.01	2.45	6.40	0.26	1.72	4.40	50[10]
PO4	0.02	1.71	11.2	0.01	1.86	8.20	0.4 [11]
K	0.20	1.56	7.00	0.10	1.15	2.20	20 [11]

Note: NO_3 is nitrogen in the form of nitrate and PO_4 is phosphorus in the form of phosphate

The highest concentration of phosphate (6.17 ppm) occurred in March for groundwater wells located in the non-irrigated fields while nitrate concentration became higher in May, and for potassium concentration, the peak value (1.63 ppm) was found in January (Figure 3b). The concentrations of the three macronutrients varied throughout the year due to the temporal and spatial variation of human activities and the natural process. The maximum phosphorus content was produced in March and April for both irrigated and non-irrigated fields. This was due to the presence of precipitation in addition to irrigation during these months. In both cases, the rate of phosphorus leaching increases along with its concentration.

The one-way analysis of variance (ANOVA) results showed a significant difference in nitrate concentration between irrigated and non-irrigated fields at $P < 0.05$. However, due to their nature of movement in the soil and their inability to reach the groundwater within a short irrigation season, there is no discernible difference in the content of phosphate and potassium.

Table 4 One-way ANOVA analysis of groundwater quality between sampling fields (6 wells were taken at both fields)

Sampling field	Source of variation	NO_3^-	PO_4	K
Irrigated and non-irrigated	df	23	23	23
	F	3.51	0.08	3.83
	Sig.	0.08^n	0.07^n	0.06^n

Note: n = non-significant at $P < 0.05$, df =degree of freedom, F represents F statistics, and Sig is a significant level or P-value.

In general, the trend of the concentration of nitrogen, phosphorus, and potassium in groundwater increased according to the position of the well in the irrigated field, however, the oscillations in a few months were detected for all nutrients (Figure 3) analyzed within and outside the command area. Consequently, these changes in nutrient concentration occurred because of the addition of high chemical fertilizers and unforeseen biological activities. The highest concentration of both nitrate and potassium was recognized in July due to the presence of extra chemicals applied in the rainy season in addition to the previously added fertilizers and the concentration is detected within a short period due to the rapid movements of the nutrients, i.e., nitrogen. On the other way, the concentration of nutrients in groundwater increased as the amount of irrigation water increased for irrigated fields and the concentration of those nutrients considered in this study was lower in the non–irrigated fields.

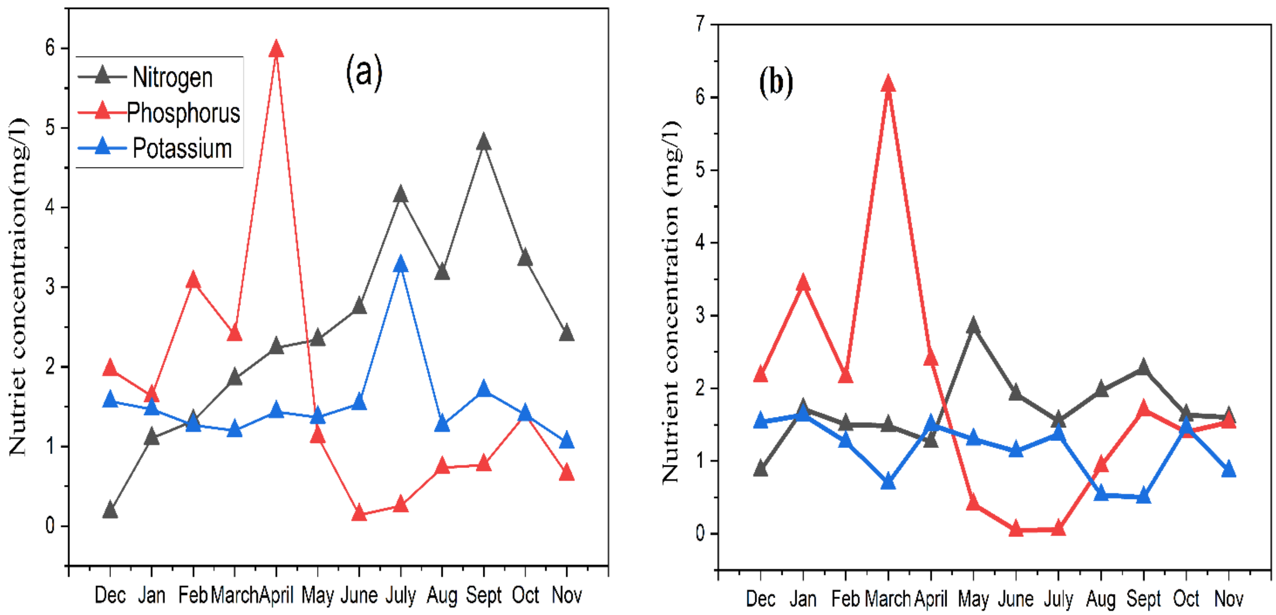

Figure 3 Monthly fluctuation of the nutrient concentration in groundwater within (a) and outside (b) the irrigation scheme

For wells located inside and outside the irrigated field, the natural process and human activities had great impacts on the spatial and temporal changes in nutrient concentration in the groundwater. Additionally, the movement of the nutrients into the groundwater was facilitated by the presence of precipitation and runoff.

Figure 3 depicts the effect of excess flow on nutrient leaching and the pattern of nutrient concentration along the month. The trends of nutrient concentration in each month were similar for wells located in the irrigated and non-irrigated fields, but a markedly higher concentration was obtained for wells found in the irrigated field, specifically the concentration of nitrate is higher in the irrigated area. For nitrate, the maximum values of 4.8 ppm and 4.14 ppm were obtained in September and July respectively, for potassium 3.27 ppm in July was gained and a higher phosphorus concentration was detected in April which is 5.97 ppm (Figure 3a) occurred in wells positioned in the irrigated area. These indicated that irrigation had a significant effect on the concentration of nutrients in groundwater.

Based on the WHO guidelines, the groundwater quality in the study is classified as moderately pure since the higher concentration values of all nutrients considered in this research were below the established limits (Table 3). However, the graph depicted a noticeable trend indicating that irrigation activities influence the characteristics of the groundwater. This finding emphasizes the necessity for implementing best management practices, such as effective water management and judicious nutrient application to ensure sustainable and optimal outcomes.

The box plot clearly showed that irrigation activities lead to a rise in the concentration of nutrients, specifically the nitrate concentration increased as compared to wells located in the non-irrigated field. But the concentration of phosphate is higher in the wells located in the non-irrigated field (Figure 4). The visible effect of irrigation practices was detected after the end of the irrigation season and half of the rainy season in most selected wells. In terms of those nutrient concentrations, the groundwater quality was considered not highly degraded and contaminated but indicates the signal that the groundwater quality, as well as the water table, may raise and result in salt concentration in the soil to reduce production in the irrigation field.

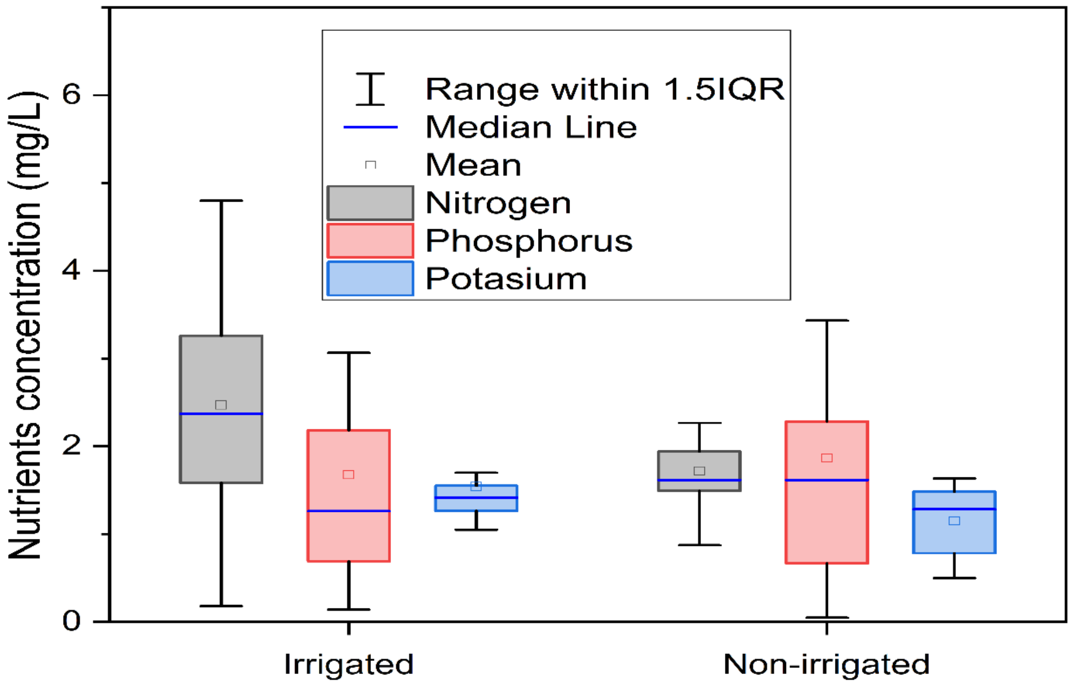

Figure 4 boxplot expression of the overall mean concentration of nitrogen, phosphorus, and potassium in wells located in irrigated and non-irrigated fields.

3.2 Effect of Irrigation on groundwater level

Short-term trends in groundwater levels of shallow and deep aquifers across the Koga irrigation scheme are shown below (Figure 5). The figure shows the groundwater level declining trends for the sampled wells and the magnitudes of these trends vary across the well temporarily. Strong declining trends ranging from (0.12 to 0.78 m/yr.) groundwater depths are observed for wells (W1, W4, W5, and W6) found in both irrigated and non-irrigated sites. The raised water levels ranged from (0.03 to 0.04) m/yr.) were observed for shallow wells (W2 and W3) located inside the irrigated field. According to Shamsudduha, Chandler [12] research result, this finding is slightly higher and smaller than the research findings conducted by [9]. In general, the groundwater wells located in the irrigation command area did not decline in the water level and the groundwater wells found in the non–irrigated area showed that decreased trend of water level changes under dry conditions. The groundwater level fluctuation is more of a location-specific response to recharge and discharge [13]. Similarly in this study, the change in groundwater level indicates the location and time-specific patterns [14]

Table 5 Groundwater level changes (m) over the months for wells located inside and outside of the irrigation scheme.

Month	Wells inside the scheme			Wells outside the scheme		
	W1	W2	W3	W4	W5	W6
December	-	-	-	-	-	-
January	+0.03	+0.04	+0.20	+0.50	-1.40	+0.80
February	+0.05	+0.16	+0.10	+1.30	-0.10	+1.20
March	+0.32	+0.44	+0.10	-1.80	-0.80	+5.70
April	+1.88	+1.10	+0.30	+0.98	-1.32	-1.94
May	+0.85	-2.50	+0.15	-1.28	-4.91	-8.26
June	-2.25	-1.12	-0.60	-2.15	-0.47	-1.50
July	-2.80	-0.63	-0.65	-3.25	0.83	-1.01
August	+0.40	+1.55	-0.35	+0.70	+0.80	+0.61
September	-0.20	+0.90	+0.25	+0.26	-0.19	+1.4
October	0.00	+0.20	+0.50	+1.03	-0.34	+1.1
November	0.00	+0.15	+0.39	+0.59	-0.70	+0.63
Mean	-0.15	+0.03	+0.04	-0.28	-0.78	-0.12

The positive (+) sign shows rising in the water level and the negative (-) sign indicates a decline in the water level

The greatest depth of water table reduction for wells outside the irrigation system was reported in May (8.26 m), whereas the greatest depth for wells inside the irrigation scheme was recorded in July (2.80 m). However, wells placed inside and outside the irrigation scheme, respectively, recorded the largest rise of the water table depth change in March (5.70m) and April (1.88m). The water table depth was raised during the irrigation season (October to May) as a result of the irrigation practice; this conclusion is consistent with earlier observations [9, 15]. The change in water table depth was detected in various seasons (Table 5).

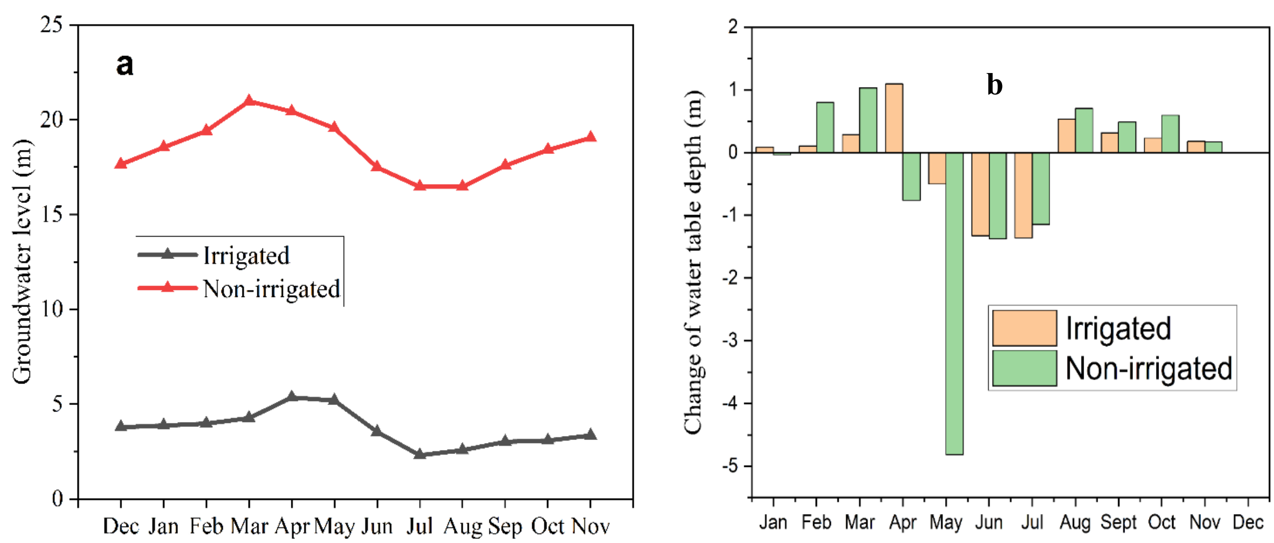

Figure 5 trends of groundwater level change (a); the rise and decline of groundwater table depth (b) over the month in the irrigated and non-irrigated fields, the negative sign showed a decline of the groundwater table depth and values above zero indicates the rise of the water table depth.

Even while our study is mainly focused on the drier parts of the season, the overarching trend is visible during both wet and dry seasons. This demonstrated that the groundwater level fluctuations in the watershed were significantly influenced by irrigation, rainfed, and agricultural activities carried out by the local farmers.

4. Conclusion

Agricultural irrigation practices have an impact on groundwater quality and water levels for both shallow and deep wells. Groundwater is contaminated by nitrate and phosphorus possibly due to excessive use of fertilizers and irrigation water in agriculture. The concentrations of nutrients in the groundwater vary between irrigated and non-irrigated areas. The result illustrates that the maximum amount of nitrate, phosphorus, and potassium was deposited in the groundwater wells located in the irrigated area as compared to wells found outside the irrigated field. At the same time, the water level declined in the wells outside of the irrigated area and the effect of the change in groundwater level occurred over a long period. Our analysis of the dataset on the groundwater level and quality observations in consideration of wells located within and outside irrigated areas provides insight into trends and seasonality in shallow groundwater levels expected in other irrigation schemes in Ethiopia influenced by surface irrigation practices and chemical applications. Also, we observed that the poor management of irrigation water amplifies the change in groundwater characteristics and increase the recharge amounts for both shallow and deep wells under irrigation condition. In general, the results of the study are believed to give directions for future groundwater, irrigation water, and crop nutrient management options to decision-makers and laid the foundation for the establishment of strong agricultural water management for monitoring and evaluation of the effect of irrigation practices on groundwater resources located in the command area.

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Conflict of interest

The authors declare that no conflict of interest.

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