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Integrated assessment of groundwater sustainability using GRACE satellite data and GIS in Debre Markos, Ethiopia

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Abstract
Groundwater resources in Debre Markos, Ethiopia, are under increasing pressure from urbanization, agricultural expansion, and climate change. This study integrates GRACE satellite data (2002–2017) and GIS-based land use/land cover (LULC) analysis to assess groundwater storage variations, identify contamination risks, and propose sustainable water supply strategies. Results show a persistent decline in groundwater storage and yield, especially in wells surrounded by high-risk land uses. Buffer zone analysis revealed substantial encroachment by agriculture and built-up areas within 300 m protection zones. A spatial buffer analyses around wells in the Wutren and Sentera fields reveal, significant overlap in drawdown zones and inadequate well spacing some as close as 16 m leading to increased mutual interference and aquifer stress. Moreover, risk zones, delineated based on land use encroachment and proximity-based interference, highlight critical areas where agriculture and built-up zones compromise source protection. The study recommends enforcing groundwater protection buffers, optimizing well spacing, regulating land use within critical zones, and expanding remote sensing tools for continuous groundwater monitoring and sustainable water supply planning.

Keywords GRACE, Groundwater depletion, GIS buffer analysis, LULC, Water source protection, Ethiopia

1 Introduction

Groundwater plays a vital role in sustaining water supply in Ethiopia, particularly in urban and semi-arid regions such as Debre Markos [7]. Despite Ethiopia's estimated 40 billion cubic meters of groundwater potential, only a small fraction is effectively utilized due to over-extraction, pollution, and limited monitoring capacity [24]. The Wutren and Sentera well fields in Debre Markos have experienced a decline in discharge, with contributing factors including land use change, unregulated urbanization, and lack of protection zones. Previous studies have emphasized the vulnerability of groundwater in Ethiopia due to land use pressure and climate variability [5, 16]. Recharge rates vary significantly depending on environmental and anthropogenic factors. In regions like the

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Fetam catchment, recharge is below the national average due to intensive agriculture. Vulnerability models like DRASTIC have revealed the heightened risk of nitrate contamination from surface activities [34]. Remote sensing, especially the GRACE satellite mission, has been successfully applied in groundwater assessments worldwide, including Africa, due to its ability to track terrestrial water storage anomalies [17]. In Egypt, GRACE revealed rapid depletion rates in arid aquifers [29], and similar applications in the Central Valley (USA) and Middle East confirmed its reliability in regions with limited ground observations [10]. GIS techniques, particularly buffer zone delineation, have been used to assess source vulnerability and land use impacts [39]. WHO recommends 300 m protective zones around wells [36]. Studies in Morocco, Turkey, and Côte d'Ivoire confirmed GIS effectiveness for managing such zones [12]; [14]l & Onuşluel Gül 19. LULC changes, especially urban expansion and agriculture, are strongly linked to groundwater contamination, with impacts like nitrate leaching and reduced recharge capacity [20, 22].

To enhance decision-making, integrated approaches combining satellite data, GIS, and field data are increasingly promoted [2, 13]. These tools help delineate groundwater potential zones and inform protective and rehabilitative strategies The novelty of this study lies in its integrated use of GRACE satellite-derived groundwater storage data, GIS-based land use/land cover (LULC) analysis, well spacing assessment, and spatial risk prioritization to evaluate groundwater vulnerability in Debre Markos, Ethiopia. Unlike prior studies that treat remote sensing, land use analysis, or hydrogeological data in isolation, this research offers a holistic, multi-scale framework that simultaneously addresses both quantity and quality threats to urban groundwater systems. This approach is particularly valuable for data-scarce environments, where traditional monitoring is limited or absent. Despite groundwater being the primary source of water supply in many Ethiopian towns, including Debre Markos, there has been limited integration of GRACE and GIS-based tools to assess well field sustainability and spatial risks. Existing research often focuses on either groundwater potential or contamination risk in isolation, such as the studies by [24] and [16], which overlook the cumulative impacts of land use encroachment, aquifer stress, and poorly regulated well siting. This study fills that gap by offering a spatially informed strategy for groundwater protection, combining temporal groundwater storage trends with spatially explicit land use and well interference analysis. Furthermore, the study addresses a pressing water resource challenge in Debre Markos, where overexploitation, rapid urbanization, and weak land use enforcement have contributed to declining well yields and increasing aquifer vulnerability. Through the integration of GRACE data, LULC and buffer zone mapping, and detailed local well data, this research provides actionable insights for improving water supply resilience. The findings emphasize the urgent need for implementing groundwater protection buffers, regulating land use within critical recharge areas, optimizing well spacing to reduce interference, and adopting remote sensing tools for ongoing monitoring and planning. Based on the identified gaps, this study aims to provide an integrated, multi-scale assessment of groundwater sustainability in Debre Markos. The specific research objectives are: (1) To quantify regional temporal trends in Terrestrial Water Storage (TWS) using GRACE satellite data from 2002 to 2017; (2) To analyze recent land use/land cover (LULC) changes (2014–2024) and assess encroachment within groundwater protection zones; (3) To evaluate well performance and correlate discharge

decline with surrounding LULC; and (4) To assess the risk of well interference through spatial analysis of well spacing. Ultimately, these analyses are synthesized to achieve a fifth, overarching objective: (5) To develop a spatial risk prioritization map for the well fields that integrates the findings on regional storage trends, LULC-driven vulnerability, and well-field management inefficiencies. This integrated framework is designed to bridge the gap between regional storage trends and local aquifer stress, providing a comprehensive and actionable basis for guiding groundwater protection and management strategies.

2 Material and methodology

2.1 Study area

Debre Markos is in East Gojjam, Amhara Region. The town relies heavily on groundwater from Wutren (9 wells) and Sentera (4 wells). The region features a humid climate, with average annual rainfall of 1308 mm and temperature of 16 °C [1]. According to the Central Statistical Agency (2021), the population projection figure of the town had been estimated 133,710. The office supervises the production and distribution of water to over 20,000 customers while safeguarding critical water sources. The total area of the focused study zone is approximately 29.5 km², encompassing the critical Wutren and Sentera well fields. Hydrogeologically, the area is characterized by Tertiary basaltic formations with low primary porosity. Consequently, groundwater availability is highly dependent on secondary fracture systems, which are often poorly connected or silted, limiting recharge efficiency. This geological setting, combined with dominant clay-rich soils of low permeability, creates a naturally constrained aquifer system Table 1 Fig. 1.

2.2 Data type collection and sources

2.2.1 GRACE data analysis

GRACE Tellus Level-3 Mascon solutions (RL06 M) from the Jet Propulsion Laboratory (JPL) were used for the period April 2002 to June 2017. These mascon solutions, with a spatial resolution of approximately 110 km, were chosen for their reduced leakage errors and because they do not require empirical destriping or Gaussian filtering. The data, provided as monthly Terrestrial Water Storage Anomalies (TWSA) in equivalent water

Table 1 Summary of methodology for assessing well discharge decline and land use impact

Data type	Method/tool/source	Purpose/description
GRACE TWSA Data (2002–2017)	NASA GRACE	• Analyze groundwater storage trends
Well coordinates, & discharge	Field Records	• Collected historical and current discharge data, well depths, and installation years from the local utility office.
Land Use/Land Cover (LULC) Map	Satellite image (Landsat OLI 8)	• Identify land use change/Performed supervised classification of 2014 and 2024 imagery to generate land use maps
Digital Elevation Model (DEM)	USGS	• Terrain (slope), soil texture analysis
GIS layers (shape files)	Field survey & secondary sources	• Mapping the study area, buffer zones delination
Jupyter Notebook, GEE	Python, Google Earth Engine Platform	• Generated spatial maps to visualize well interference, discharge loss, and encroachment severity, GRACE data analysis
FAO Soil portal	FAO	• Soil texture classification
Surficial geology of Africa	USGS	• Geological map classification

Well coordinates, discharge rates, and construction details were obtained from the long-term operational records of the Debre Markos Water Utility

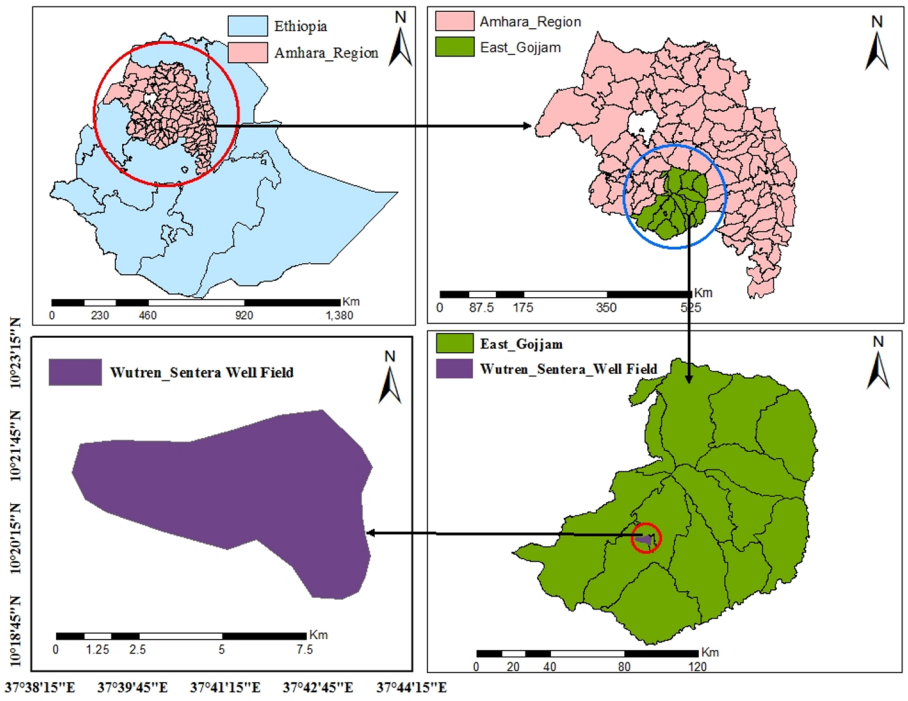


Fig. 1 Geographic location map of the study area

height (cm), were extracted for the study area. To isolate Groundwater Storage Anomalies (GWSA), the soil moisture and surface water storage components from the Global Land Data Assimilation System (GLDAS NOAH-2.1 model) were subtracted from the GRACE-derived TWSA using the formula: *GWSA = TWSA - (Soil Moisture + Surface Water)*. The temporal trends were then visualized and analyzed to understand long-term groundwater dynamics.

A recognized limitation of this approach is the coarse spatial resolution of GRACE (~110 km), which means the derived storage anomalies represent an average over a large area and may not capture intense, localized depletion in the well fields [3]. Furthermore, while GLDAS is widely used, its performance in representing soil moisture for the specific highland conditions of Ethiopia carries inherent uncertainties. It is important to note the temporal mismatch between the GRACE data period (2002–2017) and the LULC analysis (2014–2024). The GRACE period was selected to utilize the full, consistent record of the original GRACE mission, providing a 15-year baseline of regional groundwater storage trends. This baseline is crucial for understanding the longer-term hydrological context against which the more recent, intensifying local land-use pressures (captured by the 2014–2024 LULC data) are acting.

2.2.2 LULC classification

Land use/land cover data for the town were derived from Landsat 8 OLI (Operational Land Imager) imagery for the years 2014 and 2024 (Path 169, Row 53). Level-1 C1 Landsat 8 images were obtained from the United States Geological Survey (USGS) EarthExplorer platform (https://earthexplorer.usgs.gov). Supervised classification was performed using ArcGIS 10.1 software, utilizing bands 4 (red), 3 (green), and 2 (blue) to produce false-color composites [9]. The classification process generated thematic maps

depicting LULC changes over the study period. The land cover was categorized into four classes: agricultural & bare land, built-up area, forest, and grassland.

2.3 GIS buffer and risk analysis

The risk scores were assigned based on established literature concerning groundwater contamination potential. Built-up areas (score = 3) pose a high risk due to point-source pollutants from sewage, fuel, and chemicals, alongside reduced recharge from impervious surfaces [37], combined with a significant reduction in natural recharge caused by impervious surfaces [15]. Agricultural land (score = 2) represents a moderate risk primarily from non-point source pollution like nitrate leaching from fertilizers [22]. Forest and grassland (score = 1) are considered low risk as they promote infiltration and generally involve minimal chemical application [19]. It is important to note that the 300 m buffer is a generalized protective standard. A more accurate, hydrogeologically-defined protection zone would require site-specific vulnerability assessment, for instance using a DRASTIC model, which was beyond the scope of this study but is recommended for future work.

2.4 Discharge performance

Well discharge trends were analyzed and compared with their corresponding design discharge values to assess performance and sustainability. In addition, spatial heatmaps were generated to visualize and identify potential zones of well interference, highlighting areas where overlapping cones of depression may affect groundwater extraction efficiency.

2.5 LULC classification accuracy assessment

The accuracy of the supervised LULC classifications for 2014 and 2024 was assessed using a confusion matrix based on ground truth data collected from high-resolution Google Earth imagery and field knowledge. For the 2014 map, the overall accuracy was 88% with a Kappa coefficient of 0.84. For the 2024 map, the overall accuracy was 91% with a Kappa coefficient of 0.88. These values indicate a substantial agreement between the classified maps and the reference data, confirming the reliability of the LULC data for subsequent analysis.

3 Results

3.1 Temporal changes in terrestrial water storage (TWS) from GRACE (2002–2017)

Figure 2 presents the temporal variability of Terrestrial Water Storage (TWS) over Debre Markos well field using GRACE satellite data from three processing centers: CSR, GFZ, and JPL. Time-series plot showing Strong seasonal fluctuations are evident, with significant recharge events and depletion phases occurring over the 15-year period. The data show consistent seasonal patterns with high TWS values during wet seasons (peaking at approximately + 15 cm) and lower values during dry seasons (dropping to nearly − 12 cm). While there is no strong evidence of a sustained long-term decline or increase in storage, interannual variability is clearly observed. But, these trend does not show a more consistent long-term gain or loss. Because Notable recharge years include only 2007 (15.35 cm/year), 2008 (13.00 cm/year), 2012 (14.63 cm/year), and 2014 (15.8 cm/

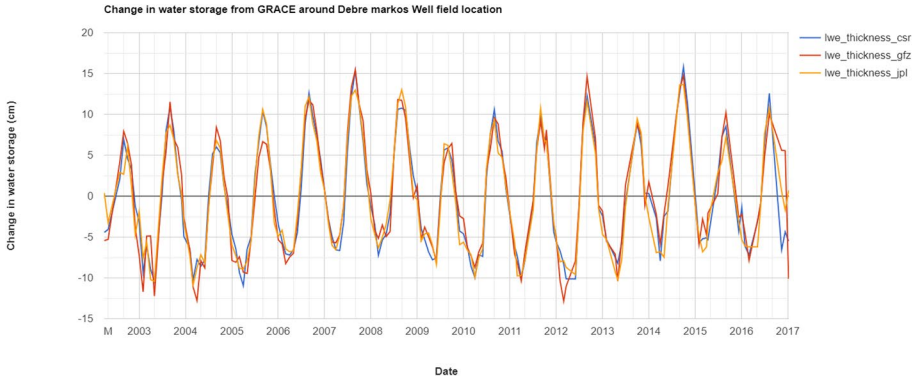


Fig. 2 Change in water storage from GRACE satellite data around well field (2002–2017)

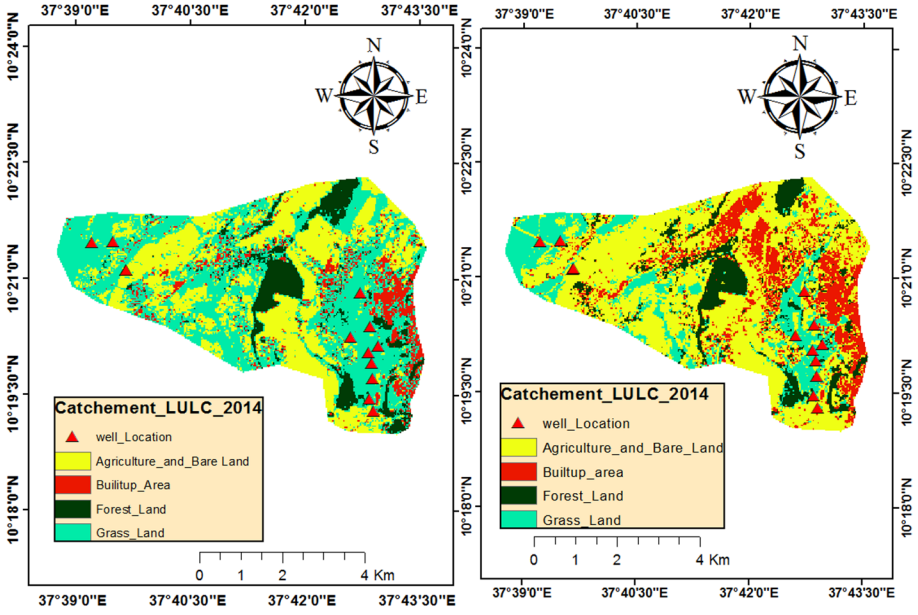


Fig. 3 Land use land cover change map of the study area from 2014 & 2024

Table 2 Land use land cover percentage change of the study area from 2014–2024

	2014	2024	Increment
Agriculture land	35.14%	53.96%	34.88%
Built up area	8.24%	16.47%	50%
Grass land area	46%	17.8%	–61.3%
Forest land area	10.62%	11.76	0.37%

year), while the most severe depletion occurred in 2012, with a maximum loss of 12.86 cm/year.

3.2 Land use change (2014–2024)

Figure 3 shows the classified images and the land cover changes for the years 2014, and 2024. The total classified area for each thematic map was 32.3km^2 Table 2.

The land use analysis revealed significant changes over the study period. Agricultural land increased by 34.88%, expanding from 35.14% to 53.96% of the total area. Similarly, built-up areas grew by 50%, rising from 8.24% to 16.47%. In contrast, grassland coverage

declined sharply by 61.3%, decreasing from 46% to 17.8%. These shifts indicate a reduction in natural recharge zones and suggest a heightened risk of contamination in the area.

3.3 Spatial arrangement of Wutren and Sentera well fields

The spatial layout of the wells in the Wutren and Sentera well fields is illustrated in Fig. 4.

The Sentera wells are located in the eastern part of Debre Markos, while the Wutren wells are situated to the southern. The map shows that Sentera wells are more densely clustered, particularly Wells 6, & 13 and also well 1, and 11, indicating potential spatial interference. In contrast, Wutren wells such as Wells 5 and 8 are more widely spaced. This distribution provides a visual basis for evaluating well interference, land use interactions, and protection zoning.

3.3.1 Buffer zone encroachment

High-risk land use types, specifically agricultural and built-up areas, dominate the protection zones surrounding many wells. Within the 300-meter buffer zones, these land uses collectively cover more than 50% of the area. Notably, significant encroachment of such high-risk land uses was observed in close proximity to Sentera Well_1 & Well_11 and Well_6, and also Wutern well field Well 10 & Well 11, highlighting increased vulnerability of these wells to contamination and may reduced recharge potential [11] Fig. 5.

3.3.2 Groundwater discharge decline patterns in relation to surrounding LULC

The land use and land cover (LULC) patterns within a 300-meter buffer zone around wells in the Sentera and Wutern well fields were assessed for the year 2024. In the Sentera well field, significant discharge declines were observed at Well 13 (30.0 l/s), Well 6

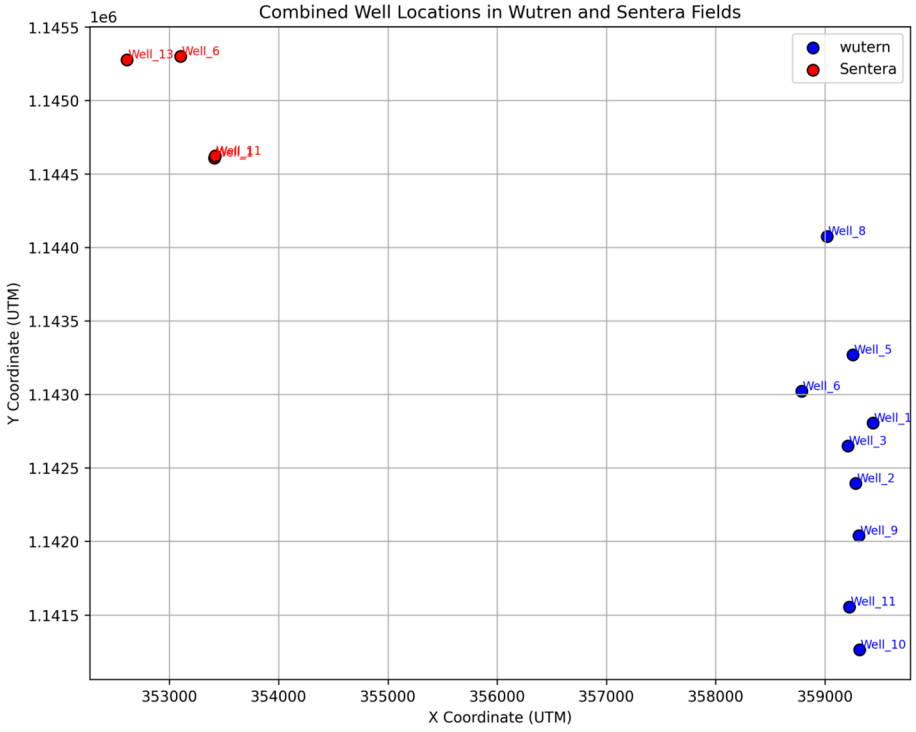


Fig. 4 Spatial distribution of wells in the Wutren and Sentera well fields

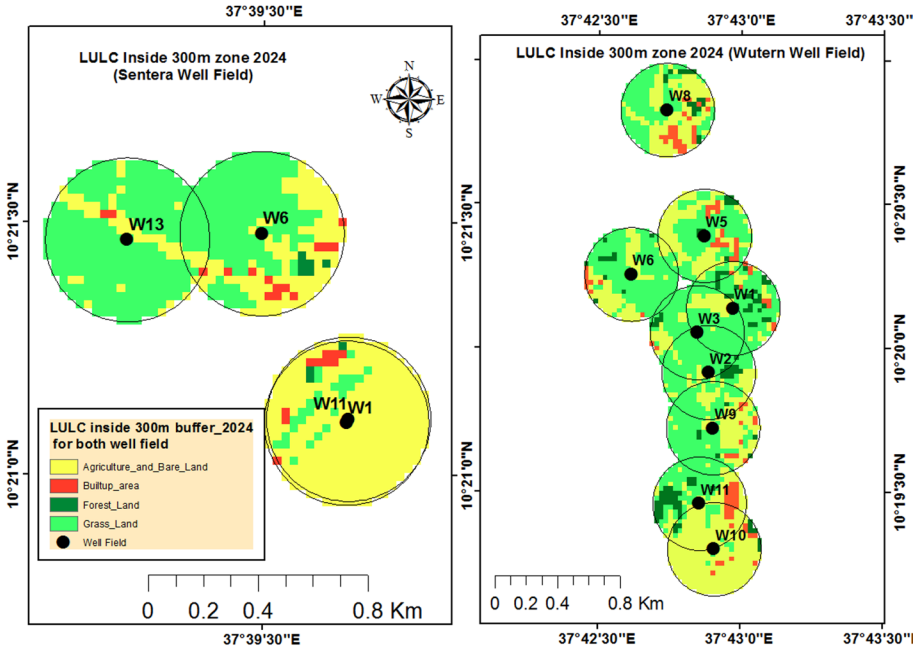


Fig. 5 Spatial Distribution of Land Use Types within Protection Buffer Zones (300 m)

(15.0 l/s), Well 11 (9.0 l/s), and Well 1 (6.0 l/s). These wells are located in zones primarily dominated by agricultural and bare land, with some patches of built-up areas. The surrounding landscape shows fragmented forest and grassland cover. In contrast, wells in the Wutern well field demonstrated relatively lower discharge declines. For instance, Well 8 and Well 3 showed minimal discharge reductions of 0.2 l/s and 0.5 l/s, respectively. These wells are located in areas predominantly covered by forest and grassland, with fewer built-up and agricultural patches. Moderate declines were noted at Wells 9, 1, 2, and 5 (ranging from 2.0 to 4.0 l/s), which are situated in more mixed-use landscapes. These spatial trends indicate variation in discharge decline among wells based on surrounding land cover types Fig. 6.

The above bar chart illustrating the decline in groundwater discharge (in liters per second) for individual wells in the Sentera and Wutren well fields. Higher discharge reductions are observed in Sentera wells, particularly in W_13 and W_6, compared to relatively lower reductions in Wutren wells.

3.3.3 Statistical correlation for well discharge decline

To quantitatively assess this relationship, a Pearson correlation analysis was conducted. The results revealed a very strong, statistically significant positive correlation between the percentage of high-risk land use (agricultural and built-up areas) within the 300 m buffer zones and the percentage decline in well discharge ($r = 0.79$, $p = 0.001$). This provides robust quantitative evidence that wells surrounded by more intensive anthropogenic land uses experience substantially greater reductions in yield Table 3.

3.4 Geological and soil constraints

3.4.1 Geological conditions

The geologic assessment indicated that the Wutren and Sentera well fields are primarily underlain by Tertiary igneous formations (Ti), consisting mainly of basalt and intrusive

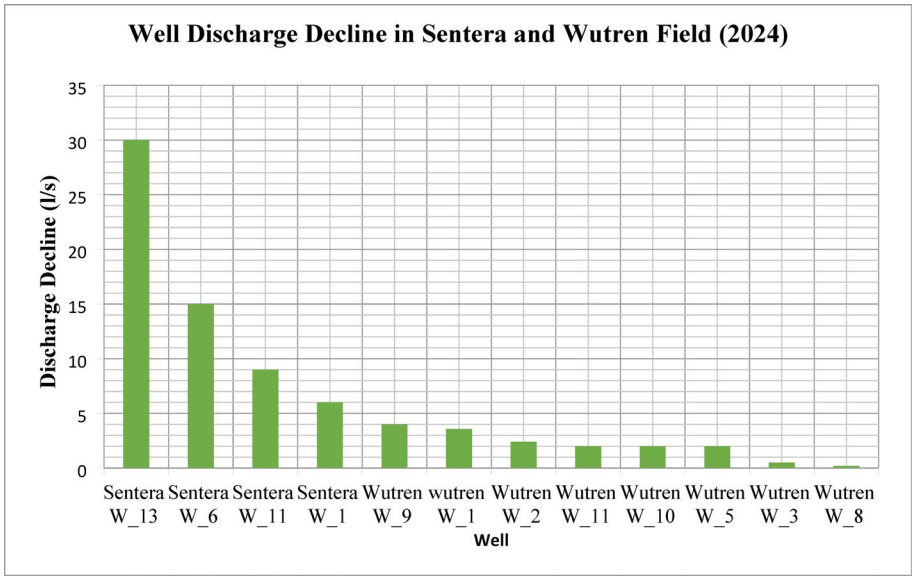


Fig. 6 Well Discharge Decline Across Sentera and Wutren Fields in 2024

Table 3 High risk land use well discharge decline for stastical correlation

Well ID	% High-Risk Land Use	% Discharge Decline
wutern_W1	59%	64.16%
wutern_W2	44%	48.00%
wutern_W3	15%	16.67%
wutern_W5	61%	66.67%
wutern_W6	2%	0.00%
wutern_W8	6%	2.78%
wutern_W9	36%	40.00%
wutern_W10	26.00%	28.57%
wutern_W11	15.00%	16.67%
Sentera_W1	28.00%	31.58%
Sentera_W6	39.00%	42.86%
Sentera_W11	39.00%	25.00%
Sentera_W13	39.00%	100.00%

rocks. These formations exhibit low primary porosity, meaning that they have limited inherent capacity to store and transmit groundwater. Consequently, groundwater recharge in these areas relies heavily on secondary porosity features such as fractures and joints. However, in many locations, these fractures are poorly developed, silted, or clogged with clay and chemical precipitates, reducing their ability to transmit water. This condition contributes to inefficient recharge and declining well yields in the study area Fig. 7.

3.4.2 Soil condition

Soil texture analysis showed that the dominant soil type in both well fields is clay-rich, characterized by fine particles and very low permeability. The infiltration capacity of these soils is significantly limited, resulting in minimal groundwater recharge during rainfall events. Instead, a large proportion of rainfall becomes surface runoff, reducing subsurface water replenishment. The low permeability of clay soils also leads to

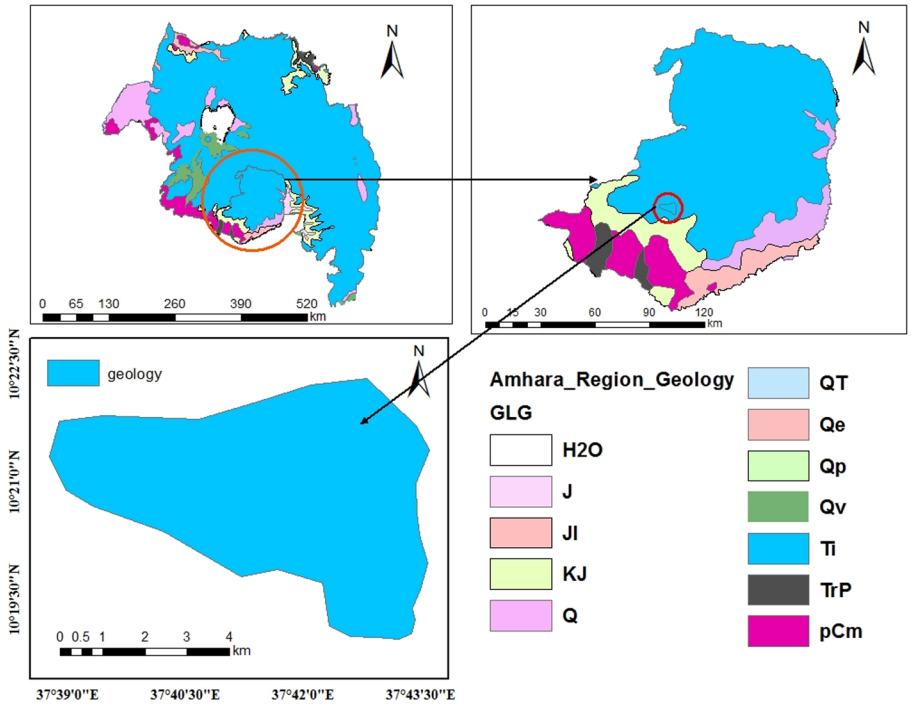


Fig. 7 Geological Map of Wutren and Sentera Well Fields

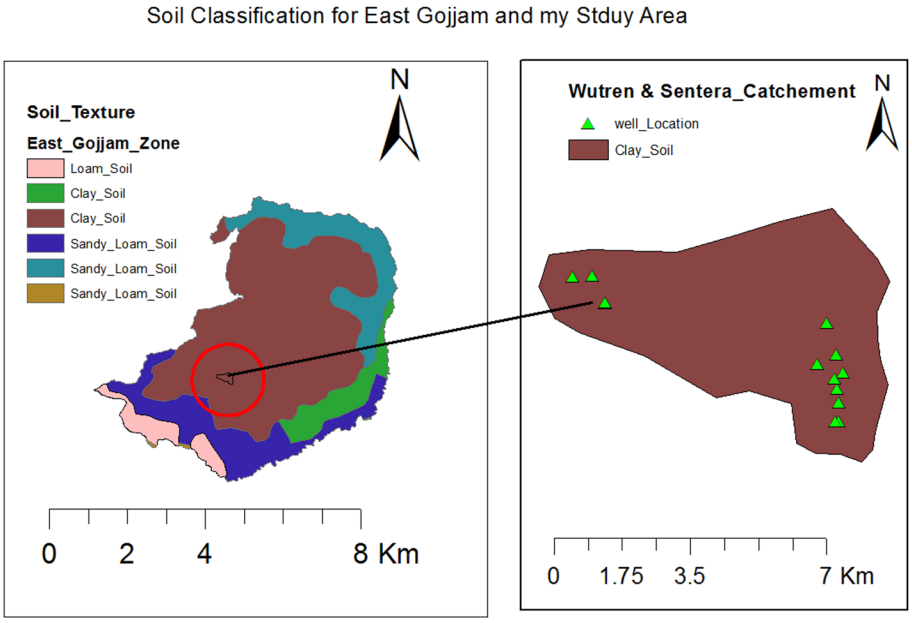


Fig. 8 Soil Texture Distribution Map of the Study Area

prolonged well recovery times and exacerbates the risk of groundwater depletion, especially in high-demand periods Fig. 8.

3.5 Slope condition and analysis

Slope analysis of the Wutren and Sentera well fields revealed that the majority of the wells are located on gentle slopes, predominantly less than 5%. These low-gradient areas

are favorable for groundwater recharge as they allow more time for surface water to infiltrate. In contrast, steeper slopes in the surrounding terrain promote rapid surface runoff, reducing infiltration opportunities and increasing the potential for soil erosion. This topographic variability directly influences recharge efficiency and supports the spatial prioritization of well protection based on slope suitability Fig. 9.

3.6 Risk score and priority wells

A GIS-based land use risk assessment was conducted by overlaying 300-meter buffer zones around each well and assigning weighted scores to different land use types based on their contamination potential. Built-up areas were classified as high-risk (score = 3), agricultural land as moderate risk (score = 2), and forest/grassland as low risk (score = 1).

The analysis revealed that several wells are situated in zones dominated by high- and moderate-risk land uses. Sentera Well_13, Well_6, and Well_11 received the highest risk scores, primarily due to significant encroachment by built-up and agricultural land

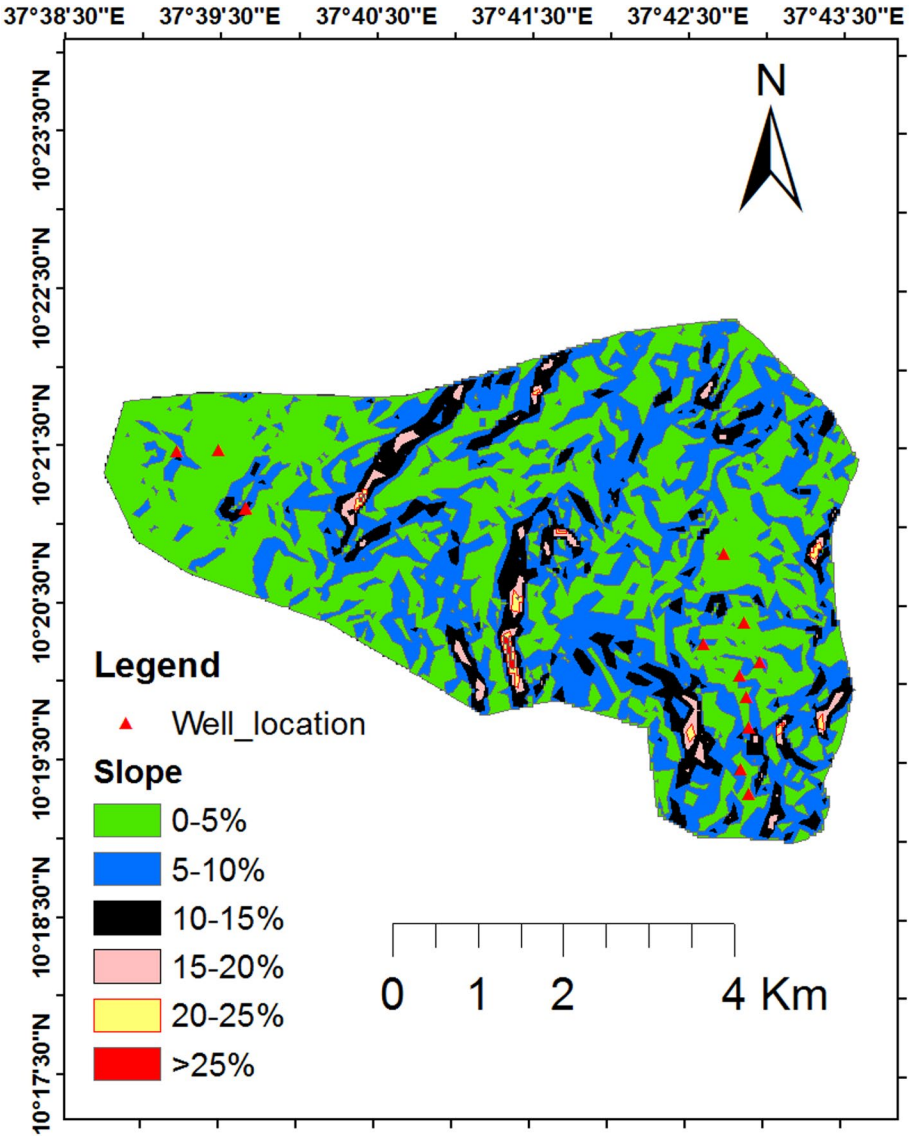


Fig. 9 Slope Map of Wutren and Sentera Well Fields Supportive Gentle Slopes (< 5%)

within their protection zones. These wells also showed the most substantial declines in discharge, indicating a strong correlation between land use pressure and groundwater vulnerability.

Wells such as Wutren Well_6 and Well_8, which are surrounded by low-risk land uses like forest and grassland, were categorized as low-risk and maintained relatively stable discharge levels. The spatial risk ranking serves as a practical tool for prioritizing well protection and rehabilitation interventions Fig. 10.

3.7 Well spacing and potential interference zones

Figures 11 and 12 present the spatial well spacing heatmaps for the Wutren and Sentera well fields, respectively. The distances between wells were calculated based on their geographic coordinates using the Euclidean method. In the Wutren field (Fig. 11), well distances vary widely, with the closest spacing observed between Well_2 and Well_3

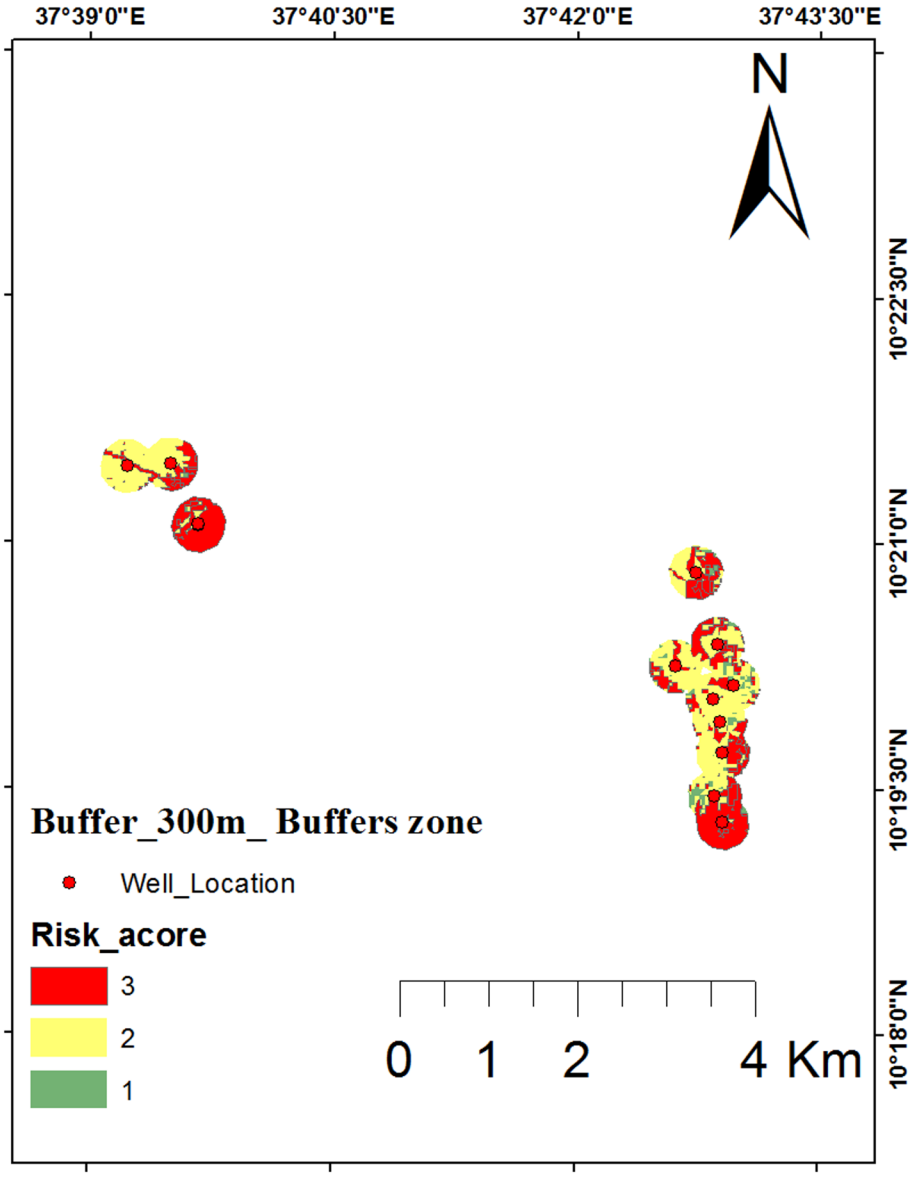


Fig. 10 Risk Score Map of Wutren and Sentera Wells Based on Land Use within 300 m Buffer Zones

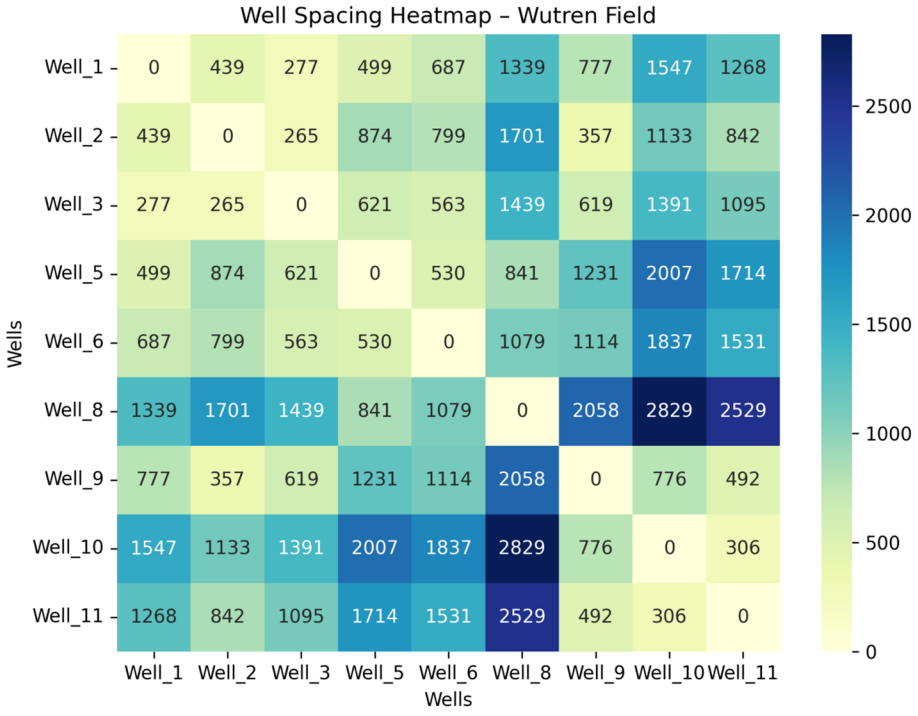


Fig. 11 Well Spacing Heatmap – Wutren Well Field

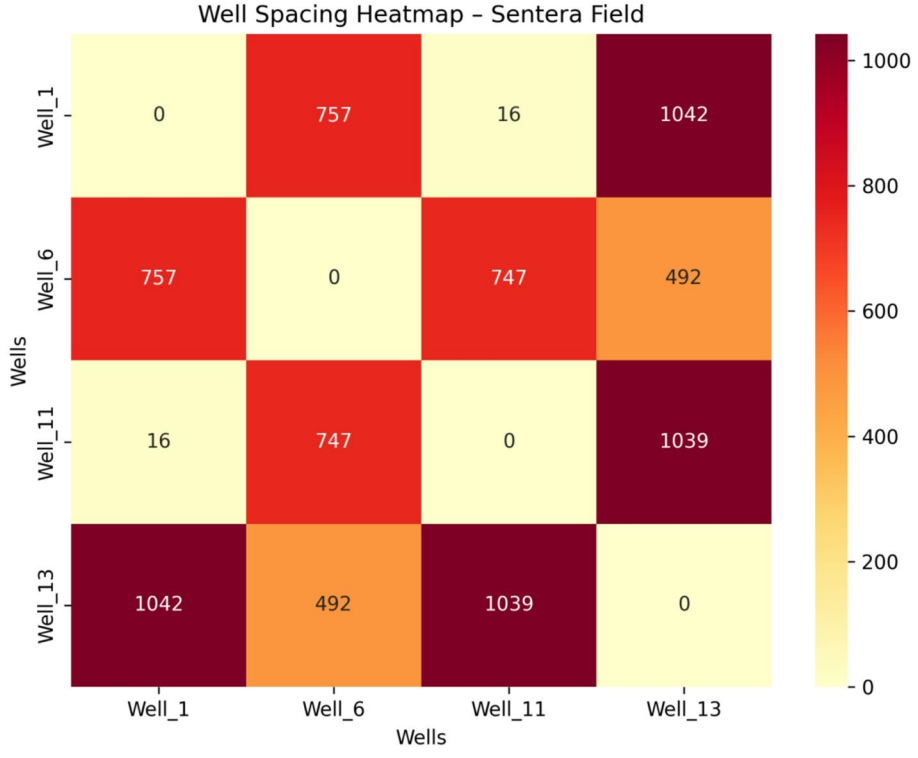


Fig. 12 Well Spacing Heatmap – Sentera Well Field

Table 4 Minimum well spacing distances within the Wutren and Sentera well fields. Pairs falling below the 300 m recommended spacing are highlighted

Well field	Well pair (Closest)	Distance (m)	Below 300 m?
Sentera	Well_1 - Well_11	16	Yes
Wutren	Well_1-Well_3	277	Yes
Wutren	Well_2 - Well_3	265	Yes

(265 m), and the farthest between Well_8 and Well_10 (2829 m). In the Sentera field (Fig. 12), Well_1 and Well_11 show the shortest spacing of just 16 m, indicating a very high risk of interference, while the maximum spacing exceeds 1000 m. These results indicate that several wells in both fields fall below the recommended minimum spacing of 250–300 m, which may lead to potential drawdown interference. The spatial heatmaps clearly highlight these zones with lighter shades (closer proximity), aiding in identifying vulnerable clusters Table 4.

4 Discussion

This study integrates GRACE satellite data, GIS-based land use analysis, well performance monitoring, and spatial interference assessment to evaluate groundwater sustainability in Debre Markos. The results reveal important patterns consistent with global and regional research, while providing new, localized insights for groundwater management.

4.1 Seasonal variability, long-term trends, and the critical scale mismatch

The GRACE-derived Terrestrial Water Storage (TWS) anomalies from 2002 to 2017 provide a vital regional perspective on groundwater dynamics in the Debre Markos area. The data from all three processing centers (CSR, GFZ, and JPL) show high consistency, revealing pronounced seasonal fluctuations driven by the region's monsoonal climate. These cycles are characterized by storage peaks during wet seasons (reaching up to + 15 cm) and troughs during dry seasons (dropping to nearly − 12 cm), reflecting the annual cycle of recharge and discharge. While the data does not indicate a statistically significant, sustained long-term decline in storage at this regional scale, it reveals critical periods of episodic stress. The most severe depletion event occurred in 2012, with a loss of −12.86 cm/year, likely associated with drought conditions and increased abstraction. This pattern of high interannual variability, consistent with findings in other parts of the Upper Blue Nile Basin [5, 35], underscores the aquifer's sensitivity to climate variability. However, this regional picture of cyclical resilience stands in stark contrast to the severe and persistent discharge declines documented at individual wells in the Sentera and Wutren fields. This apparent contradiction is a classic manifestation of a scale mismatch between satellite observations and ground-based measurements. The GRACE mission, with a spatial resolution of approximately 110 km, measures an integrated water storage signal averaged over a very large area (~ 11,000 km^2) [17]. This coarse resolution effectively "smoothes over" intense, highly localized depletion phenomena. The sharp, point-source declines in wells like Sentera W13 (30 l/s) and W6 (15 l/s) are diluted within the broader regional signal, which may include areas of stable or even increasing storage. The integration of our local-scale analyses resolves this contradiction and reveals the mechanisms behind the localized aquifer stress that GRACE cannot detect. The GIS-based well spacing analysis identified extreme clustering, with wells as close as 16 m apart. In such a configuration, the cones of depression from individual

wells significantly overlap, leading to mutual interference, accelerated drawdown, and a drastic reduction in yield that is confined to the immediate well field area. This effect is compounded by the geological and soil constraints identified in the study; the low-permeability, fractured basalt aquifer and clay-rich soils have limited capacity for rapid, widespread recharge, causing pumping to draw down local water levels rapidly without being quickly replenished from the broader aquifer system. Furthermore, the LULC and buffer zone analysis provides the link between human activity and the stressed wells. The strong statistical correlation ($r = 0.79$, $p = 0.001$) between high-risk land use (agriculture and built-up areas) and discharge decline demonstrates that the most affected wells are precisely those where contaminant loading is highest and natural recharge is most inhibited by impervious surfaces. This localized anthropogenic pressure further exacerbates the drawdown caused by poorly spaced wells. Therefore, the integrated assessment demonstrates that the GRACE data and the well performance data are not in conflict but are complementary. GRACE correctly indicates that the regional aquifer system is not in a state of catastrophic, widespread collapse. However, the local-scale GIS and well data reveal that within this regionally stable system, critical "hotspots" of extreme stress exist due to the synergistic effects of poor well siting, geological constraints, and intensive land-use encroachment. This finding powerfully underscores the limitation of relying on GRACE data alone for local groundwater management and validates the core premise of this study: that a multi-scale, integrated approach is essential to diagnose the true nature of groundwater sustainability challenges, distinguishing regional trends from critical local failures. This aligns with the assertions of [3] on the necessity of bringing GRACE down to earth with ground-based validation.

4.2 Impact of land use and buffer zone encroachment

Buffer zone analysis revealed substantial encroachment by agricultural and built-up land uses, with over 50% of the 300-meter buffer zones surrounding many wells occupied by high-risk activities. This finding is consistent with [20] and [22], who documented nitrate contamination and groundwater quality degradation linked to similar land use pressures in West Bengal and Tanzania. The increase in built-up area (from 8.24% to 16.47%) and reduction in grassland (from 46% to 17.8%) observed in Debre Markos highlights a rapid urbanization pattern threatening aquifer sustainability. While WHO, (2006) and [19] advocate for a 300-meter protective buffer, this study demonstrates that even where such guidelines exist, enforcement is weak. The encroachment trend mirrors findings in Morocco and Côte d'Ivoire [12, 14], where buffer delineation without land use regulation fails to prevent groundwater vulnerability.

4.2.1 Influence of land use and land cover on well discharge decline

The comparative analysis of land use/land cover (LULC) patterns and groundwater discharge trends across the Sentera and Wutern well fields highlights a significant relationship between anthropogenic activities and local groundwater depletion. In the Sentera field, wells experiencing the most substantial discharge reductions—particularly Well_13 (W13) and Well_6 (W6)—are located within 300-meter buffer zones dominated by intensive agricultural activities and built-up infrastructure. These findings align with prior research indicating that irrigated agriculture is a major driver of groundwater over-extraction [28], while urban land cover, through the expansion of impervious surfaces,

reduces infiltration and natural recharge [31]. The co-occurrence of these two land use types likely exerts a compounded stress on local aquifer systems, contributing to the sharp discharge declines observed in these wells. Conversely, in the Wutern well field, wells such as W3 and W8 surrounded largely by forest and grassland—show minimal discharge reductions. These vegetated areas are known to support enhanced recharge by promoting infiltration and limiting surface runoff [26]. This contrast supports the assertion that natural land cover plays a protective role in sustaining groundwater levels. Moreover, this observation is consistent with regional studies [35], that found forested landscapes to be associated with more stable well yields in highland East African settings. While previous studies have established broad regional links between land cover and groundwater variability [27, 28], they often lacked high-resolution, field-level validation. This study helps to fill that gap by providing well-specific evidence that links land use composition within localized buffers to measurable discharge outcomes. Furthermore, it builds upon the work of [3], who emphasized the limitations of satellite-based GRACE data in resolving local groundwater dynamics, by integrating LULC data and well discharge records to assess site-specific anthropogenic impacts. These findings underscore the critical need to integrate land use planning into groundwater resource management. Protecting and restoring natural vegetation around well fields, particularly in recharge-sensitive zones, may serve as a practical and cost-effective strategy for mitigating groundwater depletion. Therefore, this study contributes new insight into the role of land cover at the micro-watershed scale, reinforcing the urgency of harmonizing land development with hydrogeological sustainability.

4.2.2 Qualitative assessment of the R/n between LULC and well discharge decline

Visual analysis of land use and land cover (LULC) around the Sentera and Wutern well fields reveals a clear pattern linking LULC to groundwater discharge trends. In Sentera, wells such as W13 and W6, located near agricultural and built-up areas, showed significant discharge declines. These land uses are known to drive over-abstraction for irrigation and reduce recharge due to impervious surfaces [28]. Conversely, wells in the Wutern field—surrounded mainly by forest and grassland—exhibited more stable discharge. These cover types promote infiltration and recharge [10], suggesting a protective effect on groundwater. The qualitative spatial patterns are strongly supported by statistical evidence, which confirmed a very strong positive correlation between high-risk land use coverage and discharge decline ($r = 0.79$, $p = 0.001$). This highly significant relationship underscores that land-use encroachment is a primary driver, rather than merely a coincidental factor, in the observed aquifer stress. While the statistical correlation was performed, the spatial trends support findings from [27] and [3] on the importance of integrating LULC in groundwater assessments. This study helps fill a gap by qualitatively linking well-level discharge trends with local land use patterns—offering practical insights for managing groundwater in data-scarce areas.

4.3 Geological and soil constraints

The dominance of basaltic (Ti) formations with low porosity means groundwater recharge in the study area relies heavily on secondary permeability, such as fractures—a condition also noted in the Upper Blue Nile basin by [4] and [25]. However, unlike regions with well-connected fracture networks, this study identified poor fracture

connectivity and infill (e.g., clay or precipitates), contributing to aquifer inefficiency and well underperformance. Clay-rich soils further exacerbate recharge limitations by significantly reducing infiltration, as previously observed in [8] for parts of Debre Markos. This dual constraint of low-permeability geology and clay-rich soils creates a fundamentally different hydrogeological setting compared to the high-recharge volcanic aquifers of the Central Ethiopian Rift. The challenges observed in Debre Markos are, however, highly consistent with those documented in other parts of the Upper Blue Nile Basin underlain by similar Tertiary basalts, where groundwater availability is critically dependent on fractured zones [4, 25]. The spatial variability in well performance is fundamentally linked to the aquifer's geological heterogeneity. The Tertiary basalts have low primary porosity, making groundwater flow dependent on secondary fractures. Wells that intersect well-connected, open fracture networks will have higher yields and be more resilient. Conversely, the sharp discharge declines in wells like Sentera W13 and W6 are likely situated in zones where fractures are poorly developed, silted, or isolated. This heterogeneity explains why some wells fail rapidly under pumping stress while others maintain stable yields, highlighting that aquifer properties, not just extraction rates, control local groundwater sustainability.

4.4 Well spacing and analysis of Spatial interference

The heatmaps (Figs. 11 and 12) provide critical insights into the spatial arrangement and potential interference between wells in the Wutren and Sentera well fields. In the Wutren field, wells such as Well_2, Well_3, and Well_10 are situated closer than the minimum spacing of 250–300 m, forming dense clusters. This close spacing increases the likelihood of cone-of-depression overlap, leading to declining yields—an issue also reported by [32] in conflict-affected aquifers and [33] in high-demand areas of Poland. This clustering heightens the risk of overlapping cones of depression, which can lead to mutual drawdown effects and reduced well efficiency—a finding that aligns with the results of [6], who demonstrated that closely spaced wells are prone to hydraulic interference, particularly during peak extraction periods. Specially, the two Sentera well field reveals even more severe proximity issues, with wells like Well_1 and Well_11 located only 16 m apart. Such extremely tight spacing significantly elevates the risk of mutual interference, corroborating earlier findings by Shamsudduha et al.,(2011), who reported that improper well spacing in clustered configurations accelerates aquifer depletion and reduces sustainable yields. The potential for drawdown interference in such configurations may lead to reduced performance, increased operational costs, and long-term aquifer stress. In contrast, the two Sentera well field and most wutren well fields demonstrated better overall spacing, localized clustering near high-yielding wells like Well_6 and Well_11 suggests that even modest spatial interference, when combined with land use pressure and low recharge, can contribute to significant discharge decline. This finding contrasts with [2] and [13], who emphasized that optimized well spacing can sustain yields even in constrained hydrogeological settings—an approach not yet practiced in Debre Markos, highlighting the need for planning reform. These visual observations reinforce the importance of strategic well placement and adaptive groundwater management. As supported by [18], maintaining appropriate well spacing and monitoring interference zones are key to optimizing groundwater extraction and ensuring long-term aquifer sustainability. Based on the heatmap analysis, it is recommended that densely

clustered wells be managed through staggered pumping schedules or phased operations, particularly in the Sentera field. Where feasible, future well siting should consider spatial optimization algorithms or simulation-based planning, as advocated by [21], to minimize the risk of interference.

4.5 Risk mapping for prioritization

Integrating discharge data and land use risk scores enabled the identification of priority wells requiring urgent protection and rehabilitation. Wells surrounded by intensive agriculture and built-up areas—such as Sentera Well_13 and Well_6—showed the highest vulnerability, reflecting a practical application of vulnerability mapping approaches similar to those by [23]. This approach offers a replicable and straightforward method for data-limited settings, complementing large-scale satellite assessments [38]. Wells such as Sentera Well_13 (100% yield loss) and Well_6 were ranked as high priority, while Wutren Well_6 and Well_8—surrounded by low-risk land uses and gentle slopes—were categorized as low priority. This practical framework complements previous work by [38] on GRACE-driven groundwater vulnerability visualization and emphasizes the importance of integrating physical, spatial, and socio-economic indicators for local decision-making.

4.6 Synthesis of an integrated assessment

This study was founded on the premise that an integrated approach is necessary to fully diagnose groundwater sustainability challenges. The individual methodological strands—GRACE-based storage trends, LULC change, well spacing, and geological analysis—collectively reveal a more nuanced and actionable narrative than any single method could provide.

The GRACE satellite data provided the essential regional context, indicating a groundwater system characterized by strong seasonal and interannual variability without a consistent long-term declining trend. This suggested that, at a macro-scale, the aquifer is in a state of precarious balance. However, this regional perspective alone would lead to a false sense of security. The local-scale analyses exposed the acute stresses operating beneath this broad average. The severe discharge declines in wells like Sentera W13 and W6 were not reflected in the GRACE signal due to a fundamental scale mismatch; the intense, localized depletion was averaged out over the satellite's large footprint.

It was the integration with GIS and field data that diagnosed the cause of this local stress. The spatial well spacing analysis identified the physical mechanism of overexploitation: critically close well spacing (as little as 16 m) leading to overlapping cones of depression and mutual interference. The geological and soil assessment explained the aquifer's inherent vulnerability to this stress, revealing a low-permeability, fractured system with inefficient recharge capacity. Finally, the LULC and buffer zone analysis quantified the anthropogenic pressure, demonstrating a strong statistical link between high-risk land uses and well performance decline, thereby identifying the zones where contamination risk and recharge reduction are highest.

Therefore, the integration of methods demonstrates that the problem in Debre Markos is not one of regional aquifer collapse, but of critically located hotspots of acute stress. These hotspots are created by the synergy of three factors: (1) sub-optimal infrastructure planning (poor well siting), (2) inherent physical vulnerability (low-permeability geology and soils), and (3) intensifying anthropogenic pressure (land-use encroachment). The

spatial risk prioritization map is the direct product of this integration, translating the combined findings into a practical tool for managers. It highlights that wells like Sentera W13 and W6 are high-priority not for one reason, but because they represent a convergence of all these negative factors. This holistic understanding is critical for moving beyond generic conservation measures to implementing targeted, effective interventions that address the specific drivers of groundwater vulnerability in Debre Markos.

5 Conclusion

This study revealed that groundwater resources in the Wutren and Sentera well fields of Debre Markos are increasingly threatened by both natural and human-induced factors. The integration of GRACE satellite data, GIS-based buffer analysis, and field discharge measurements demonstrated a consistent decline in groundwater storage over the past two decades, largely driven by land use and land cover (LULC) changes. Agricultural expansion and urban encroachment within critical well protection zones—particularly within the 300-meter buffers—have significantly affected natural recharge processes. These impacts are compounded by the region's geological characteristics, such as low-permeability clay soils and fractured basalt formations, which limit infiltration and recharge capacity. Additionally, poor spatial arrangement and clustering of wells have led to interference effects and declining yields, particularly in the Sentera well field. Given these findings, to ensure the sustainability of groundwater in such rapidly urbanizing areas, it is recommended that comprehensive land use planning, groundwater protection policies, and well field management strategies be developed and implemented. Emphasis should be placed on improving land cover conditions that support natural recharge, enhancing monitoring systems through the use of remote sensing and GIS tools, and promoting awareness and cooperation among stakeholders. While this study provides valuable insights, it also faced limitations. The spatial resolution of GRACE data is too coarse to detect fine-scale well-level changes, and the 2002–2017 timeframe excludes recent developments in climate variability and urban expansion. Moreover, the lack of comprehensive water quality data limits the assessment of groundwater contamination risks. Future research should incorporate high-resolution remote sensing, detailed hydrochemical analysis, and predictive groundwater modeling that accounts for both environmental and socio-economic variables. Addressing these gaps will not only enhance the scientific understanding of groundwater dynamics but also support the design of more resilient and equitable water management strategies for Debre Markos and similar water-stressed regions in Ethiopia. The reliability of the analysis is also contingent on the quality of historical well data obtained from the water utility, which may contain unquantified measurement uncertainties. Furthermore, the study period for GRACE data (2002–2017) does not fully overlap with the LULC analysis (2014–2024). While the GRACE data provides crucial context on the historical storage trend, the LULC and current well performance data reflect the intensifying anthropogenic pressures in the most recent decade.

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Endeshaw Nibret Abeje, **Tade Mule Asrade and Fasikaw Fentie Cherie. The first draft of the manuscript

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Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. The GRACE satellite data used in this study are publicly available from NASA's Jet Propulsion Laboratory (https://grace.jpl.nasa.gov/). Landsat imagery was obtained from the USGS EarthExplorer platform (https://earthexplorer.usgs.gov). Soil data were acquired from the FAO Soil Portal (https://www.fao.org/soils-portal), and geological maps were derived from the USGS publication on the Surficial geology of Africa (https://doi.org/10.5066/P9RGTRMC).

Declarations

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