

Impact of Urban expansion on groundwater and land use/land cover in Duhok city: A GIS and remote sensing approach

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Abstract: Unplanned urban development and population increase have notable impact on the land-use changes and groundwater dynamics. This research analyzes the impact of land use/land cover (LULC) changes and its correlation with the groundwater levels in Duhok city, Iraq, over the period of 10 years (2015–2025) by integration the Geographic Information Systems (GIS) with Remote sensing techniques. The Sentinel 2 imagery were used for LULC mapping, while 83 wells were monitored for groundwater trends. The results showed notable trends of changes in land features. Noticeable regions of vegetation were declined from 788.17 km² to 675.39 km². However, significant regions of built-up and barren lands were expanded by 27.5 km² and 84.73 km², respectively. Moreover, the groundwater depth, static water level, and dynamic water level showed negative increases in Duhok, Semel, and Zawita regions. The results of NASA GRACE Satellite also aligned with the ground real well data, highlighting the declining pattern of groundwater storage availability in the region for the period of 10 years (2015-2025). Results of this investigation provide valuable insights for policy makers and government entities to implement sustainable measures such as green infrastructure to preserve the groundwater resources in the region.

Keywords: Groundwater Level Change, Land Use/Land Cover (LULC) Change, Remote Sensing, GIS Analysis, Duhok

1. Introduction

Groundwater is a crucial component of the Earth's hydrological cycle, serving as a significant source of freshwater for various uses, including domestic, agricultural, and industrial purposes. Groundwater is the water found beneath the earth's surface at varying depths, which may be a few meters deep in some places, or hundreds of meters deep in others (Kuang et al., 2024; Ndehedehe et al., 2024; Giordano, 2009). This water is found within the pores of rocks and soil layers. The main sources of groundwater include rainfall, snowfall, or perennial or seasonal rivers, which facilitate water infiltration into the ground. The process of infiltration depends on the geology of the area, as the looser and more porous the soil, the more it facilitates water infiltration, resulting in a stable reservoir over time. Additionally, wells are one of the most common methods used to obtain groundwater. Wells can be shallow or deep depending on the depth of the groundwater reservoir (Ojoawo & Adagunodo, 2023, Lachassagne, 2020). The 30% of world's freshwater resources is based on the groundwater and which is extensively used for domestic, industrial, and agricultural purposes, also 80% of the world's food depending on groundwater (Lachassagne, 2020, Barceló, 2022). To ensure the long-term availability and quality of groundwater resources, it's essential to implement sustainable management practices (Ojoawo & Adagunodo, 2023).



Multiple studies have described the relevance of different hydrological aspects, geomorphology, geology, slope, soil cover, drainage density, surface temperature, land use/land cover and controlling groundwater potential in any area. Yet, the extent of their effects may vary from place and time (Kumar et al., 2016). These can be studied using satellite images and geospatial techniques that provide detailed information about a large area of the Earth's surface in a very short time (Patra et al., 2016). Geographic Information System (GIS), Remote Sensing (RS), Global Positioning Systems (GPS) and various statistical software have been widely used recently in Iraq and Kurdistan region of Iraq to monitor and study the change in groundwater levels, land use/land cover dynamics, and the overuse of surface water which has a significant impact on groundwater and is affected by climate change (Hameed et al., 2015; Mohammed and Sayl, 2021; Sangawi, et al., 2023; Sulaiman and Mustafa, 2023). Despite of the impact of rapid urbanization and declined groundwater in the region, no investigations were conducted in Duhok center and Zawita district to analysis this challenge. Therefore, Dohuk was chosen based on its importance in terms of population growth in the urban area, land use, and geology of the area, to better understand the impact of rapid urbanization on groundwater resources.

Urbanization have significant impact on changes in LULC which is caused by the natural and human activities (Nath, et al., 2021; Pokhariya, et al., 2022; He et al., 2006). Having accurate maps of LULC aid urban planners and policy-makers for better decision making and sustainable management (Pham et al., 2011). The temporal analysis using satellite imagery have been used wildly for land use changes and urbanizations which offers notable insights about the extent of development more efficiently compared to traditional methods and by using update satellite imagery the development can be tracked continuously (Chomani and Pshdari, 2024). GIS and remote sensing techniques play huge role in facilitating this process, specifically in developing countries and regions with rapid urbanization (Wang, et al., 2023). The impact of LULC changes and urbanization on the groundwater levels widely documented in the world regions, such as India (Nath, et al., 2021), Tanzania, (Olarinoye, et al., 2023), Afghanistan (Zaryab et al., 2022), and other parts of the world (Yadav, 2023). This investigation provides notable insights about the urbanization and land use patterns and its correlation with the groundwater variations in Duhok region. The rapid urbanization was witnessed in Duhok region which had notable impact on the agriculture and environment of the surrounding areas as large coverage of agricultural fields transformed to built-up areas due to the economic development and increased population, leading to decreased groundwater level as highlighted by literature (Mohammed and Gruehn, 2016).

The objective of this investigation is to assess the impact of urban development in Duhok region on the groundwater fluctuation using the integration of geospatial technologies such as GIS and remote sensing techniques. This study provides valuable insights about the primary causes of the groundwater deviations and its causes, also highlights the significance of LULC changes and its impact on the environment and groundwater resources.

2. Materials and methods:

2.1. Study area

The study area for this investigation is Duhok city which is located in north of Iraq. In this research, the number of wells in the Dohuk region, located in northern Iraq, was studied during (10 years) from 2015 to 2025. The study area, located between latitudes 36°45'N–37°03'N and longitudes 42°37'E–43°21'E. Recently, the drilling of wells in this region has increased for many reasons, including the reduction in the amount of rain and snow falling during the past 10 years, and climate change, including rising temperatures and humidity. Moreover, the most common causes of increased number of wells are urban expansion and the large and unexpected population growth in the Dohuk region, as well as the increase in industrial facilities, and the extensive exploration of groundwater for agriculture and other domestic purposes, which affects the continuous decrease in the groundwater level. It is known that Dohuk city is located between two mountain slopes (Mount Zawa, Mount Shada) and urban expansion is longitudinal. The wells that were chosen for the study are located in mountainous, undulating, and flat areas (with different terrain). Consequently, the depth of well drilling and the quantity of groundwater are different. The Duhok Governorate in the Kurdistan Region of Iraq, particularly Duhok city, Semel, and Zawita, presents a compelling study area for investigating land use/land cover (LULC) changes and groundwater trends. In the past years, due to the rapid urbanization and population growth, significant areas of agriculture were converted to impervious surfaces which have impact on the groundwater recharge (Ibrahim, 2017). This urbanization also have impact on changing the surface

runoff which influence the surface water management and quantity of groundwater, threatening the communities which rely on groundwater for drinking in their daily life (Mishra, et al., 2014). The study area illustrated in (Fig. 1).

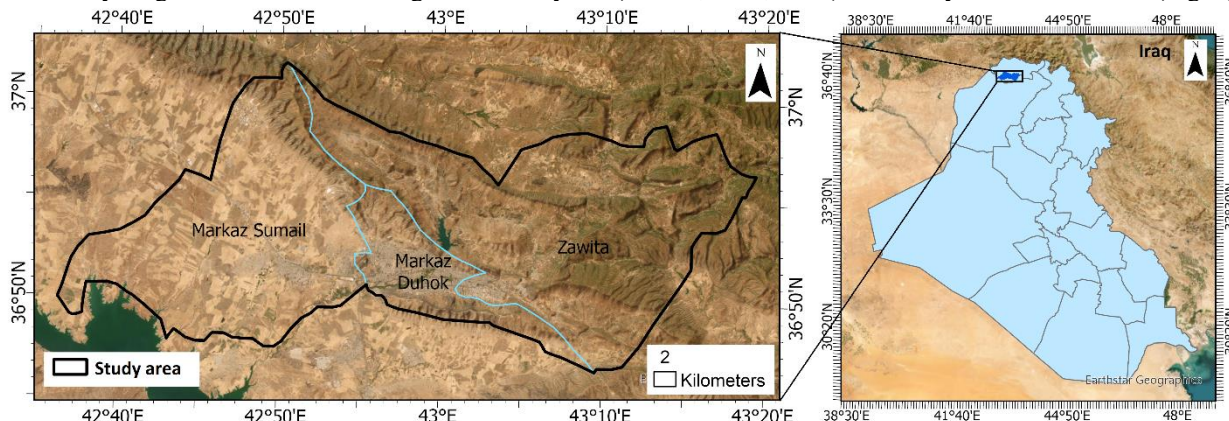


Fig. 1. The location of the Study area, Duhok center, which is located in north of Iraq.

2.2. Datasets

For generating the LULC map for the study area between 2015 and 2025, two satellite imagery from Sentinel 2 were used in this study. The imagery were downloaded from Google Earth Engine platform, which masked for the study area and preprocessed to include in ArcGIS Pro version 3.5, then georeferenced. Moreover, the location and details of wells were collected in the study area for groundwater analysis from Directorate of Ground Water and Wells which consisted of 84 wells that used for irrigation, industrial and domestic used in Duhok, Semel, and Zawita regions. Furthermore, average rainfall data for between 2010 and 2024 were collected from Duhok Directorate of Meteorology and Seismology for better analysis of the groundwater conditions in the region. Furthermore, to compare the ground truth groundwater level fluctuations to the satellite data, the Equivalent liquid water thickness were downloaded from GRACE using the NASA Jet Propulsion Laboratory which offers valuable insights about the groundwater. The detailed datasets were presented in Table 1.

Table 1. The detailed characteristics of the utilized data.

Dataset	Time (years)	Data	Source
GRACE Monthly Mass Grids Release 6.3 Version 4 - Global Mascons	2002 - 2024	Equivalent liquid water thickness in centimeters.	NASA Jet Propulsion Laboratory https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/
Sentinel 2 (10 m resolution)	2015 and 2025	LULC maps	Google Earth Engine (GEE)
Well data	2010 to 2025	Groundwater level	Directorate of Groundwater and Wells
Meteorology data	2010 to 2025	Rainfall map	Duhok Directorate of Meteorology and Seismology

2.3. Land use land cover (LULC)

The land use features and their changes have significant contribution on the hydrological characteristics of the region and groundwater resources. For that, two thematic maps were generated in this study from 2015 to 2025 using Sentinel 2 imagery. The Support Vector Machine (SVM) classifier from ArcGIS Pro version 3.5 was used to classify and process the satellite imagery to four classes, such as Built-up, bare land, water, and vegetation. The reason of choosing SVM and Sentinel 2 imagery was due to the superior performance of SVM with Sentinel 2 imagery in identifying accurate built-up region in literature (Chomani and Pshdari, 2024). SVM is a non-parametric supervised machine learning techniques which is based on finding maximum margin among the different classes in the pixel values of the satellite imagery. SVM is based on the statistical learning which introduced first by Vapnik in 1979, which is known for its effectiveness for high dimensional data with low noise (Basheer et al., 2022). Moreover, for assess the accuracy of LULC results, the kappa coefficient (KC) model applied in this study for both results of LULC in 2015 and 2025. For the ground truth data, the stratified randomised sampling points technique was utilized to select the ground points randomly across the study area, and the results of KC showed acceptable accuracy with 86.4% (LULC 2015) and 89.5% (LULC 2025), (Table 2).

Table 2. The kappa coefficient agreement.

Value of Kappa	Classes
< 0.2	Bad
0.21 – 0.4	Reasonable
0.41 – 0.6	Adequate
0.61 – 0.8	Good
> 0.8	Very Good

The KC and overall accuracy (OA) in this study were measured utilizing the equation 1 and 2, respectively (Chomani and Pshdari, 2024):

$$UA = \frac{CR}{TR} \quad (1)$$

Where UA is the user accuracy, and the CR is the amount of rows which correctly identified, while the TR is the sum of all pixels in the same row.

$$PA = \frac{PC}{TC} \quad (2)$$

Where PA is the Producer's accuracy, PC is the total number of correctly classified pixels in each column, and TC is number of pixels in the column.

$$OA = \frac{CD}{TR} \quad (3)$$

The CD is the diagonal classified pixels. While, the amount of all pixels is represented by TR.

$$KC = \frac{(TP*CD) - \sum(TC*TR)}{TR^2 - \sum(TC*TR)} \quad (4)$$

3. Results

3.1. Land use/land cover change

Two satellite imagery from Sentinel 2 were used to generate the LULC map between 2015 and 2025 for the study area, and the results overlaid to find the transitioned areas and land—use changes in the period. The results showed notable patterns and significant changes in different types of land features. The LULC transition maps showed that the most significant change was the significant mitigation of green areas which reduced from 788.17 km² (81.94%) to 675.39 km² (70.21%) in only 10 years period, resulting in losing 112.79 km² of vegetation in the study area (Fig. 2). The primary cause of this reduction is due to the rapid urban development and population growth and demand for changing the type of land feature, along with the climate change impacts. In contrast, the settlement areas considerably increased, which covered 10.45% (101.42 km²) in 2015, but it increased to 13.41% (128.97 km²) in 2025. This showed that the urban regions increased by 27.54 km² (2.86%) in only 10 years, primarily due to the rapid development and population growth in Duhok city and its surrounding. Furthermore, the barren lands also increased significantly as they covered 69.63 km² (7.24%) of the study area in 2015 and increased to 154.36 km² (16.05%) in 2025. The bare lands showed significant increase by 84.73 km² (8.81%), which highlights the environmental changes in the region and suggesting the severe impact of drought, desertification and converting green areas to urban regions. Furthermore,

a minor increase of surface water in the regions was detected as it increased from 2.68 km² (0.28%) to 3.19 km² (0.33%) in the period (Fig. 3). This trends highlighted a significant change in different land features in the study area, specifically in vegetation and built-up areas, which notable land from vegetation replaced by the built-up and barren land, suggesting immediate need for informed decision making for sustainable urban planning and resource management to reduce the impact of land use change and rapid urbanization in the region.

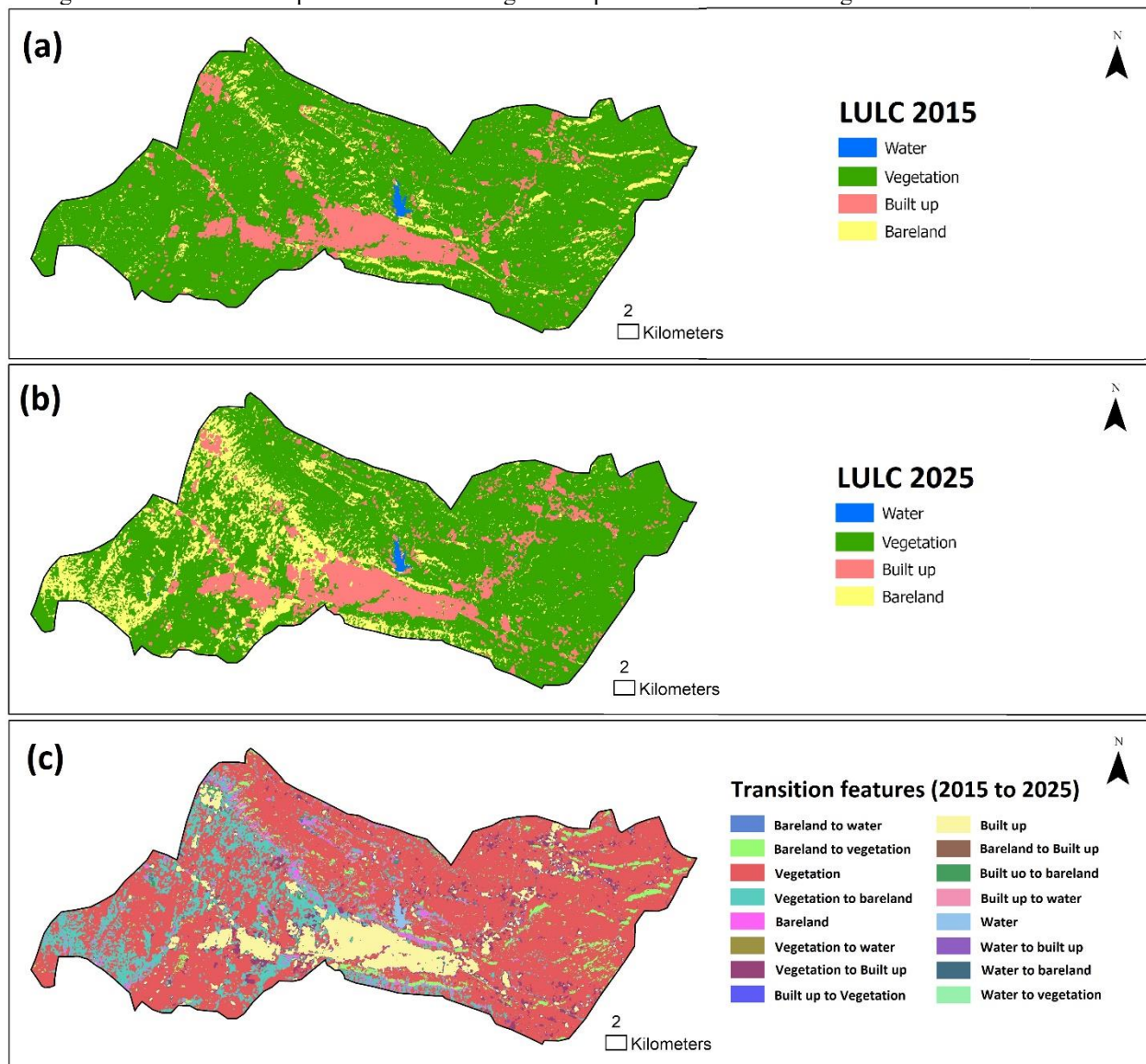


Fig. 2. The LULC map for 2015 (a), LULC map of 2025 (b), the transition map between 2015 and 2025 (c) for the study area.

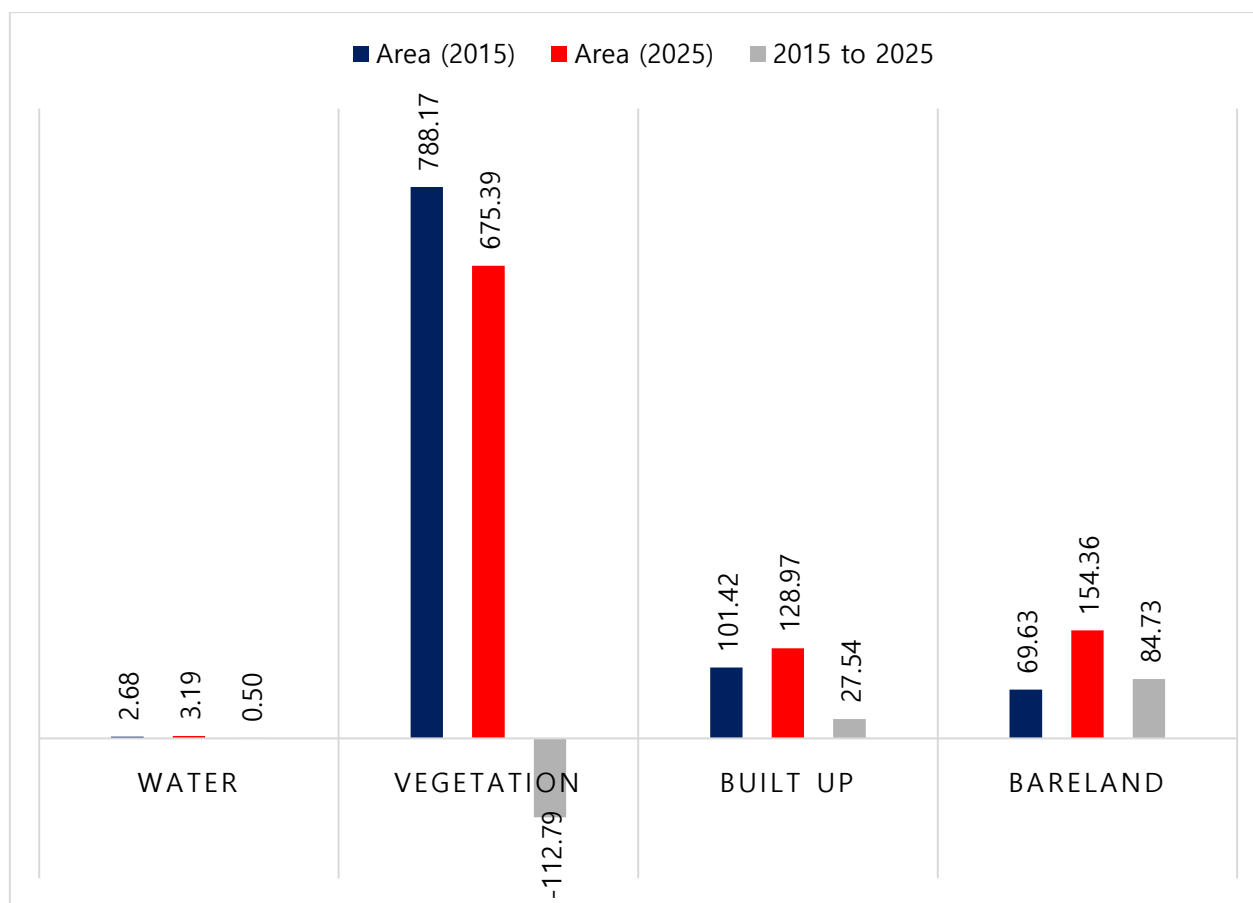


Fig. 3. Comparison of LULC Classes in Duhok for 2015 and 2025, and the Change from 2015 to 2025 for four different classes: Water, Vegetation, Built-up, and Bare land. The vertical axis represents the area of each class (km²), while the horizontal axis represents the LULC categories for the two study years and their overall change.

Furthermore, to better understand the land-use changes in the study area, overlay analysis was performed to measure the transitioned areas for all four land features. The results showed that as 626.17 km² (65.10%) of vegetation covers remained unchanged (Fig. 4). However, total amount of 122.82 km² (12.77%) of green areas has been replaced by the barren land, due to the deforestation and agricultural expansion. Moreover, built-up areas replaced 38.86 km² (4.04%) of vegetation due to the rapid urbanization and infrastructure development. Also only 0.32 km² (0.03%) of green areas converted to water bodies. In contrast, there was also a transition between barren lands to green areas, as 41.74 km² (4.34%) of barren land transformed to vegetation, highlighting the afforestation of seasonal vegetation dynamics. Also only 0.46 km² (0.05%) of barren land replaced by water coverage. The results indicated that only 6.70 km² (0.70%) of built-up regions changed to barren lands, but 2.61 km² (0.27%) of barren land has transitioned into built-up areas. Regarding the dynamics of built-up areas, the analysis showed notable patterns in the Duhok city and its surroundings. The result documented a significant urban expansion, however, the assessment showed that 7.32 km² (0.76%) of developed regions replaced by vegetation covers, suggesting land reclamation. These land-use changes highlight the impact of rapid urbanization and environmental changes on the land conversion dynamics in Duhok city, suggesting immediate sustainable land management policies and environmental resource management. The observed increase in surface water bodies may indicate enhanced water availability in certain areas; however, it can also lead to higher water consumption rates and potential shifts in groundwater recharge dynamics due to changing urban demand and runoff patterns.

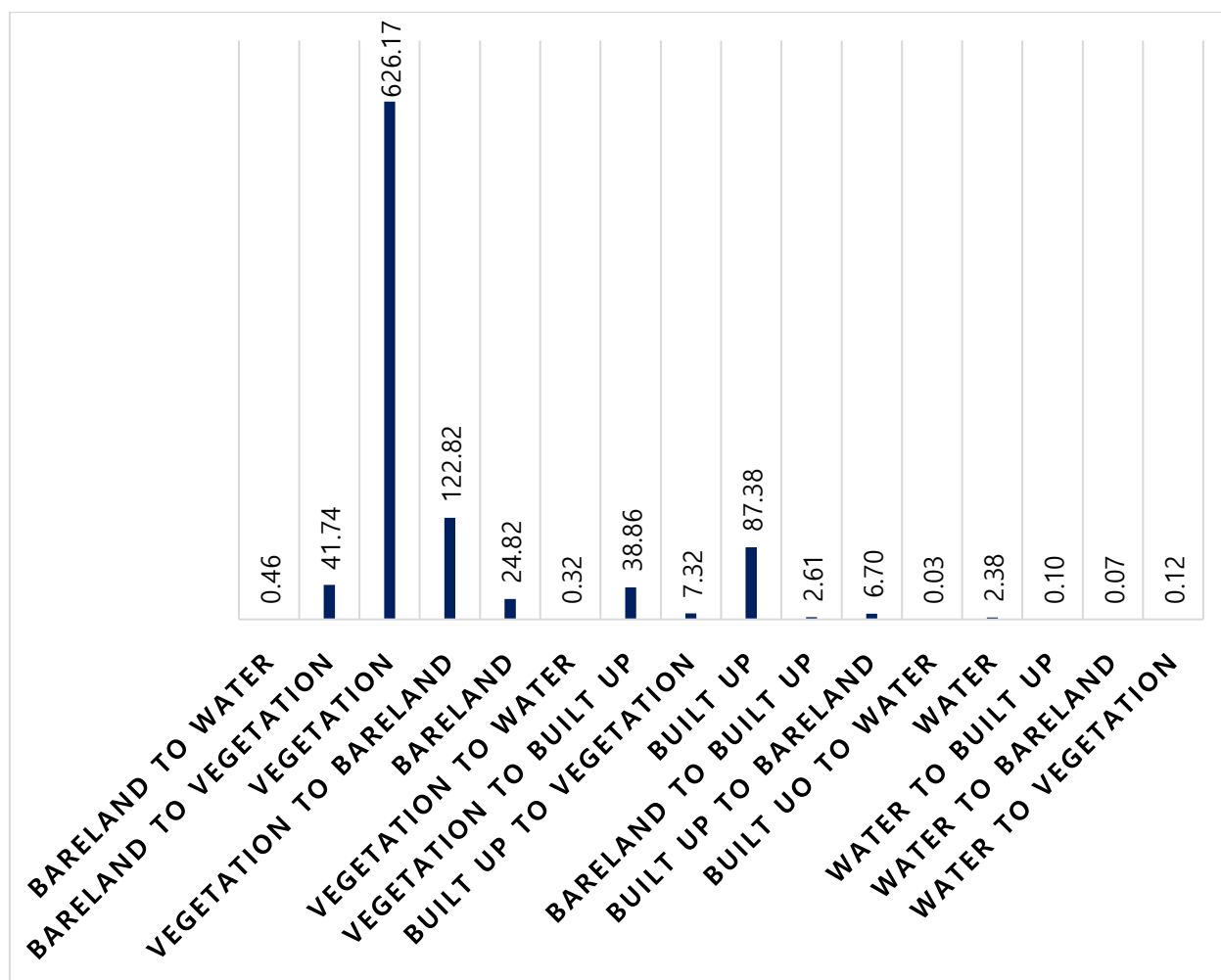


Fig. 4. LULC class transition areas in km² for study area between 2015 and 2025. The vertical axis represents the area of each LULC class in square kilometers (km²), while the horizontal axis represents the LULC categories observed during the study period.

3.2. Rainfall

To understand the dynamics of the environment in the Duhok city and its possible impact on the groundwater, the rainfall patterns from 2015 to 2024 was assessed and analysed using the precipitation recorded in the past decade. The results showed that 2018 recorded the highest annual rainfall with 953 mm, followed by 2019 with 909.4 mm, however, the rainfall significantly decreased in following years as the lowest rainfall recorded in 2021 with only 231.7 mm, suggesting the impacts of drought in the region (Fig. 5). Moreover, other years such as 2017 and 2022 showed below average records with 358.4 mm and 319.2 mm, respectively. However, 2015 and 2016 showed moderate rainfalls with 504.3 mm and 511.1 mm, respectively. Notably, after the lowest record in 2021, the rainfall trend slightly increased in 2023 and 2024, as they recorded 520.7 mm and 667.8 mm, respectively, highlighting the increased precipitation levels and recovery from dry years in the past. Moreover, the average monthly rainfall in the study area showed similar patterns of arid regions, as the highest rainfall occurred in winter and spring, while significant decline occur in the summer months. The spring months show highest recorded rainfalls, such as March (127.22 mm), followed by the winter months such as January (99.9 mm) and December (80.11 mm). However, the summer months such as July, show lowest or no rainfall

data (Fig. 6). These diverse and precipitation variations suggest the regions vulnerability to changes of the climate which significantly have impact on the groundwater, agriculture and sustainability. Analysing this trends and patterns helps the policy makers to better understand the environmental impacts and to implement adaptive strategies to reduce the influence of extreme precipitation and dry period in Duhok city and its surroundings.

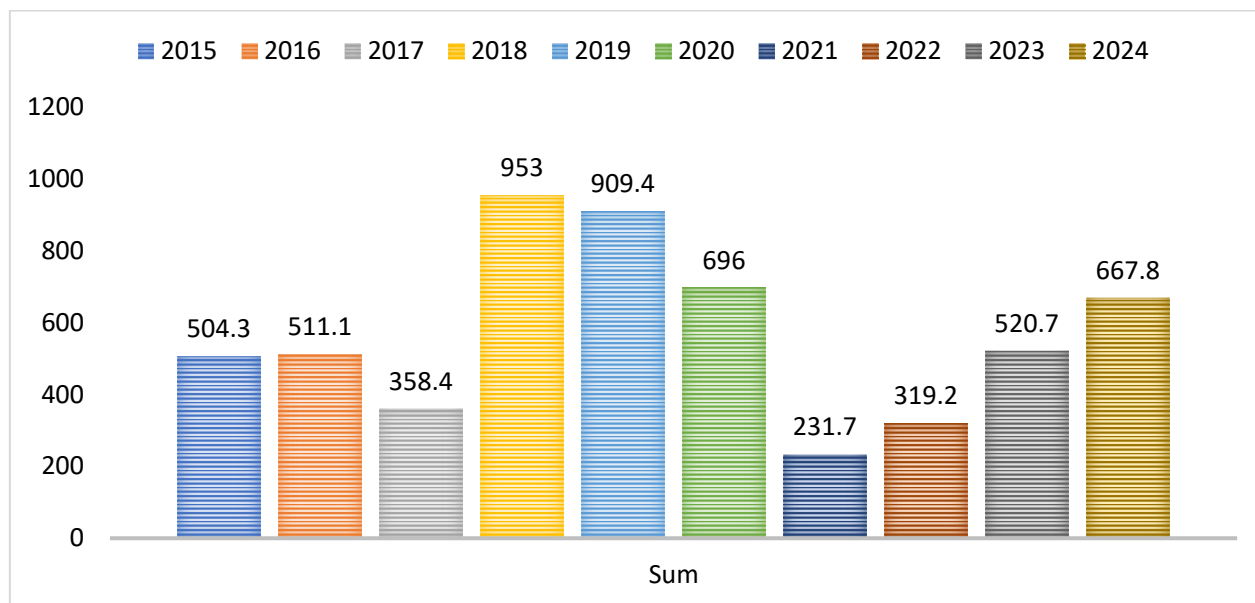


Fig. 5. The annual rainfall records 2015 and 2024 in Duhok station. The vertical axis represents rainfall amount (mm), while the horizontal axis represents the years of the study period.

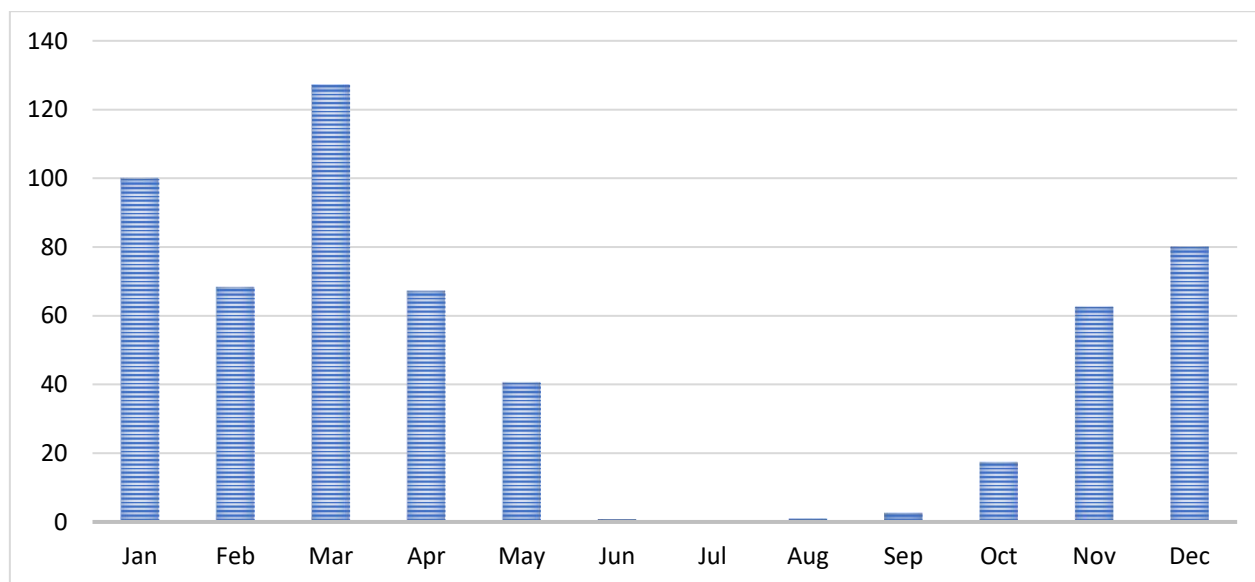


Fig. 6. The average monthly rainfall records in Duhok city. The vertical axis represents the rainfall amount (mm), while the horizontal axis represents the months of the year.

3.3. Groundwater assessments

To understand the distribution and fluctuation of groundwater levels, 83 wells from study area were used which distributed across Duhok, Semel, and Zawita. The purpose of the wells were for irrigation, industrial, and domestic

uses, and the highest usage was for domestic use (60 wells), highlighting the significant reliance of the households on the groundwater. The results showed that the most Zawita had most domestic wells (29 wells), followed by Semel with 23, while Duhok had only 7. However, the most Irrigation wells were located in Duhok and Zawita, with 7 and 8 wells, respectively, which used for agricultural activities and emphasize the significance of agriculture in Duhok and Zawita (Fig. 7 and Table 3). Moreover, industrial wells were primarily located in Semel region. These distribution shows the diverse characteristics of the region with different reliance on groundwater, suggesting a robust framework of sustainable water management and policy making in the region to balance the groundwater usage to reduce the over-extraction and shortage of water.

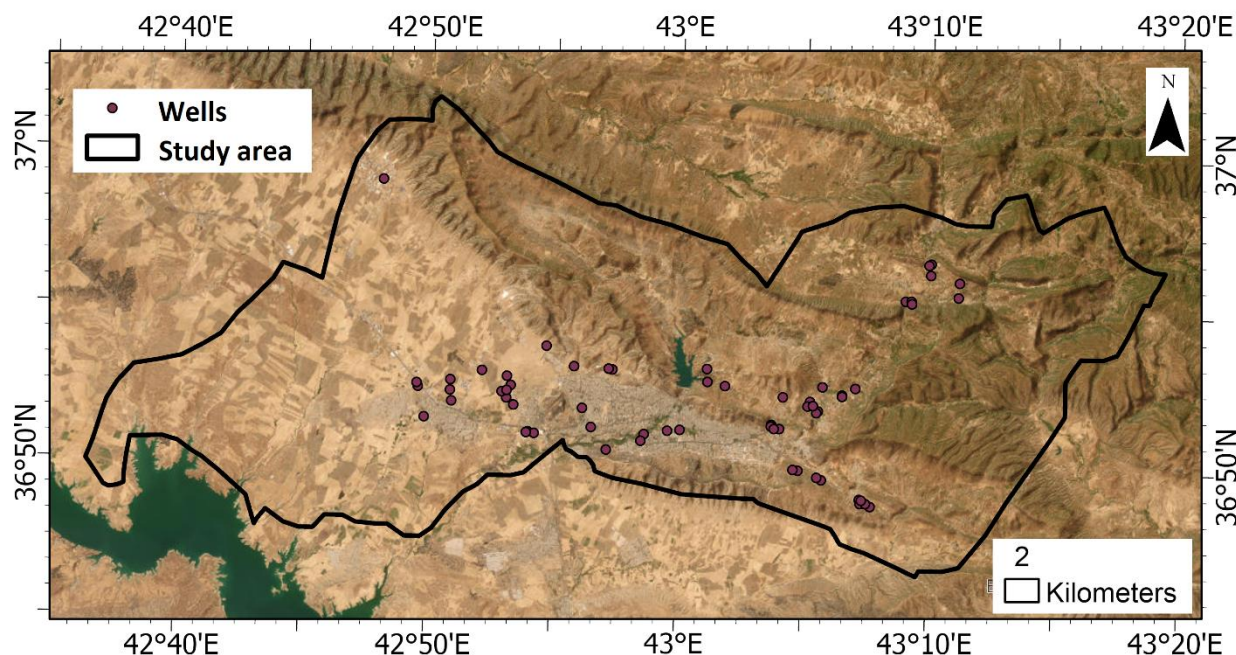


Fig. 7. The location of Wells in the study area.

Table 3. Groundwater usage distribution in Duhok, Semel, and Zawita regions.

Region	Well types		
	Irrigation	Industrial	Domestic use
Duhok	7	0	7
Semel	0	7	23
Zawita	8	2	29

Moreover, the depth and static water level (SWL) also showed notable patterns in the region. The well depth (Fig. 8a) and SWL (Fig. 8b) maps were generated using the wells in the region to better understand the groundwater level dynamics. The maps showed notable variations in the different parts of the study area, highlighting the diverse groundwater characteristics and availability across the area. The deepest well was recorded to be 300 meter in Semel region, which used for Industrial purpose, while the shallowest was 81 meter in 2022 and used for domestic use. The maps indicated that the shallower well depth were located in Zawita and east of the study area, while the deepest wells were located in the west and Semel region. Moreover, regarding the static water level, the shallowest well was from Semel with only 3 meter and used for domestic use, however, the deepest static water level was from Zawita with 140 meter in 2024 and also used for domestic activities. The maps of SWL indicated that the shallower SWL were witnessed primarily in center of Duhok and Center of Semel, which were near to the settlement areas, however the largest SWL were located in the south of Zawita region. These different distribution and variations in depth and SWL in the region highlights the significance of implementing sustainable groundwater management. These maps aid policy makers and urban planners to better understand the groundwater usages and demands in the region.

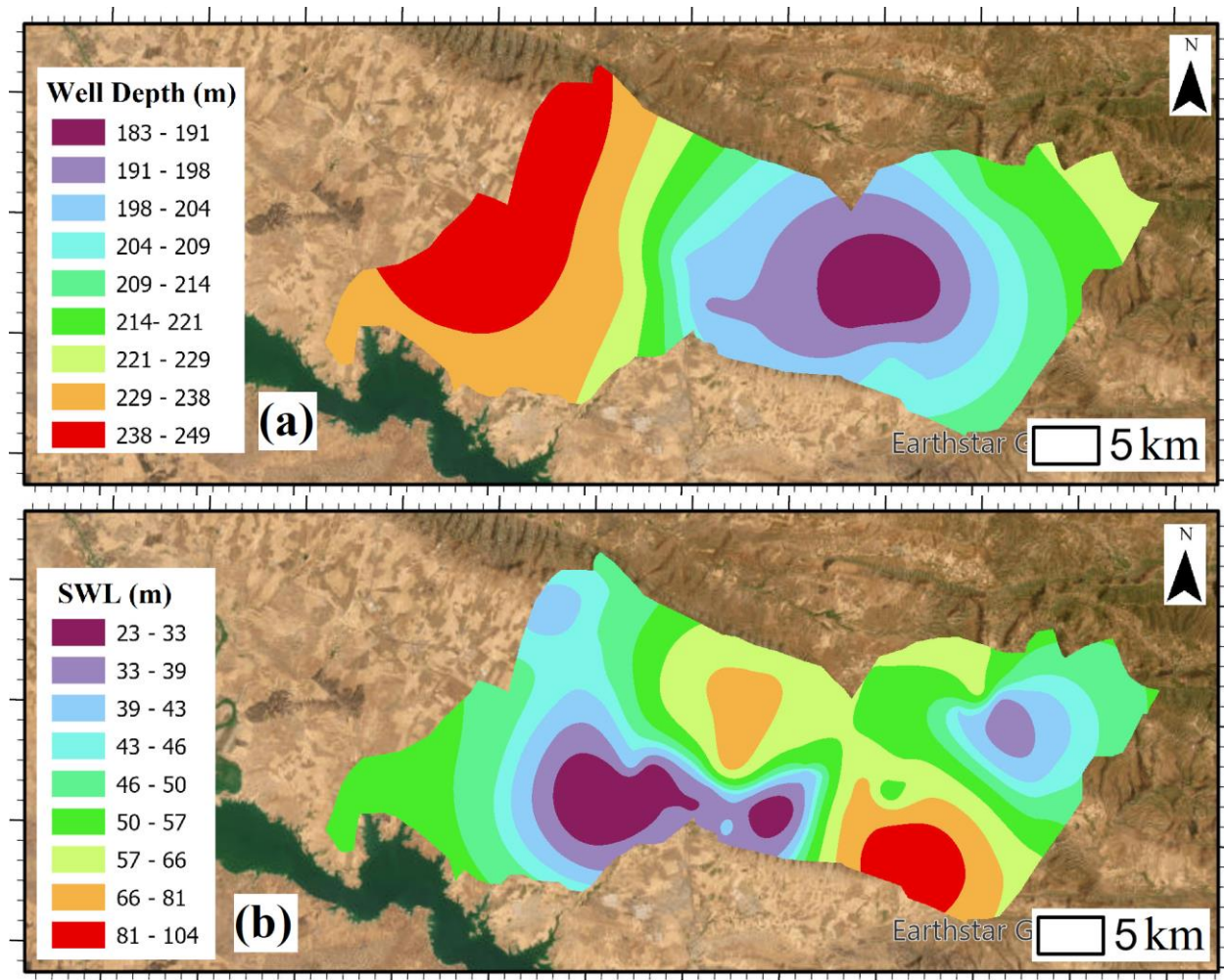


Fig. 8. The well depth (a) and SWL (b) for the study area using well points and Kriging tool.

Furthermore, the records of groundwater levels from 2010 to 2024 showed notable fluctuations in the study area, emphasising the dynamics of groundwater and its trends. The trends of well depth, static water level, and dynamic water level in the periods showed a significant rise, suggesting the decrease of groundwater in the region due to the extensive extraction and environmental changes (Fig. 9). These variations between 2010 and 2024 shows the impact of climate and environmental changes combined with increased demand on groundwater and unsustainable usage of wells on the availability and dynamics of groundwater. These results highlight the necessity for sustainable water management strategies to ensure the long-term availability of groundwater resources in the Duhok and its surroundings.

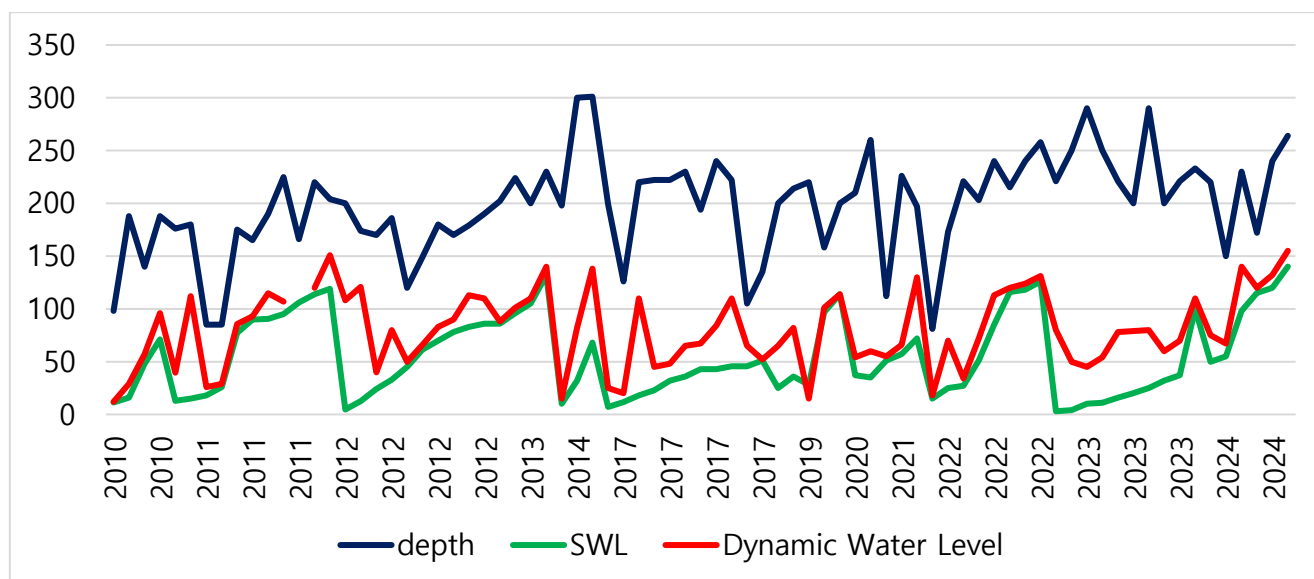


Fig. 9. The well depth, SWL, and Dynamic water level trends between 2010 and 2024 in the study area. The vertical axis represents depth in meters, while the horizontal axis represents the years of the study period.

To better understand the dynamics of groundwater in each region of the study area, specific wells were analysed in each region. The results showed significant changes in behavior of the groundwater regarding the depth, static water level and dynamic water level (DWL) for Duhok, Zawita, and Semel. The depth of wells between 2010 and 2023 for Semel fluctuated and increased from 225 meters to 251 meters. However, the SWL showed slight improvement as it decreased from 95 meters in 2011 to 19 meters in 2023, suggesting a slight groundwater recharge which influenced by the climate factors in the region. Moreover, the depth groundwater during pumping which is known as the DWL, also showed improved trends as recorded 107 meters in 2011 and decreased to 67 meters in 2023 (Fig. 10).

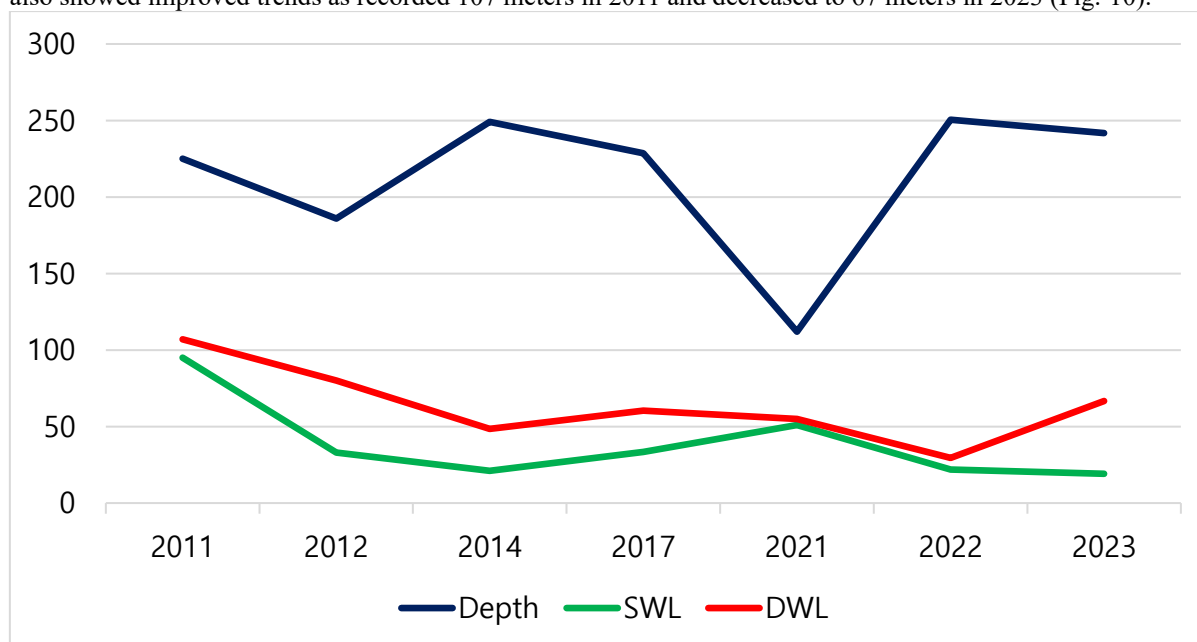


Fig. 10. The well depth, SWL, and Dynamic water level trends between 2011 and 2023 in the Semel region. The vertical axis represents depth in meters, while the horizontal axis represents the years of the study period.

However, the groundwater characteristics of Duhok region showed a slightly more negative trends regarding the trend of depth and DWL. The results showed that the depth of wells increased over the years due to the declining groundwater levels and increased demand, however, the SWL showed fluctuated trends between 2010 and 2023. Moreover, the DWL levels also showed negative trends as the DWL in 2010 recorded 46 meters while it was increased

to 79 meters, indicating the reduced patterns of groundwater levels in Duhok city (Fig. 11). These trends and patterns suggests the declining trends of availability of the groundwater due to the extensive demand and to solve this, it's necessary to implement sustainable water management.

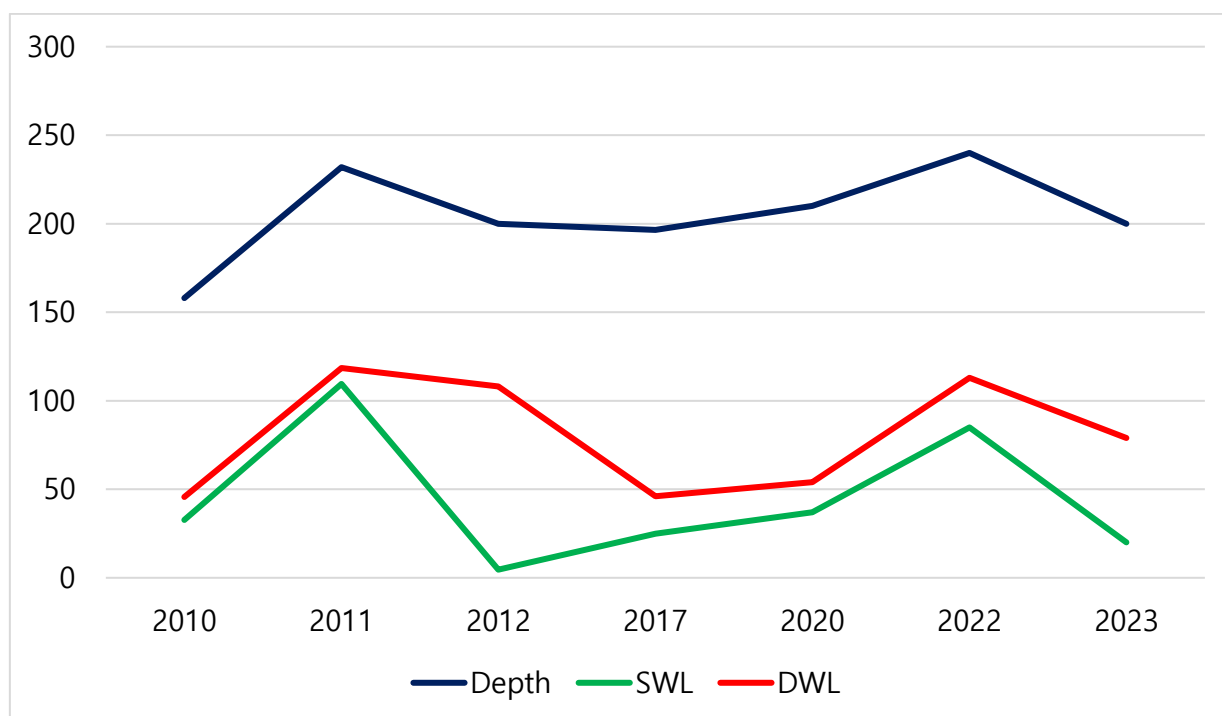


Fig. 11. The well depth, SWL, and Dynamic water level trends between 2010 and 2023 in the Duhok city. The vertical axis represents depth in meters, while the horizontal axis represents the years of the study period.

Moreover, the groundwater trends in Zawita region showed a significant negative patterns compared to the Duhok and Semel region, as it showed a substantial increase in depth, SWL, and DWL. The results showed that due to the extensive demand on the groundwater for domestic se and irrigation which were highest in Zawita, the groundwater continuously declining, this reflects the increasing in depth, SWL, and DWL in this region. The depth of wells increased from 159 m in 2011 to 227 m in 2024, suggesting deeper well drilling in the future to reach the groundwater (Fig. 12). Moreover, the SWL also showed a significant decline as it increased from 71 m in 2011 to 118 m in 2024. Furthermore, the DWL also indicated worsening situation as it rose from 78 m to 137 m. These declining trends in Zawita highlights the depletion of groundwater in the region due to the over-extraction and reliance on the groundwater for irrigation and domestic uses, also because of the regional climate change impacts.

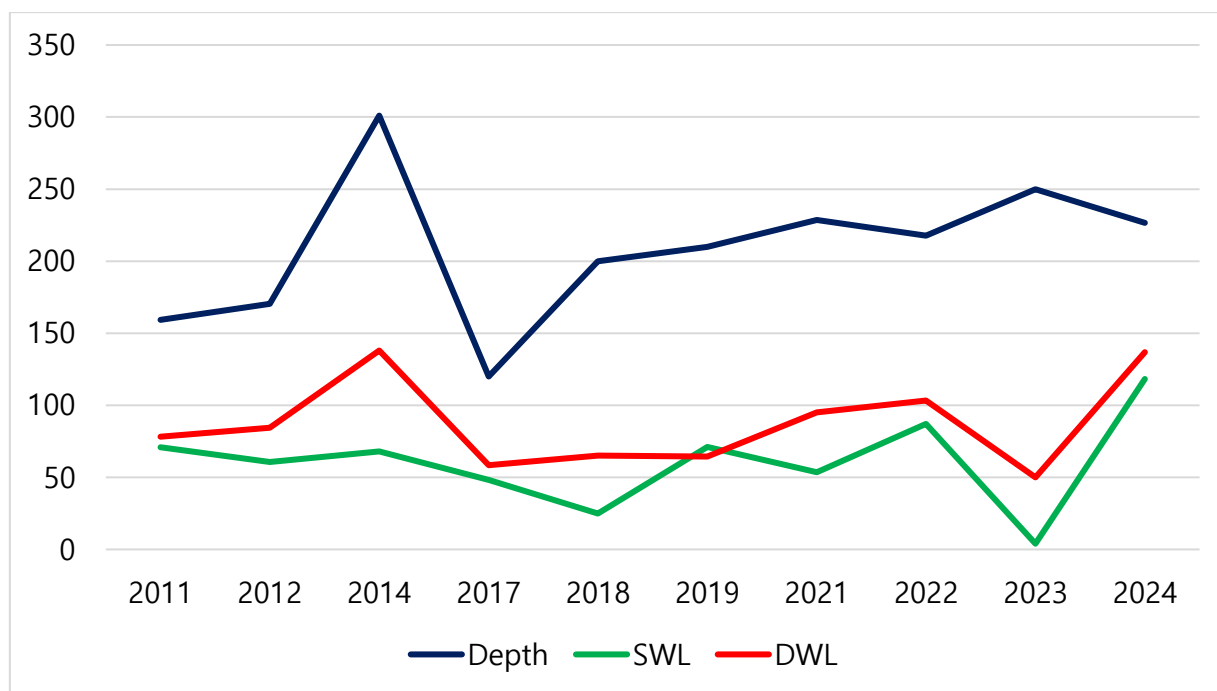


Fig. 12. Trends of well depth, static water level (SWL), and dynamic water level (DWL) in Zawita city between 2010 and 2023. The vertical axis represents depth in meters, while the horizontal axis represents the years of the study period.

4. Discussion

To ensure the results of this study and better understand the dynamics of groundwater in the study area in regional scale, it's essential to compare the findings to the remote sensing data. For that, the Liquid Water Equivalent (LWE) Thickness data covering the period from 2005 to 2024 was used in the study area, which aids critically to better understand the seasonal and long-term trends of water storage in the region. Notably, the LWE Thickness trend aligns significantly with our results, as the patterns shows a long-term decline trend covering the period from 2006 and 2024, suggesting a noticeable reduce in water storage in the study area (Fig. 13). This decline could be related to the regional climate change, precipitation patterns, and increased water demand due to the rapid urbanization. Using Remote sensing technology is essential to better understand and monitor the dynamics of groundwater in larger scales and longer periods to address the groundwater challenges and provide invaluable insights for policy makers.

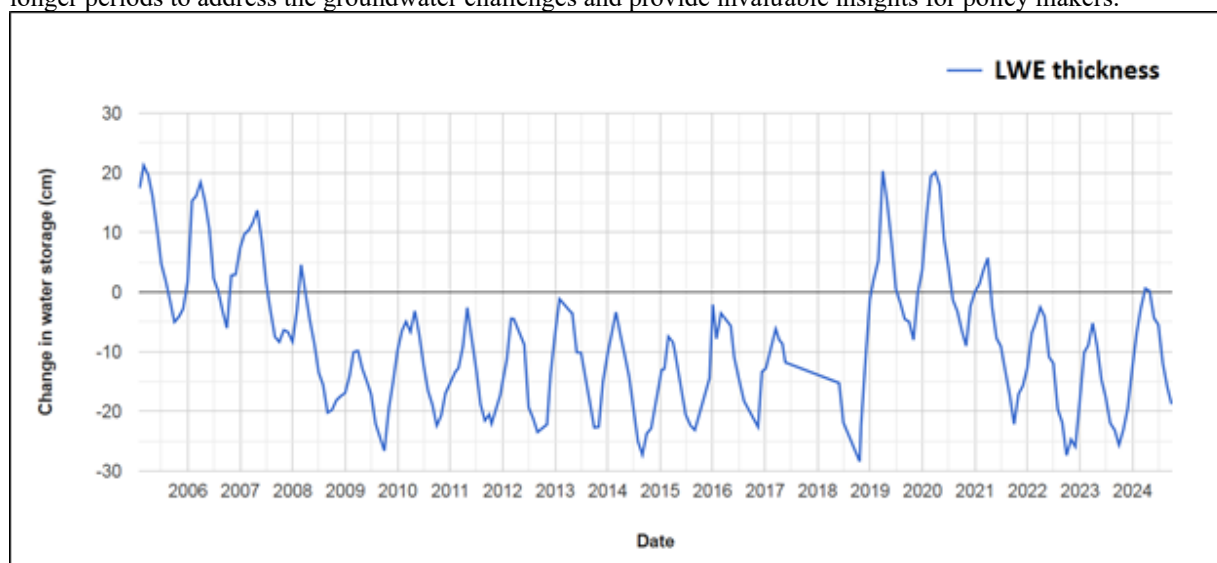


Fig. 13. The change in water storage (cm) for the study area between 2005 and 2024. The vertical axis represents the change in water storage in centimeters, while the horizontal axis indicates the corresponding years of the study period.

The results of this study regarding the impact of urbanization and land-use changes on groundwater decline aligns with the similar investigations on arid regions. As the rapid urban development caused a significant loss in the amount of vegetation with groundwater reduction in the region, the similar patterns also recorded in the studies in Kurdistan region of Iraq, such as in Erbil city. A study for Erbil showed the strong correlation of rapid urbanization with groundwater decline, which recorded 54% covering the period from 2004 and 2014 (Faqe and Hashemi, 2015). Moreover, the groundwater decline was reported widely in other studies in the Gulf Cooperation Council countries and its correlation with the land use changes and urban expansion (Helal, et al., 2024). These consistency of the results with the similar studies in the regions highlights the common trend in the arid and semi-arid regions which have the groundwater issues due to the rapid urbanization, and indicate a need for immediate approach to increase the natural infiltration and support groundwater recharge strategies (Mishra, et al., 2014). The drought and soil degradation also witnessed in the study area reflecting the increase of barren lands, which shows the regional challenges that faced and highlighted in the literature due to the desertification. Moreover, the groundwater extraction was primarily due to the agricultural activities in semi-arid regions such as in Tabuk, Saudi Arabia (Helal, et al., 2024), while the domestic and irrigated usage of groundwater was the primary reasons of groundwater reduction in Duhok and its surrounding areas. The main causes are the unsustainable management of groundwater extraction. The results of this investigation have a strong convergence with literature for similar regions and cities, highlighting the environmental consequences of unplanned urban expansion.

5. Conclusion

Rapid urbanization and land-use changes in semi-arid regions combined with the environmental changes have notable impact on the groundwater resources. The unsustainable management of groundwater resources and unplanned urban growth in Duhok region resulted in a pressing challenge and groundwater decline. The rapid urbanization of Duhok region covering the period from 2015 and 2025 resulted in a significant decline of vegetation cover and notable increase of urban regions due to the environmental factors and population growth. These changes had a notable impact on the decline of groundwater levels, increasing the depth of wells and declining the SWL and DWL in the study area, which have significant implications for water availability, agriculture, and environment.

Several proactive policy measures are recommended to ensure the sustainable management of water resources to mitigate the environmental degradation and groundwater preservation. It's recommended to implement sustainable urban planning and strict the expansion of regions considered as recharge zones and agricultural fields. It's essential to preserve green areas to maintain the natural infiltration, also the land-use plantings consider the water resource management. Also, the government entities should implement more strict policies for permitting wells and establish monitoring network for groundwater levels to have up-to-date data to better management as recommended by the similar studies in MENA region. Also it's suggested to implement sustainable urban drainage systems such as permeable pavements in the cities to increase the infiltration rates and recharge rates. Furthermore, innovative technology can be used to save water and upgrade the infrastructure of irrigation system by using drip irrigation and scheduled watering. Also recycling the water is another techniques to use the water for agricultural purposes. The results of this investigation provides notable insights for policy makers and urban planners to better understand the land-use changes and groundwater patterns in Duhok and its surroundings to implement the mentioned recommendations.

Declaration of interest's

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.

Data Availability

The data used in this research are available from the corresponding author upon reasonable request.

Author Contribution:

H.A.A was responsible for data curation. M.M.Y. contributed to the investigation and conducted the literature review. K.C led the conceptualization and methodology, performed the formal analysis and visualization, and was responsible for writing the original draft, reviewing and editing the manuscript.

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