Spatiotemporal Analysis of Landscape Degradation Due to Drought in Duhok and Semel Districts for the Period 2004–2024

تحليل مكاني زماني لتدهور المناظر الطبيعية نتيجة الجفاف في قضاءي دهوك وسميل

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عبد الله ، هايدا جلال، ليدا عيسى زاده، تحليل مكاني زماني لتدهور المناظر الطبيعية نتيجة الجفاف في قضاءي دهوك وسميل،مجلة مركز بابل للدراسات الانسانية، حزيران 2026،المجلد:16 ،العدد:6.

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Spatiotemporal Analysis of Landscape Degradation Due to Drought in Duhok and Semel Districts for the Period 2004–2024

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Keywords : Drought; Landscape degradation; NDVI; NDWI; VCI; SPI; Spatiotemporal analysis; Duhok; Semel.

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ملخص

أدى الجفاف المطول وتزايد تقلبات المناخ إلى إجهاد بيئي كبير في المناطق القاحلة وشبه القاحلة. وقد ساهمت هذه الظروف في تدهور المناظر الطبيعية على نطاق واسع، لا سيما في شكل فقدان الغطاء النباتي وندرة المياه. وقد شهدت قضائيا دهوك وسميل، المعروفان بقيمتهما الزراعية وأهميتهما البيئية والجمالية، تغيرات بيئية ملحوظة على مدى العقدين الماضيين. وقد تم اختيار الغطاء النباتي والمياه كمؤشرين رئيسيين للتدهور لأنهما أكثر مكونات المناظر الطبيعية تضررًا وأهمية جمالية. تناولت هذه الدراسة مدى وأنماط التدهور المكاني الناجم عن الجفاف في منطقة الدراسة خلال الفترة من 2004 إلى 2024. وطُبِّق نهج مكاني زماني باستخدام مؤشرات الاستشعار عن بُعد، بما في ذلك مؤشر الفرق المعياري للغطاء النباتي (NDVI)، ومؤشر الفرق المعياري للمياه(NDWI) ، ومؤشر حالة الغطاء النباتي(VCI) ، لرصد

التغيرات في الغطاء النباتي والمياه السطحية. واستُخدم تصنيف استخدام الأراضي والغطاء الأرضي (LULC) والتحليل القائم على نموذج الارتفاع الرقمي (DEM) لتقييم تأثير الارتفاع والانحدار والجانب على أنماط التدهور. كما حُللت المتغيرات المناخية، مثل هطول الأمطار ودرجة الحرارة، إلى جانب بيانات الموارد الزراعية والمائية المستمدة من المديريات الحكومية. واستُخدم مؤشر هطول الأمطار المعياري (SPI) لتقييم تواتر الجفاف ومدته. وأُجريت مسوحات ميدانية ومقابلات مع مصادر معلومات رئيسية لدعم نتائج الاستشعار عن بُعد والتحقق من صحتها. وطُبقت تحليلات الارتباط والانحدار لاستكشاف العلاقة بين مؤشرات الغطاء النباتي والمتغيرات المناخية. أظهرت النتائج انخفاضًا مستمرًا في الغطاء النباتي وتوافر المياه، لا سيما خلال سنوات الجفاف الطويلة. وتفاوتت شدة التدهور باختلاف الظروف الطبوغرافية وأنواع استخدامات الأراضي، حيث أظهرت المناطق المسطحة والسهلية تأثرًا أكبر. وعالجت النتائج أهداف البحث من خلال تحديد اتجاهات التدهور المكاني، والمناطق المعرضة للجفاف، والعوامل البيئية المؤثرة على التأثر. ووفرت النتائج أساسًا علميًا لاستراتيجيات محتملة لتخفيف آثار التدهور واستعادته في المناطق المتدهورة استنادًا إلى الأنماط المرصودة.

الكلمات المفتاحية:

Abstract

Prolonged drought and increasing climate variability have led to significant environmental stress in arid and semi-arid regions. These conditions have contributed to widespread landscape degradation, particularly in the form of vegetation loss and water scarcity. Duhok and Semel Districts, known for their agricultural value and ecological and aesthetic importance, have experienced noticeable environmental changes over the past two decades. Vegetation and water were selected as primary indicators of degradation because they are the most visibly affected and aesthetically significant components of the landscape.

This study examined the extent and spatial patterns of drought-induced degradation in the study area from 2004 to 2024. A spatiotemporal approach was applied using remote sensing indices, including the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Vegetation Condition Index (VCI), to monitor changes in vegetation cover and surface water. Land Use and Land Cover (LULC) classification and Digital Elevation Model (DEM)-based analysis were used to assess the influence of elevation, slope, and aspect on degradation patterns.

Climatic variables such as precipitation and temperature were analyzed alongside agricultural and water resource data obtained from governmental directorates. The Standardized Precipitation Index (SPI) was used to evaluate drought frequency and duration. Field surveys and key informant interviews were conducted to support and validate the remote sensing findings. Correlation and regression analyses were applied to explore the relationship between vegetation indices and climatic variables.

The results showed a consistent decline in vegetation and water availability, especially during years of prolonged drought. Degradation severity varied across topographic conditions and land use types, with flat and plain areas showed greater vulnerability. The findings addressed the research objectives by identifying spatial degradation trends, drought-prone zones, and the environmental factors influencing vulnerability. The results provided a scientific basis for potential strategies to mitigate and restore degraded landscapes based on the observed patterns.

Keywords:

1. Introduction

Over the past few decades, rising temperatures, frequent drought events, and notable shifts in precipitation patterns have been arising globally (Easterling, 2000). Among the many effects of climate change, drought has emerged as one of the most serious and widespread threat. It has the capacity to reshape natural landscapes, damage ecosystems, accelerate the loss of vegetation, deplete water resources, and disrupt agricultural systems that local communities depend on [1].

This crisis is more apparent in arid and semi-arid regions like Iraq, where environmental and agricultural systems are under severe threat. The International Federation of Red Cross and Red Crescent Societies has reported that recurrent droughts have arisen as a critical issue, exerting severe pressure on Iraq's natural landscapes, particularly in water-stressed areas [2].

Duhok Governorate is among the regions most affected by these environmental challenges. The region is known for its diverse mix of mountains, valleys, and plains. Historically, the natural beauty of this region has been a foundation for agricultural activities, particularly in Semel and Duhok districts, where most of the population resides. They have been significantly impacted by water scarcity and drought [3]. The ongoing drought has changed the visual character of these districts. Once vibrant landscapes covered in healthy crops and vegetation have transformed into barren, dry land. This transformation not only disrupts livelihoods but also deteriorates the aesthetic and identity of these regions. Given the severity of the impacts, this study focuses on the Duhok Governorate, with a particular emphasis on drought-induced landscape degradation, including water scarcity and vegetation loss in both Duhok and Semel districts.

The ongoing drought has resulted in visible changes in the landscapes of Duhok Governorate, specifically within the Semel and Duhok districts. Among these changes is the deterioration of the aesthetic and visual quality, with the most visible signs being the loss of vegetation cover and the depletion of water resources. These environmental shifts have also had serious consequences on agriculture, ecosystems, and local livelihoods that depend on natural resources for survival. This study aims to understand and examine these changes using spatiotemporal analysis, combining both satellite sensor-derived data and real-world observations and records from government directorates, to provide a clearer understanding of drought-related degradation and its development across space and time.

The following research objectives are selected to guide the study:

1.To assess how landscape degradation has changed over time and space in Duhok and Semel districts over the past two decades (2004 to 2024), focusing on vegetation loss and reduction in water resources.

2.To analyze the impact of drought intensity, duration, and frequency on vegetation in these districts.

3.To evaluate the socio-economic impacts of drought-induced degradation on local communities.

The following research questions are addressed for this study:
1.How has landscape in Duhok and Semel districts changed in terms of vegetation cover and water resources between 2004 and 2024?
2.How does drought affect vegetation health and coverage in Duhok and Semel districts?
3.How has the degradation of the landscape affected the local communities?

2. Materials and Methods

2.1. Overview

The research design for this study adopted a mixed-methods approach, combining detailed quantitative analysis with qualitative insights to understand spatiotemporal landscape degradation caused by drought in the Duhok and Semel Districts from 2004 to 2024. The quantitative part involved analyzing remote sensing data, using Landsat satellite images to generate the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Vegetation Condition Index (VCI), and Standardized Precipitation Index (SPI), This is further supported by meteorological data (trends in temperature and precipitation), agricultural and crop production data over the same periods, and Digital Elevation Model (DEM) data to evaluate topographical features like elevation, slope, aspect, and surface roughness.
At the same time, the qualitative part included field surveys such as surveys with residents and farmers using structured questionnaires, and interviews with key informant interviews from relevant government departments (Meteorology, Agriculture, Water Resources, environment, and Statistics), to facilitate satellite-based environmental changes and on-the-ground data, climate trends, socioeconomic conditions, and physical terrain attributes, leading to the identification of highly vulnerable zones and evaluate diverse impacts of drought.

2.2. Study area:

Duhok and Semel districts has been chosen as the study area for the research, which are two of the most populated and economically important districts in Duhok Governorate, Kurdistan Region of Iraq (Figure 1). The study area is bordered by the Akre district to the east, and the Zakho district to the north. It has a total area of about 2,312 km² and a population of over 711,600 individuals (Directorate of statistics,2024).

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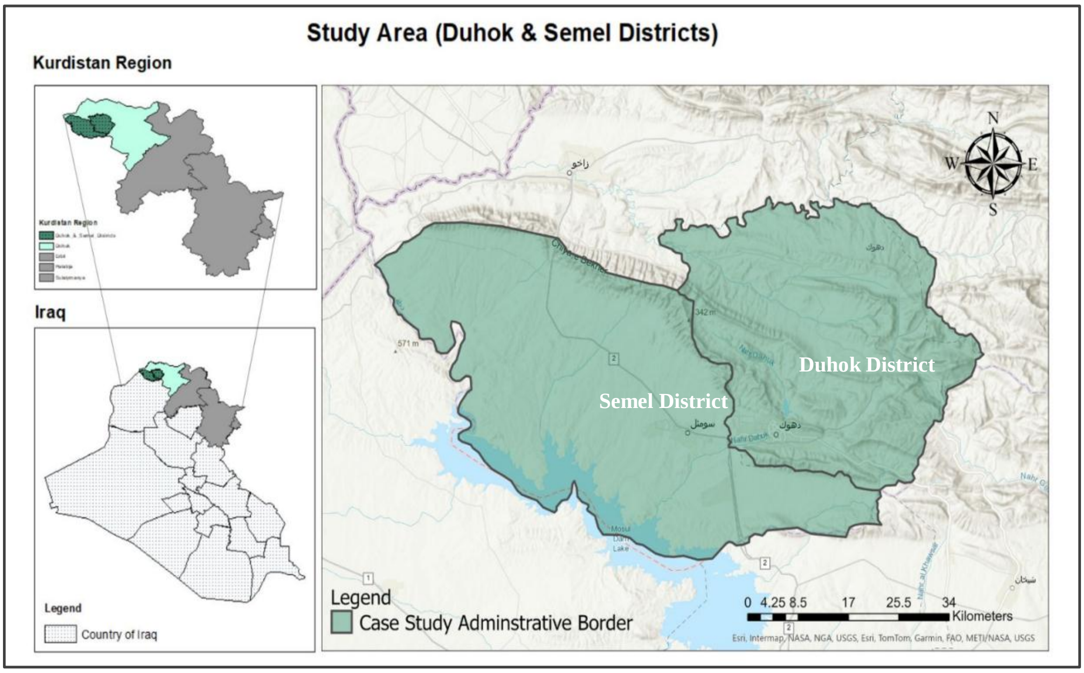

Figure 1: Location of the study area within Duhok and Semel Districts, Kurdistan Region, Iraq.

Duhok District is a key urban and economic center of the Duhok Governorate, it includes the city of Duhok, Mangesh and Zawita sub-districts, hosting a population of 473,800 individuals which makes up 26.74% of Duhok governorate's total population. The district covers an area of 989 km², equal to 9.03% of the total area of the governorate (Directorate of Statistics, 2024). The district's landscape is categorized by a mix of mountains, valleys, rivers, it is also the main hub of economic, cultural, and administrative activities within the governorate.

Semel district, on the other hand, is located 17 kilometers from the center of Duhok city, and rests at an elevation of 500 meters above sea level. Semel covers an area of 1,323 km², representing 12.08% of Duhok's governorate's area, and is home to 237,800 people, or 13.42% of the total population (Directorate of Statistics, 2024). Its landscape is primarily characterized as flat and plain area, with gentle hills and nearby mountainous terrain. Semel features a mix of rural and urban areas, which is a key area for agriculture and livestock farming, being a significant economic activity due to the fertile land along the water bodies and in the plains. The district's diverse landscapes, influenced by its proximity to nearby mountains, seasonal rivers, vineyards, farms, and or-chards, forming a patchwork of crops and verdant fields, contributes to its cultural and environmental value.

The study area is located in the northern part of Iraq within the Kurdistan Region and covers both Duhok and Semel districts of Duhok Governorate, it lies between 36°30′ and 37°20′ north latitude and 42°30′ and 44°00′ east longitude, near the borders with Turkey and Syria

Table 1: Area of Districts and Sub-districts within study area, Source: Directorate of Statistics in Duhok province 2024

District	Sub-District	Area of the Sub-district	Total area of the district
Duhok	Duhok Center	126 km^2	989 km^2
	Zawita	396 km^2	
	Mangesh	467 km^2	
Semel	Seme Center	371 km^2	1323 km^2
	Faydye	349 km^2	
	Batel	603 km^2	
Total area of the case study (both districts)			**2,312 km^2**

2.3. Climatic Characteristics:

This section included climatic conditions of Duhok and Semel districts, focusing on key variables, temperature and precipitation, it analyses monthly, seasonally and annual trends from 2004 to 2024 using data from Duhok metrology and seismology Directorate.

2.3.1. Temperature Dynamics:

Temperature data for Duhok and Semel districts over a 20-year period (2004, 2014, and 2024) indicate a clear warming trend in the study area. The average annual temperature increased steadily from 23.0 °C in 2004 to 24.3 °C in 2014, and then to 25.7 °C in 2024, reflecting a total rise of 2.7 °C. This increase is most pronounced during the summer season, while winter temperatures have also shown a noticeable rise over time.

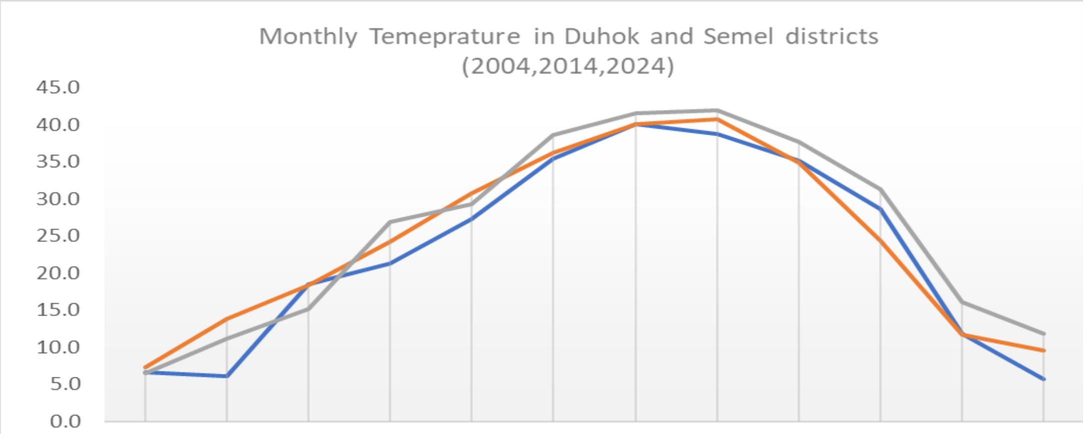

Figure 2: Monthly temperature in Duhok and Semel districts (2004,2014 and 2024), Source: Directorate of Meteorology & Seismology in Duhok Government

Monthly temperature data from 2004, 2014, and 2024 for the Duhok and Semel districts show a consistent rising trend over the last twenty years. The average annual

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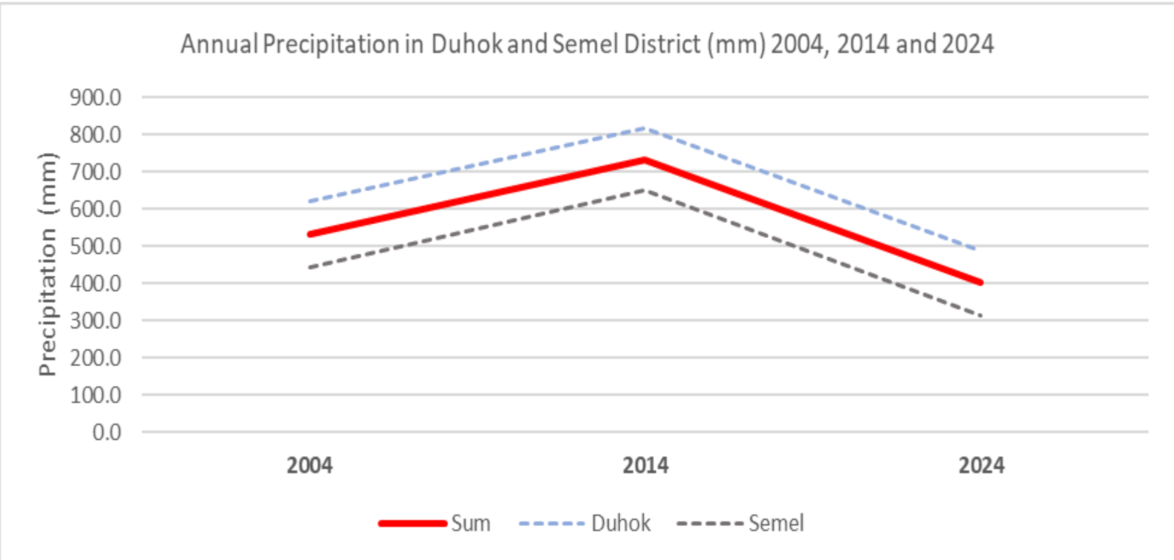
temperature in 2004 was 23.0°C. It went up to 24.3°C in 2014 and then to 25.7°C in 2024, this represents a rise of (2.7°C) locally. The rise is most obvious in the summer, when temperatures go up from 38.8°C in 2004 to 42.0°C in 2024. Winter months, including November and December, have also been a lot warmer. For instance, the average temperature in December climbed from 5.8°C in 2004 to 11.9°C in 2024. These statistics show that temperatures are rising both seasonally and yearly.

2.3.2 Precipitation

Precipitation is important for maintaining the health of the landscape, reducing erosion, supporting plant life and it also helps to maintain the water table. Duhok and Semel Districts have experienced significant reduction in rainfall between 2004 and 2024. The following figure shows the annual precipitation in the study area for the years (2004,2014 and 2024) according to the data gathered from the Directorate of Meteorology & Seismology in Duhok Government.

The below figure shows the annual precipitation in the form of rain, snow or sleet in Duhok and Semel districts from 2004 to 2024. The x-axis of the graph shows the year, and the y-axis shows the precipitation in millimeters. The graph also shows two lines, one for Duhok District and one for Semel District.

The winter season consistently receives the highest amount of precipitation, with a record of 268.4 mm in 2014 and 259.7 mm in 2004. However, in 2024, the amount of precipitation during the winter season decreased significantly to 127.8 mm, indicating that the amount of precipitation was significantly lower during this critical period. There was 192.7 mm of rainfall in the spring of 2014, compared to 143.5 mm in 2004. It had decreased to 139.9 mm by 2024. The autumn rainfall was more consistent, with a peak of 266.1 mm in 2014 and then dropping to 133.0 mm in 2024. The seasonal statistics indicate that there has been a consistent trend of decreased precipitation over time, particularly in the winter and spring, which are critical for the water supply in ecosystems and for farming.



the years (2004, 2014 and 2024). Source: Directorate of Meteorology & Seismology in Duhok Government (2024).

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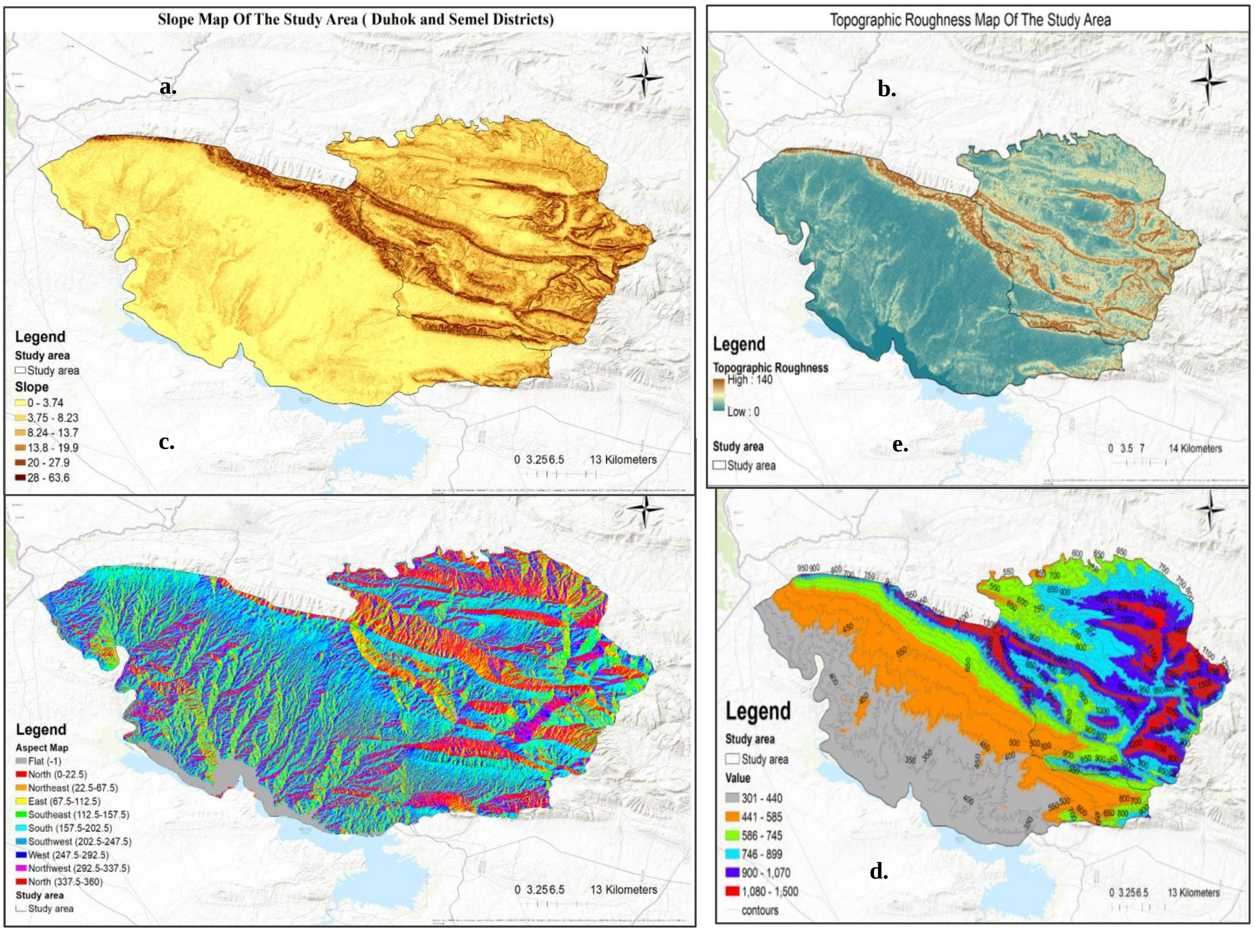
2.4. Topographic Characteristics:

In this part of the study, various maps are used to present topographic charac-teristics of the Semel and Duhok districts. These include contour lines, eleva-tion, hillshade, topographic roughness, and aspect, all contributing to a comprehensive understanding of the area's geography. The aim is to explore landscape features and evaluate drought effects, pinpointing regions at risk of environmental degradation.



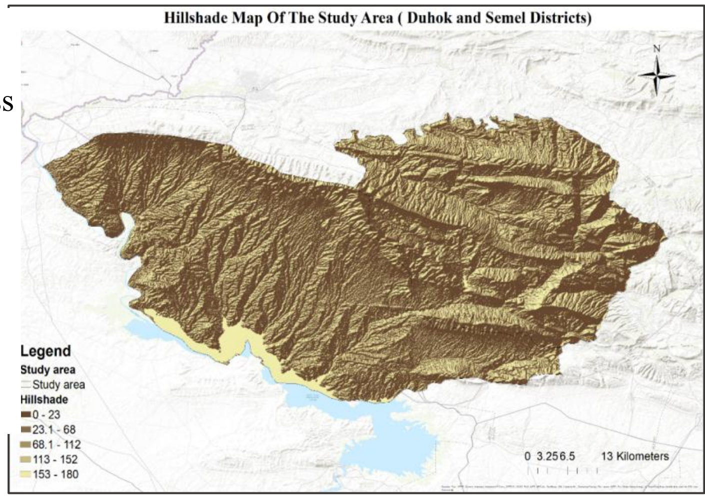


Figure 4: Topographic characteristics of the study area derived from a 30-meter resolution DEM: (a) Slope map; (b) Topographic roughness map map; (c) Aspect map; (d) Contour and elevation map; and (e) Hillshade map. These terrain parameters were used to evaluate the influence of topography on drought-induced degradation patterns in Duhok and Semel Districts.

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Slope maps (a.) are used to understand the topography of the region. It shows that the Duhok and Semel districts are characterized by a variety of slope values [4]. Steepest slopes (13.8-27.9 degrees) are in the northern and western parts of the study area, which largely cover the mountains surrounding Duhok district. The slopes gradually decrease towards Semel district. The lowest slope (0 - 3.74 degrees) category covers the largest area of the study area and is in Mosul Dam and Semel plains to the central and southern parts of the study area.
Elevation maps are useful for recognizing various land heights, such as mountains or hills. This term encompasses both natural aspects like mountains, plains, and valley [5].

Surface roughness (b.) can be regarded as the quality of a surface of not being smooth, it is an important factor in runoff and soil erosion [6]. The darkest areas on the map have the highest surface roughness values (e.g., dark brown color), while the blue areas on the map have the lowest surface roughness values. This pattern clearly reflects the topographic contrast between Semel and Duhok Districts. Semel District, located mainly in the western and southwestern parts of the study area, is dominated by blue shades, indicating low surface roughness. This flat terrain supports agriculture, settlements, and easier access to water bodies, making it more suitable for human activities. On the other hand, Duhok District, especially in the central, northern and eastern parts, contains a significant number of dark brown zones, representing rugged, elevated, and highly uneven landscapes.
Aspect (c.) is the direction that a slope faces, and it can be measured in degrees from 0 to 360. The aspect map is an important parameter to understand the impact of sun on local climate can be understood through the aspect mapping of the area, if it faces west, it's usually hottest in the afternoon. Most of the time, a west-facing spot is warmer than a spot facing east that's protected from the wind [7]. According to guidelines from ArcGIS Pro, the values of aspect are assessed. The study area is mostly sloping, with a variety of directions. The most common aspect directions are north, south, east, and west. There are also some areas with northeast, southeast, southwest, and northwest aspects. The flat areas are mostly located in the valleys and along the rivers. The aspect values of (0-32.5 and 323-360) indicate that they face north and south. These areas are likely to be the steepest and most exposed to sunlight, which can lead to increased erosion. The lightest areas on the map have the aspect values of (115-152, 153-185, and 215-248), indicating that they face east, northeast, and southeast. These areas are likely to be less steep and more protected from sunlight.
The elevation map (d.) map shows that the Duhok and Semel districts are characterized by a high degree of topographic variation. The highest elevations are found in the mountains to the north and east of the districts (Duhok district), while the lowest elevations are found in the valleys and plains to the west (Semel district). The elevation values were classified from DEM data (SRTM 30 m) using the Natural Breaks (Jenks) method in ArcGIS Pro, based on the range and statistical distribution of elevation values to represent distinct topographic zones

- Red (1300 to over 1400): represent the highest peaks reaching over 1400 meters, this area is mostly mountains.
- Dark Blue (900 to 1070): mostly represent fewer steeper mountains, hills, and valleys.

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- Orange (441 to 585): Represent the urban areas, other relatively flat areas.
- Grey (301-440): The lowest elevations (In the west) are Semel plains, Mosul Dam and other water bodies.

Hill shade map (e.) quantifies the sunlight reaching the hill's surface and replicates how the sun's impact, including lighting, shading, and shadows, shapes the topography of hills and canyons. The hillshade map displays the terrain relief and elevation patterns of the Duhok and Semel Districts. Darker areas indicate steeper and more rugged terrain, while lighter regions suggest flatter surfaces. According to the map, the southern and southwestern sections of the study area mainly within Semel District are characterized by lower elevations and smoother landforms. In contrast, the central, northern, and eastern areas primarily in Duhok District feature rugged hills and mountainous terrain.

2.5. Cultivated and Agricultural Trends:

This section explores how agricultural activities have developed over time and space in the Duhok and Semel districts, focusing on changes in cultivated land and the broader effects on the farming activities. Agricultural practices are recognized globally to be one of the leading causes of land degradation. The removal of natural vegetation for the purpose of cultivation renders soil susceptible to salinization, erosion, and the loss of nutrients. Moreover, agriculture consumes nearly 70% of the world's freshwater [8], and poor irrigation methods can exacerbate water scarcity and droughts.

Duhok and Semel have long been recognized for their agricultural abundance. The regions are characterized by a diverse and fertile terrain that supports a variety of products in various climatic zones and elevations. Wheat, barley, lentils, rice, vegetables, and fruits like grapes, apples, pears, and apricots are among the most significant commodities. Agriculture is a fundamental component of the local economy, as it guarantees the availability of sustenance and creates employment opportunities. Although the majority of produce is consumed locally, a small amount is transported to other regions of Iraq and the Middle East.

Due to the lack of data from 2004, this study compares agricultural data from 2014 and 2024, as provided by the Agricultural Directorate of Duhok. These figures show notable transformations in the types of crops grown, how water is used, and where cultivation occurs during both summer and winter seasons.

Overall Changes in Cultivated Areas (2014–2024)

As indicated in Table 2, the total area cultivated during the winter season dropped by 9%, declining from 264,468 dunams in 2014 to 241,689 dunams in 2024. The primary reduction occurred in rainfed wheat, which decreased by 15% (from 247,000 to 209,273 dunams). Rainfed barley also experienced a notable decrease of 25%. Meanwhile, the area used for irrigated wheat remained relatively constant, likely due to its low reliance on rainfall.

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Table 2: Comparison of the cultivated areas for the winter season in the study area in 2014 and 2024. Source: Directorate of Agriculture.

Winter Crop	**2014 (Donum)**	**2024 (Donum)**	**Change%**
Rainfed Wheat	247,000	209,273	-15%
Irrigated Wheat	9,370	21,000	124%
Rainfed Barley	1,950	4,870	150%
Chickpea	4,250	270	-94%
Lentil	25	-	-100%
Onion	460	755	64%
Broad bean	225	170	-24%
Turnip	25	230	820%
Cabbage	5	19	280%
Radish	41	69	68%
Chard	41	75	83%
Cauliflower	-	5	5%
Garlic	33	25	-24%
Potato	36	4,198	11561%
Beet	-	95	100%
Coriander	420	100	-76%
Corn	30	350	1067%
Sunflower	125	70	-44%
Lettuce	-	15	15%
Celery	12	-	-100%
Coriander	420	-	-100%
Total	**264,468**	**241,689**	**-9%**

Table 3: Comparison of the cultivated areas for the summer season in the study area in 2013-2014 and 2023-2024. Source: Directorate of Agriculture.

Summer Crop	**(Donum)**	**(Donum)**	**Change%**
Tomato	2,512	5,250	109%
Cucumber	1,286	770	-40%
Eggplant	331	356	8%
Zucchini	89	-	-100%
Bean	102	1,126	1009%
Watermelon	35,425	8,255	-77%
Cantaloupe	828	1,540	86%
Pepper	163	135	-17%
Onion	56	664	1086%
Armenian cucumber	103	163	58%

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Rice	-	35	100%
Potato	15	2,778	18,420%
Corn	20	-	-100%
Pumpkin	-	152	100%
Sunflower	70	67	-4%
Total	**41,000**	**21,291**	**-48%**

Despite the overall reduction trend, some drought-resistant crops, such as chickpeas, lentils, onions, cabbage, and turnips recorded a 10% increase, growing from 124,699 dunams to 135,751 dunams. This increase is mainly due to farmers shifting toward drought-tolerant and less water-dependent crops in response to reduced rainfall and limited water availability.

According to Table 3, the summer season saw a more dramatic reduction, with cultivated land shrinking by 48%. It fell from 40,999.5 dunams in 2014 to 21,291 dunams in 2024. Major summer crops like tomatoes, cucumbers, eggplants, and zucchini dropped significantly from 28,000 to 15,000 dunams. Other crops such as beans, watermelon, corn, potatoes, and sunflowers also declined, from 12,000 to 6,000 dunams.

According to the data from 2014 and 2024 reveal that Semel District had the largest cultivation area, particularly in Batel sub-district, with the recorded total 31,925 dunams of summer crops in 2014. However, Batel also saw the most obvious decline, with summer cultivation dropping by 89% to just 3,528 dunams in 2024.

In contrast, Fayda experienced remarkable growth in summer agriculture, expanding from 1,018 dunams in 2014 to 10,261 dunams in 2024. Fayda also topped winter crop production in 2024, cultivating 102,152 dunams, making it the most agriculturally active sub-district in Semel.

Table 4: Comparison of the cultivated areas for the summer and winter season in the study area in 2014-2015 and 2023-2024 for the sub-districts level. Source: Directorate of Agriculture in Duhok Governorate.

Area	*Sub-Districts of Semel*				*Sub-Districts of Duhok*		
Area of cultivated Summer Crops (in donums)	**Year**	**Semel Center**	**Fayda**	**Batel**	**Zawita**	**Mangesh**	**Total**
	2014	5022.5	1018	31925	978	2056	40999.5
	2024	2942	10261	3528	1218	3342	21291
Change %		-41%	908%	-89%	25%	63%	-48%
Area of cultivated Winter Crops (in donums)	**2014**	76820	72422	95695	3203	16328	264468
	2024	70352	102152	34310	3792	31083	241689
Change %		-8%	41%	-64%	18%	90%	-9%

In the Duhok District, Zawita sub-district had the lowest area of summer crops in 2014, with just 978 dunams, but recorded 25% increase to 1,218 dunams in 2024. Mangesh sub-district showed a notable resilience, with a 63% rise in summer crop cultivation and a 90% growth in winter crops—from 16,328 to 31,083 dunams.
Overall, Semel District experienced the most significant decline in cultivated areas, particularly due to major reductions in sub-districts like Batel, despite some progress in Fayda. In comparison, Duhok District showed greater stability and even growth, especially in Mangesh.
This trend indicates that regions experiencing an increase in agricultural activity, particularly in the cultivation of irrigated crops, are becoming increasingly dependent on water wells and surface water sources. As cultivated areas expand, especially those dedicated to water-demanding crops, the need for reliable irrigation grows correspondingly. This demand is frequently met through the development of new water wells or increased extraction of surface water. This helps to explain the rise in water well usage observed in 2024, reflecting a direct response to the prolonged drought conditions and the need to support agricultural activities

.2.6. Wildfire incidents:

Between 2012 and 2024, most wildfire incidents in Duhok Province occurred in Duhok District, which recorded about 80% of all cases. Other districts had much fewer incidents. This shows that wildfires were mostly concentrated in Duhok District.

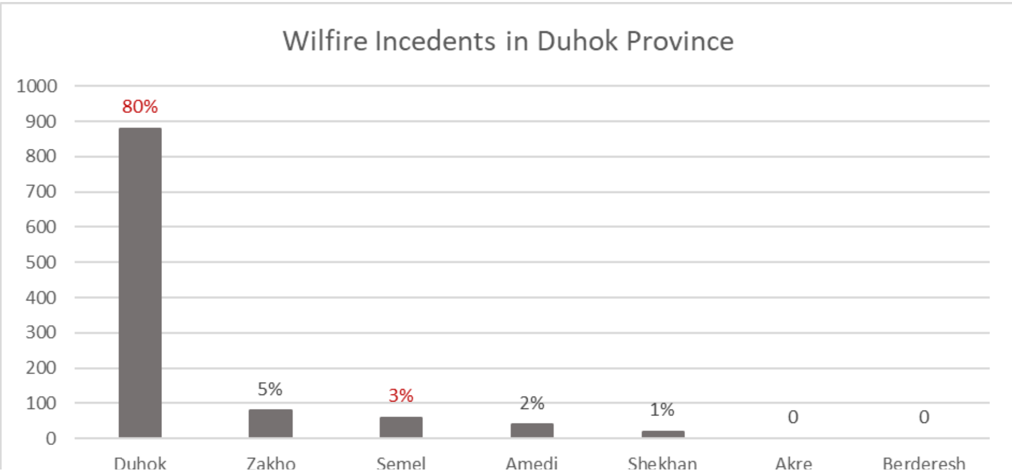

Figure 5: Wildfire incidents in Duhok Province between 2012 and 2024. The figure displays the number of wildfire incidents on the vertical axis, while the horizontal axis lists the districts. The percentages shown above each bar represent that district's proportion of the total wildfire incidents across the governorate.

One of the most serious contributing factors is recurrent drought, which has intensified wildfires in the Kurdistan Region in recent decades. The Kurdistan Regional Government has repeatedly reported increasing wildfire events in recent years, often coinciding with periods of below-average rainfall and high temperatures [9].

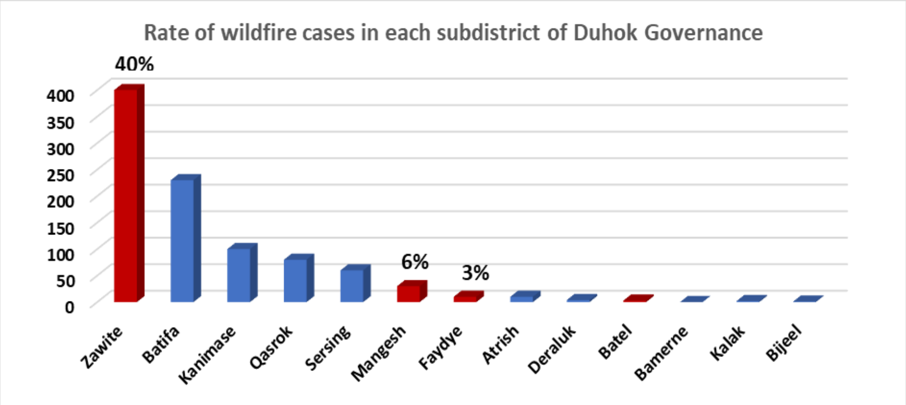

Figure 6: Rate of wildfire cases in each subdistrict of Duhok Province between 2012 and 2024. Red color columns show locations within the study area (Duhok & Semel), and blue represents other sub-districts in the Duhok Governorate. (Percentages above the bars show each sub-district's contribution to the governorate's total)

2.7. Water resources

Water sources within Semel and Duhok Districts include a variety of natural and man-made reservoirs. Their populations rely on a variety of water resources to meet their drinking, agricultural, industrial and other needs. The main types of water resources in Duhok and Semel Districts are:

- Surface water resources: Surface water resources are the main source of drinking water in both Districts. Tigris River and its tributaries are the main tributaries of the surface water in both regions. It is used for drinking and irrigation especially in summer seasons: The river flows along one side of Semel district, but it provides a significant water source for both districts in domestic and agricultural use. Water from Tigris is treated at the water treatment plant (Khrabdeem treatment plant) before being distributed to households and businesses.
- The streams: Many of the streams in Duhok and Semel Districts originate from the district's mountainous terrain, which also contributes to the local water supply for various purposes. Mountain springs are formed when groundwater flows to the surface on the side of a mountain. They come from a variety of sources, including:

- Streams fed by rainwater and snowmelt: This water flows downhill and collects into channels, forming streams.
- Streams fed by groundwater: Some of the streams in Duhok District and Semel District are fed by groundwater, which is stored in underground aquifers. When the water table intersects the land surface, groundwater flows to the surface, forming a stream.

- Rainfall: Rainfall in the region between the month of March and May (Autumn – Winter, Spring) are considered the main sources of water for irrigation, especially for the rainfed wheat and barley, the two main crops of the season.
- Ground water resources: Wells and Boreholes are the main sources of ground water in Semel and Duhok districts. They are used to extract water from underground aquifers. Both districts likely utilize wells and boreholes as decentralized sources of water, offering a degree of self-sufficiency for communities which they use for

drinking, irrigation, livestock watering and other needs in both districts specifically in rural areas which their residents greatly rely on. The accessibility and efficiency of these water sources contribute significantly to the overall water security of the respective districts.

- Wells serve as a source of drinking water for local communities, especially in areas where centralized water supply systems are not readily available. Additionally, they are used as a source for irrigation in rural areas, being predominantly agricultural rely on wells and boreholes to extract underground water for irrigation purposes to support the cultivation of crops such as fruits, wheat, barley, and other vegetables, supporting the district's agricultural activities.

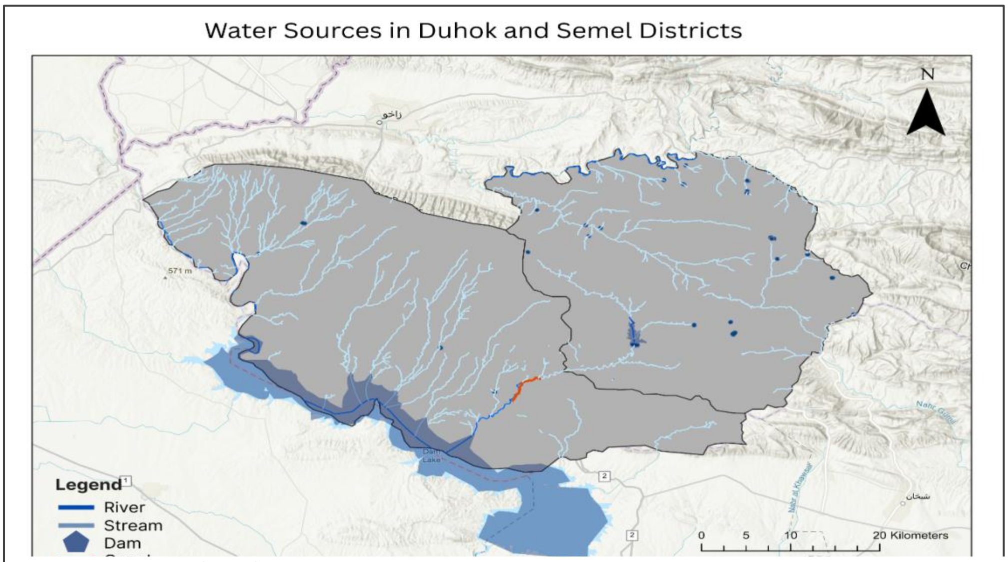

Figure 7: Map of Surface water resources in Duhok and Semel Districts. Source: Map created by the author using ArcGIS Pro.

Duhok and Semel are extracting more water from boreholes and wells in recent years than in previous years. This is due to a combination of factors, including population growth and climate change. The Kurdistan Regional Government (KRG) Ministry of Water Resources has reported that the number of active wells and boreholes in Duhok and Semel has increased by 20% in the past five years. The following table shows the number of boreholes in each of Duhok and Semel Districts in2004,2014 and 2024:

Table 5: Number of boreholes in Duhok and Semel Districts in2004,2014 and 2024, Source: Directorate of Groundwater in Duhok Governorate.

Wells	2004	2014	2024
Duhok	13	29	30
Semel	5	11	28 (including 3 artesian wells)
Total	18	40	58

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Purpose	(5) Agriculture (13) Drinking	(28) Agriculture (10) Drinking (2) Industry	(39) Agriculture (14) Drinking (5) Industry
Min Depth (m)	95	92	104
Max Depth (m)	255	330	680
Min Capacity (m^3/h)	15	15	30
Max Capacity (m^3/h)	200	300	290

According to the Directorate of Groundwater in Duhok (2024), there has been a decrease in groundwater levels in all districts of Duhok governorate, averaging between 15 to 20 meters in recent years. However, this decline is not consistent, with certain areas witnessing more substantial decreases of up to (60 to 70) meters.

Both districts are driven by extended drought conditions and heightened water demand. According to the data, Semel is the most impacted region, with a notable increase in deep wells, some reaching to depths of 600 to 680 meters, with others producing no water or categorized as artesian, signifying considerable aquifer depletion.

The increase of wells for agricultural and industrial purposes in Semel signifies a transition from dependence on surface water. Conversely, the Duhok district, especially in sub-districts such as Zawita and Mangesh, has seen heightened drilling activity and a gradual transition to agriculture. Wells are often shallower, and fewer exhibit evidence of failure or aquifer depletion. Although both districts face increasing strain, the data indicates that Semel is undergoing more severe groundwater stress and unsustainable water use, placing it at a greater risk of long-term water insecurity.

The most significant reduction in groundwater levels is observed in regions characterized by high population density and extensive agricultural practices as Semel's sub-district. Over the last two decades, the main purpose of these wells transitioned from delivering drinking water in 2004 to supporting agricultural irrigation by 2024, indicating that surface water supplies have proven insufficient to meet local agricultural demands. The growing reliance on groundwater has resulted in a notable rise in drilling depth from a maximum of 255 meters in 2004 to 680 meters in 2024, signifying a decline in shallow water tables and the need to tap into deeper aquifers. Despite these efforts, a steady decline in maximum water capacity started post-2014, indicating growing pressure on underground water sources and less natural recharge. These trends have a strong connection to the overarching degradation of the region's environment, characterized by decreased water availability, decreased plant cover, and excessive groundwater extraction, that together lead to ecological imbalance and degradation.

The administration of the Duhok dam reported that in 2022 the water level has dropped to 19 million cubic meters from 24 million cubic meters the previous year. The Iraqi Ministry of Water Resources also reported there has been a significant reduction in the water level of the Mosul Dam reservoir since 2021. In January of that year, the reservoir registered an elevation of 324.68 meters above sea level. However, by October 2024, this level had fallen to 318.5 meters, reflecting a decline of over 6 meters in just a little over two years.

The arid conditions induced by drought have also led to soil desiccation and increased salinity, further compromising the region's ecological balance. The scarcity of water resources has profound implications for both flora and fauna, disrupting habitats and triggering shifts in vegetation patterns. Additionally, the human population reliant on these water sources faces challenges in securing a sustainable and reliable water supply for agriculture, drinking, and other essential needs.

2.8. Population growth:

The population of Duhok and Semel districts saw a substantial increase, almost doubling from 374,174 to 711,600. The rise was mostly driven by urban development, with the urban population rising from 296,718 to 634,000, and the rural population had little growth, going from 77,456 to 77,600. In the Duhok district, the urban population rose from 231,424 to 451,500, whilst the rural population had a little decrease from 26,253 to 22,300. In the Semel area, the urban population increased substantially from 65,294 to 182,500, but the rural population had a moderate rise from 51,203 to 55,300. These indicators indicate a strong urbanization process and potential rural-to-urban migration.

Table 6: Population growth in Duhok and Semel District, based on data from the Duhok Directorate of Statistics.

Year	Population in Duhok and Semel district		
	Urban	Rural	Total
2004	296,718	77,456	**374,174**
2014	485,465	59,098	**544,562**
2024	634,000	77,600	**711,600**

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The Following framework illustrates research design and methodological Framework of the Study:

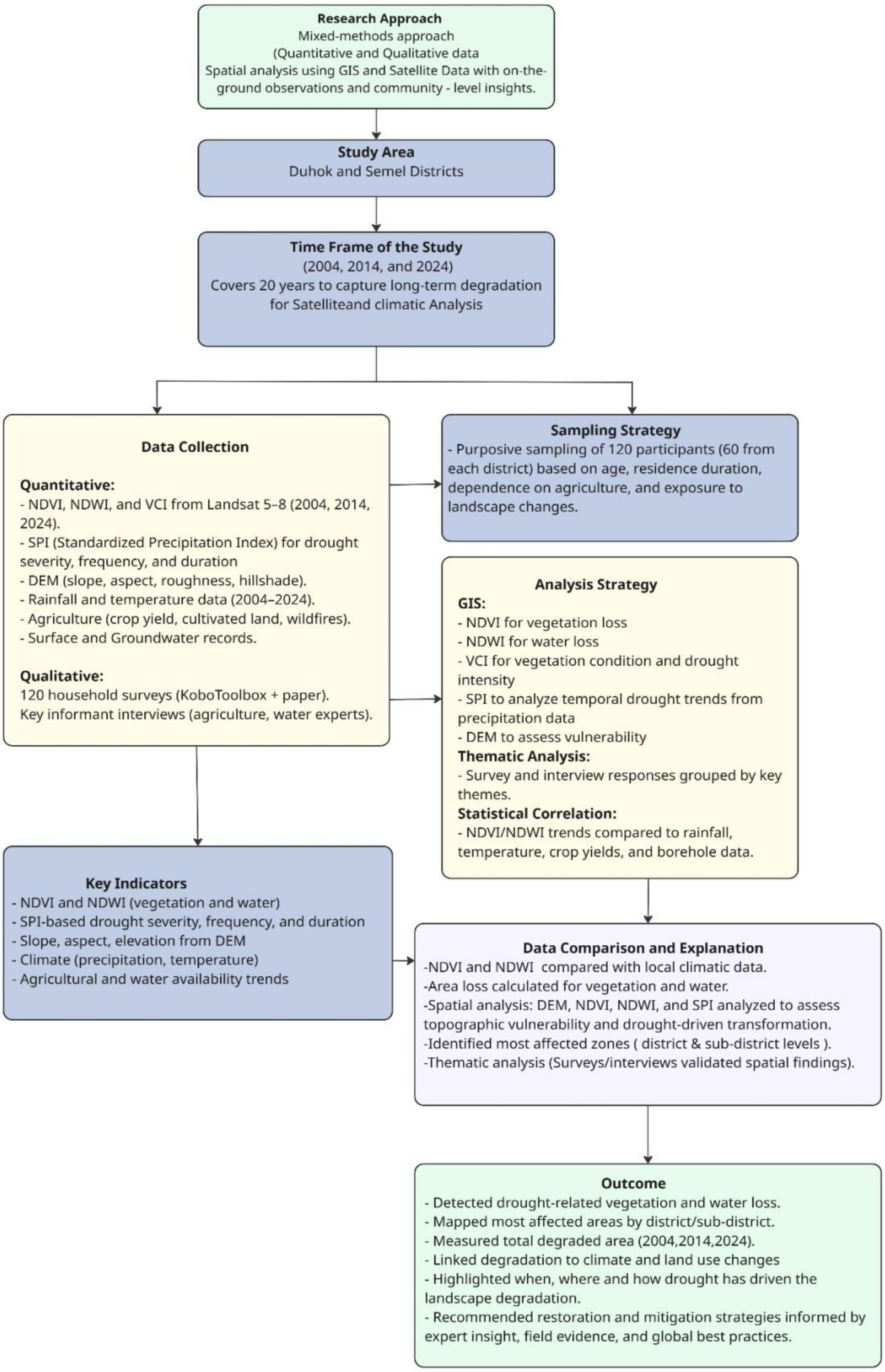


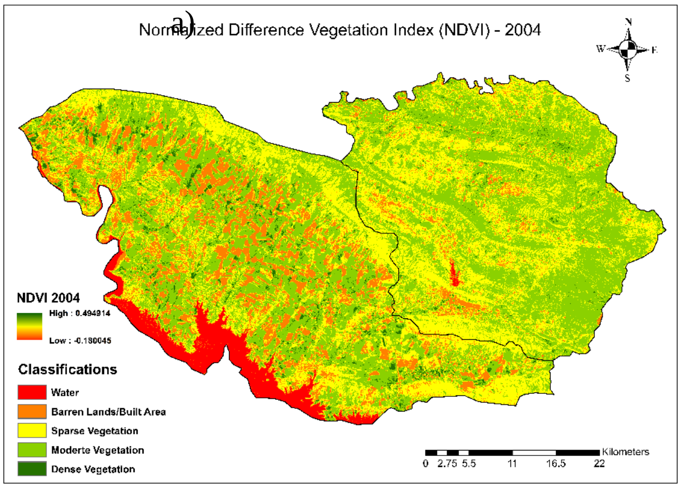
Figure 8: Research Design and Methodological Framework of the Study.

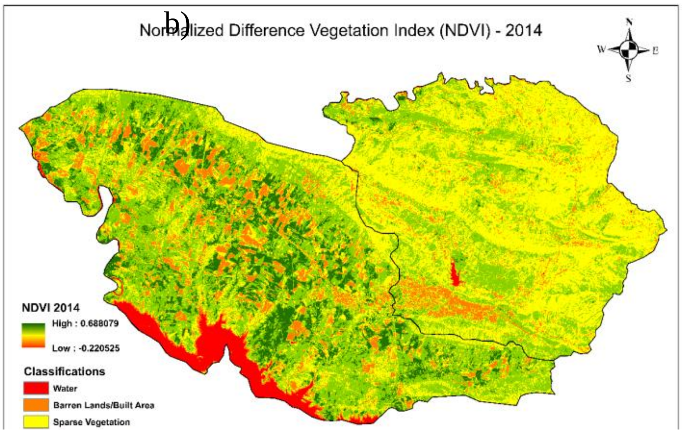
3. Discussion

This chapter summarizes the key results of a spatiotemporal study on drought-driven landscape degradation in the Duhok and Semel Districts between 2004 and 2024. The analysis integrates satellite-based vegetation indices (NDVI, NDWI, VCI), the Standardized Precipitation Index (SPI) to assess the severity, frequency, and duration of meteorological drought, the Vegetation Condition, and land use/land cover (LULC) classifications to track changes in landscape conditions over time. The findings reveal a significant decline in vegetation cover and moisture content. To better understand the variations in degradation severity, the study also considers topographic features such as elevation, slope, and hillshade. In addition, insights gathered from local communities and their observations on environmental shifts aligned the satellite-based findings. correlation and regression analysis are employed to examine the relationship between vegetation health and climate variables, confirming the influence of reduced rainfall and rising temperatures.

3.1NDVI Spatiotemporal Analysis (2004–2024):

This section presents the results of the NDVI analysis to assess vegetation cover changes in Duhok and Semel districts over a 20-year period. NDVI maps from 2004, 2014, and 2024 were generated to identify spatial and temporal vegetation dynamics.





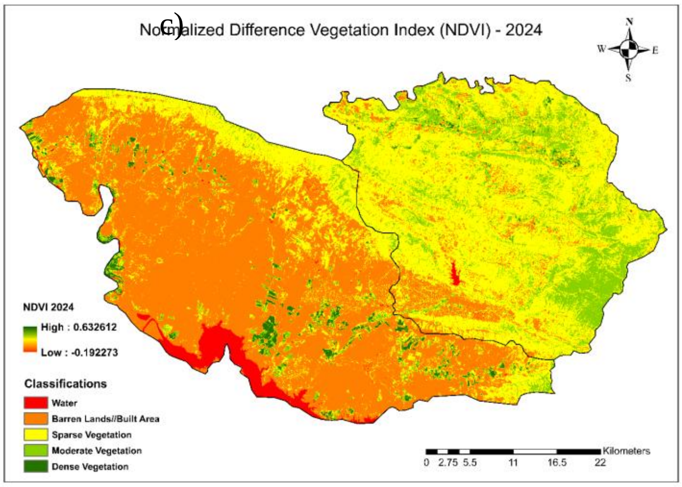


Figure 9: Normalized Difference Vegetation Index (NDVI) maps for Duhok and Semel Districts illustrating vegetation cover over time: (a) NDVI in 2004; (b) NDVI in 2014; and (c) NDVI in 2024.

The 2004 NDVI (a) values ranged from -0.18 to 0.49. Moderate and dense vegetation (green areas) dominated much of the northern and eastern parts of the study area. Sparse vegetation was widespread in southern and central Semel, with some barren land and water bodies in the far south (shown in red and orange).

In 2014 the NDVI (b)values increased, ranging from -0.22 to 0.68, indicating an improvement in vegetation in some areas. Dense vegetation expanded, especially in the western part of Semel, and moderate vegetation increased while barren lands decreased slightly compared to 2004.

In 2024 the NDVI (c) values ranged from -0.19 to 0.63, but a sharp increase in barren lands and built-up areas is visible, especially in the west and southwest. Dense vegetation was highly fragmented, with isolated green patches. The overall vegetation has significantly declined compared to 2014, reflecting severe drought and land degradation.

3.2 NDVI Change Detection and Class Area Comparison:

The change detection map derived from NDVI dataset for the years 2004, 2014, and 2024 illustrates how the landscape has changed over time in the Duhok and Semel districts. Using a threshold-based approach (±0.1 NDVI change), the maps are categorized into vegetation gain, vegetation loss, or no change. Between 2004 and 2014, vegetation noticeably increased, evident from the widespread green areas, this increase is at-tributed to the favorable rainfall during that decade. However, from 2014 to 2024, this trend reversed.

Large red patches on the map point to a sharp decrease in vegetation cover. When analyzing the entire period from 2004 to 2024, it showed an overall reduction in vegetation. This suggests that long-term environmental pressures such as recurring droughts, increasing temperatures, and changes in land use have eventually driven a decline in vegetation over the two decades. The table below shows the spatial extent (in km²) of each NDVI classification category for the years 2004, 2014, and 2024.

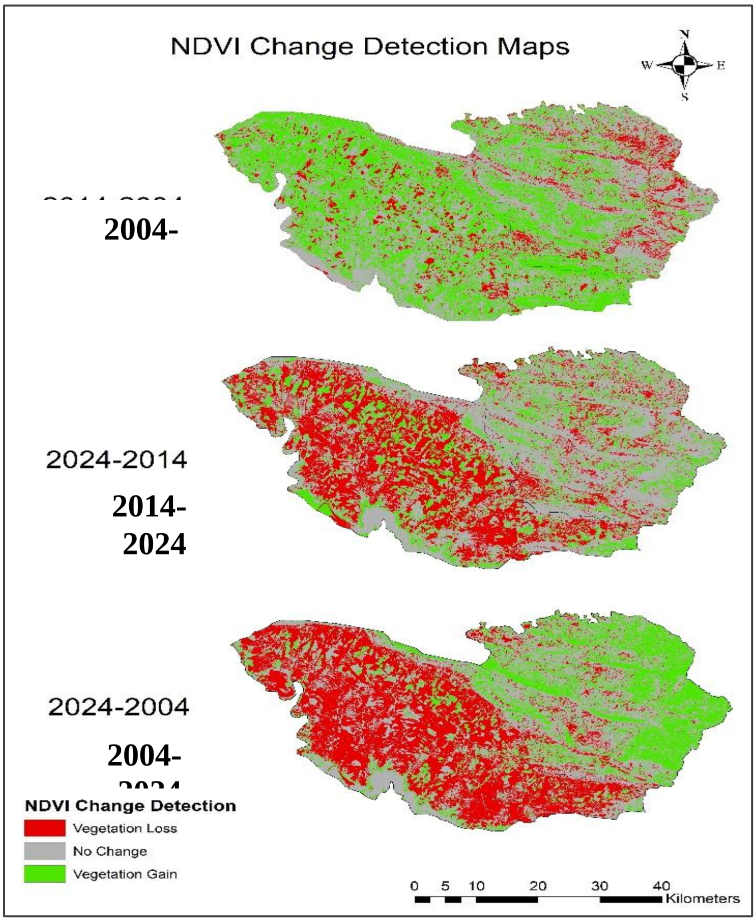


Figure 10: Vegetation Change Detection

The table below shows the spatial extent (in km²) of each NDVI classification category for the years 2004, 2014, and 2024.

Table 7: NDVI Class Area Comparison for the years 2004, 2014, and 2024.

NDVI/Year	Barren / Urban (km²)	Vegetation (km²)		Dense	Precipitation Trend	Temperature trend (Average)
		Sparse	Moderate			
2004	313.3	820.5	1105.9	52.0	533.2	23
2014	243.8	965.2	882.9	222.6	733.4	24.3
2024	1077.2	948.0	271.6	37.8	400.8	25.7

A significant decrease in dense and moderate vegetation is observed between 2014 and 2024, while barren lands expanded dramatically. These changes closely correspond to the trend of reduced precipitation throughout the same year, proving the clear correlation between decreased precipitation and vegetation degradation in the area.

In 2014, the Duhok and Semel districts saw much better vegetation and rainfall compared to 2004 and 2024, due to higher seasonal precipitation and more favorable climate conditions. That year recorded the highest annual rainfall (733.4 mm), especially during the winter and autumn—seasons crucial for replenishing groundwater and supporting agriculture. NDVI data reflected healthier vegetation in 2014, as the area had not yet been affected by the long-lasting drought, increasing temperatures, and groundwater depletion that became more severe by 2024.

3.3 NDWI Spatiotemporal Analysis (2004–2024):

This section presents the results of the NDWI (Normalized Difference Water Index) analysis for the years 2004, 2014, and 2024 to examine changes in surface water availability in Duhok and Semel districts. NDWI is a reliable indicator of water presence, and its spatial and temporal variation reflects the extent of water body reduction over time, particularly under drought stress.

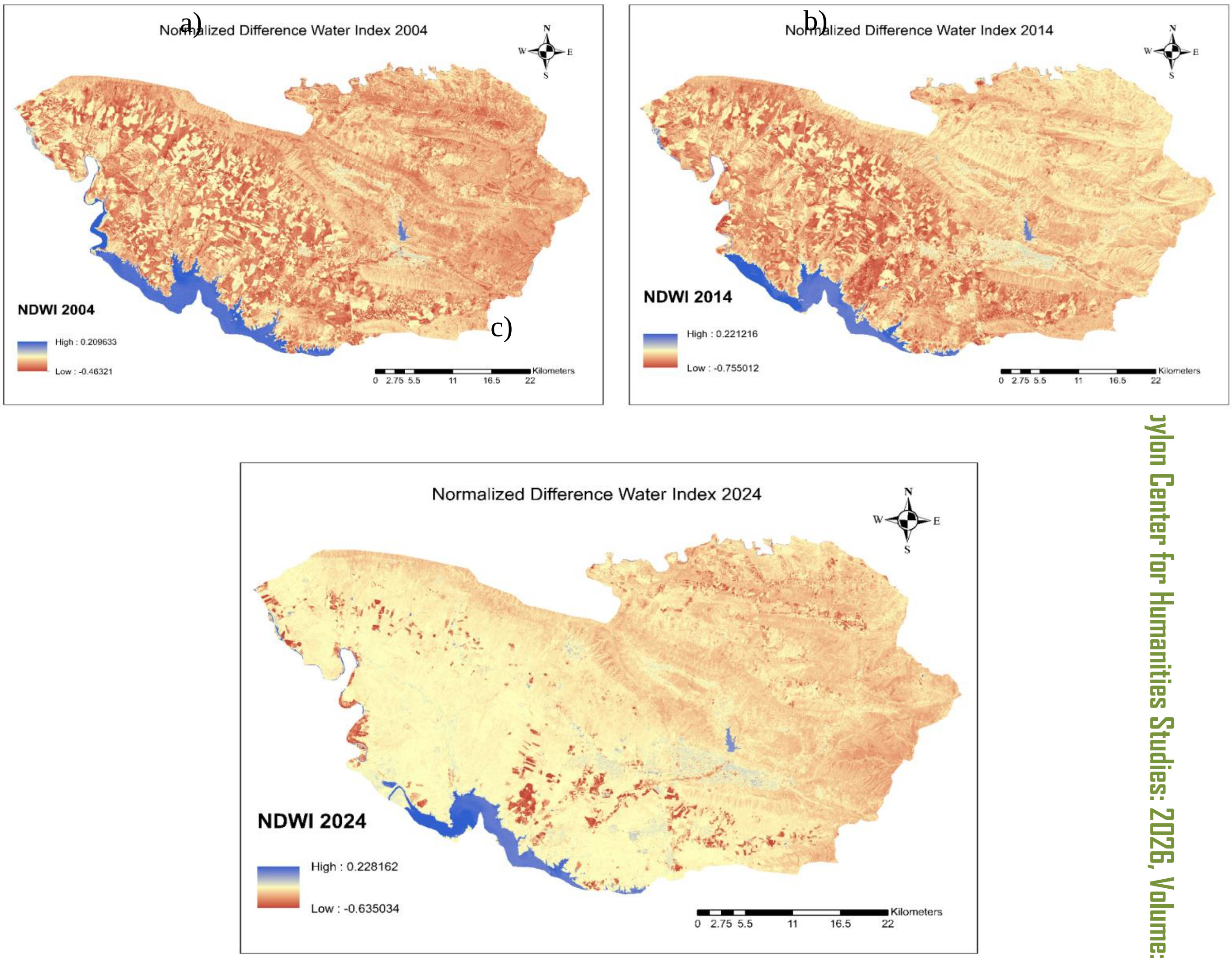


Figure 11: Normalized Difference Water Index (NDWI) maps for Duhok and Semel Districts illustrating vegetation cover over time: (a) NDWI in 2004; (b) NDWI in 2014; and (c) NDWI in 2024.

NDWI values in 2004 (a) ranged from -0.46 to 0.2. The total water-covered area was approximately 103.1 km², representing the highest extent among the three years. In 2014 (b) NDWI values increased slightly in maximum range (-0.7 to 0.22), yet water presence declined spatially. The total water area decreased to 78.9 km², reflecting a reduction of around 23.5% from 2004.

NDWI for the year 2024 (c) ranged between -0.63 and 0.22, with large portions of the map showing light yellow to red, indicating very low water presence. Water bodies became more fragmented and concentrated mainly in artificial reservoirs such as Mosul Dam and a few central streams The total surface water area declined further to 57.7 km², marking a 44.1% decrease from 2004.

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3.3. Water Change Detection and Area Comparison Over Time

To track and measure changes in surface water coverage across the Duhok and Semel districts, NDWI change detection maps were created using a threshold-based classification method applied to Landsat imagery from 2004, 2014, and 2024. NDWI values greater than 0 were categorized as water bodies, while values of 0 or less were labeled as non-water areas, three change detection maps were developed for the periods 2014–2004, 2024–2014, and 2024–2004. The 2014–2004 map shows early indications of water loss, primarily in the southern and western parts of the districts.

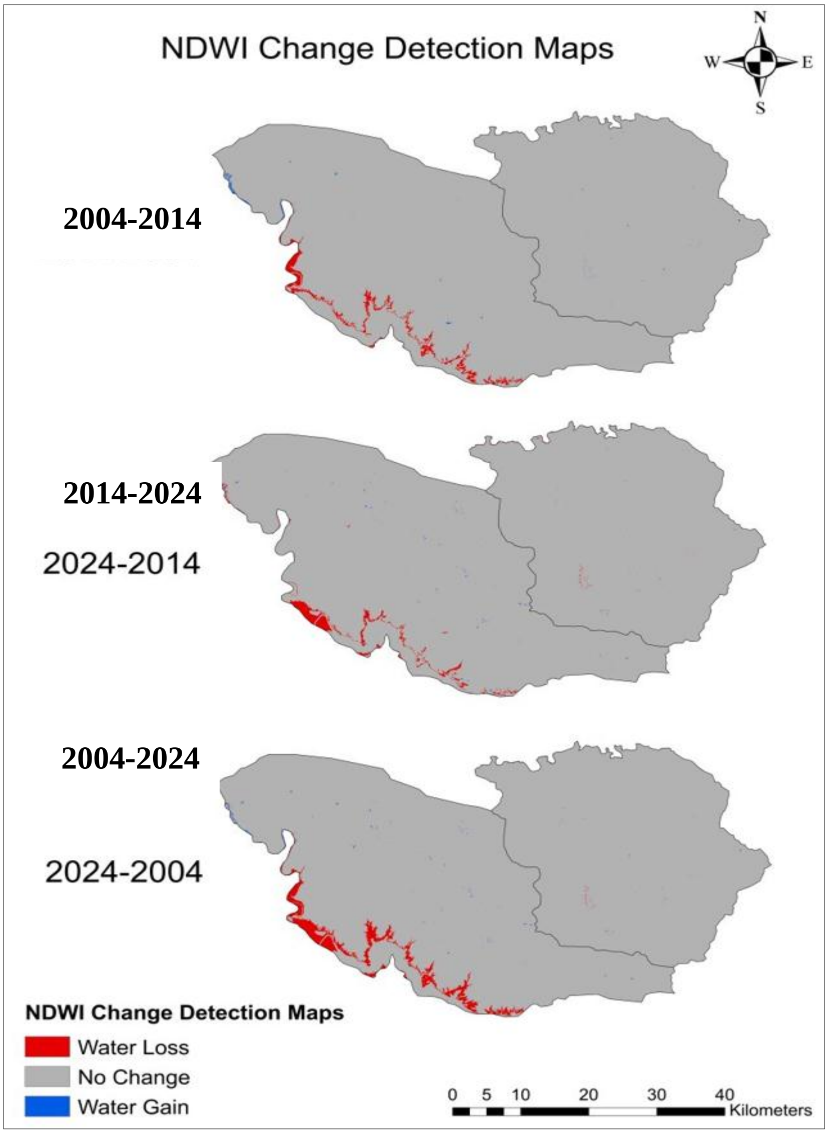

Figure 12: Water Change Detection

The 2024–2014 map continues to show water decline, though it is less extensive, pointing to a continued drying trend. The 2024–2004 map reveals the most significant long-term decline, with large red areas marking a considerable reduction in surface water. These patterns align with climatic observations and indicate rising vulnerability to hydrological drought, particularly in agricultural and semi-natural zones.

The table below shows the spatial extent (in km²) of each NDWI classification category for the years 2004, 2014, and 2024

Table 8: Water Area Comparison Over Time.

Year	Water Area (km²)
2004	103.1
2014	78.9
2024	57.7

The data indicates a consistent and significant reduction in surface water coverage over the 20-year period. Between 2004 and 2024, surface water declined by 45.4 km², equal to a 45% loss. This is a critical indicator of worsening drought conditions and escalating water stress in the Duhok and Semel districts.

3.2Land Use/Land Cover (LULC) Results (2004–2024):

The Land Use/Land Cover maps from 2004, 2014, and 2024 reveal significant changes in land cover across the Duhok and Semel Districts over a 20-year period.

In 2004, the landscape was primarily covered by agricultural areas and forests (shown in green). Sparse vegetation and barren land were also present but covered a smaller area compared to the extent observed in later years.

By 2014, built-up areas (represented in red) had expanded considerably, particularly near urban zones and transportation routes. During this period, agricultural land decreased, and sparse vegetation increased, indicating early signs of vegetation stress.

By 2024, barren land (shown in cream) had expanded further. Sparse vegetation areas also grew significantly, mainly due to vegetation loss driven by drought and land degradation. Urban areas continued to grow, while agricultural and forested areas declined further.

These trends were consistent with NDVI and NDWI data and demonstrate that both human activities and climate factors, such as drought, have played a major role in accelerating land degradation across the region. These changes can be clearly observed on the following map:

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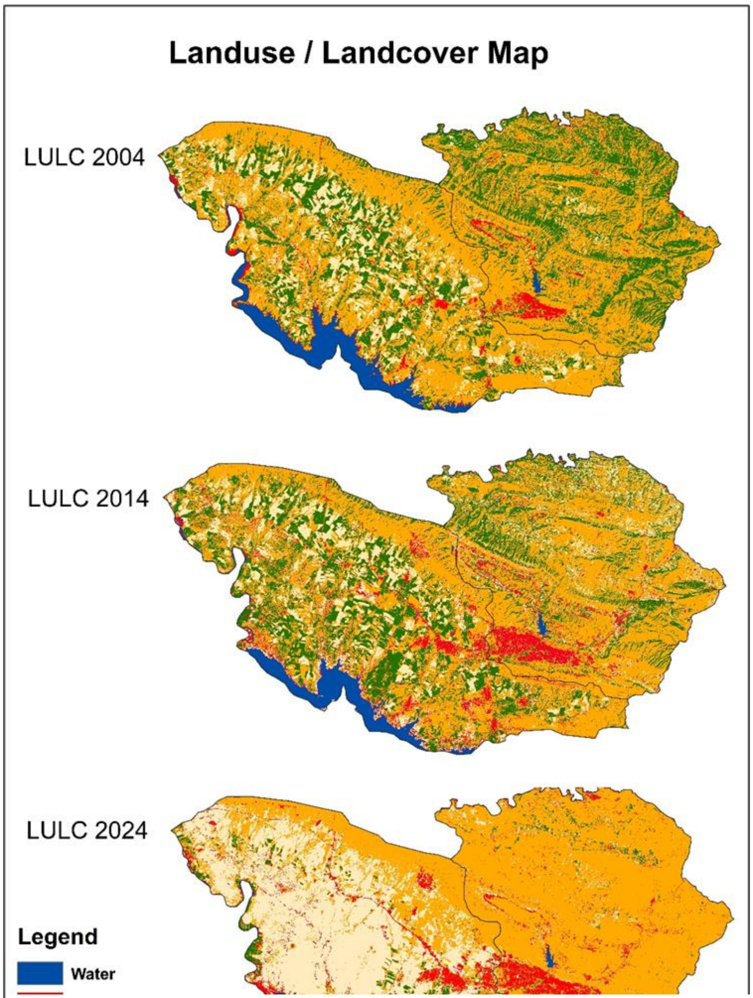

Figure 13: Landuse/landcover map 2004,2014 and 2024.

3.3Vegetation (NDVI), Topography and Water Availability (NDWI) Correlation:

The 2024 NDVI and NDWI study for the Duhok and Semel districts highlights a clear spatial connection between vegetation health, surface water availability, and the region's topography. Higher NDVI values, representing healthy plant life, often align with moderate to high NDWI values, which suggest better water retention or surface moisture. These favorable conditions are notably observed in areas like Mangesh and Zawite, which sit at higher elevations (900–1400 meters), feature steep slopes and rugged terrain. Such natural barriers limit human activity and prevent extensive land modification. Additionally, the north- and east-facing slopes reduce direct sunlight, helping to lower evaporation rates. Shaded hills, as shown by hillshade analysis, create microclimates that are especially conducive to plant growth.

On the other hand, areas such as Semel Center, Batel, and parts of Fayda show low NDVI and NDWI values, indicating weakened vegetation and a scarcity of water. These sub-districts lie in flatter lowland areas (300–600 meters) with minimal surface variation and south- or west-facing slopes that are more ex-posed to the sun, causing surfaces to dry out faster. Hillshade data supports this, showing these zones receive more direct sunlight, which increases evapotranspiration and puts additional stress on vegetation. These flatter, more accessible terrains are also more susceptible to urban development and struggle with water retention.

Overall, the findings highlight that vegetation decline in 2024 is closely tied to a combination of water availability and topographic exposure. Plants are thriving more in elevated, rugged, and shaded regions with natural moisture, while areas that are flat, dry, and exposed are seeing more vegetation loss.

3.4Drought Duration, Severity and Frequency:

This section includes the analysis of the Vegetation Condition Index (VCI) and the Standard Precipitation Index (SPI) to assess drought severity, duration, and frequency in Duhok and Semel Districts between 2004 and 2024. VCI was used to evaluate vegetation stress levels based on NDVI data, while SPI was applied to examine long-term precipitation variability. These indicators were selected to provide a clearer understanding of how drought has progressed over time and to quantify its impact on vegetation health and landscape degradation in the study area.

3.4.1 Vegetation Condition Index (VCI) Analysis:

The Vegetation Condition Index (VCI) was computed to evaluate drought severity across the Duhok and Semel Districts for the years 2004,2014 and 2024. VCI is a commonly used drought indicator derived from NDVI data, indicating how present vegetation conditions compare to the historical minimum and maximum NDVI values. It is especially effective in detecting drought stress at the pixel level. The VCI was determined using the following equation:

$VCI = (NDVI\ \text{-}Year - NDVI\_min) / (NDVI\_max - NDVI\_min) \times 100$

For this analysis, NDVI values from 2004, 2014, and 2024 were used to define the historical range.

The 2024 VCI results were categorized into five groups, based on the thresholds suggested by Kogan (1995) [10]:

-Extreme drought (VCI <10%)
-Severe drought (VCI 10–20%)
-Moderate drought (VCI 20–35%)
-Near-normal vegetation (VCI 35–50%)
-Good vegetation condition (VCI >50%)

The Following table shows the area and percentage of land in each Vegetation Condition Index (VCI) range for the years 2004, 2014, and 2024 in Duhok and Semel Districts.

Table 9: Area and percentage of land in each Vegetation Condition Index (VCI) range for the years 2004, 2014, and 2024.

Years		2004		2014		2024	
Range %	Drought Intensity	Area	Percentage	Area	Percentage	Area	Percentage
<10%	Extreme Drought	423	18%	568	24%	1671	70%
10-20%	Severe Drought	70	3%	69	3%	72	3%

20-35%	Moderate drought	131	5%	92	4%	97	4%
35-50%	No Drought	159	7%	95	4%	94	4%
50-100%	Good Vegetation	1610	67%	1570	66%	460	19%

The results show a large increase in areas with VCI below 10% from 2004 to 2024, and a significant decrease in areas with VCI above 50%. In 2004, most of the land had good vegetation conditions.

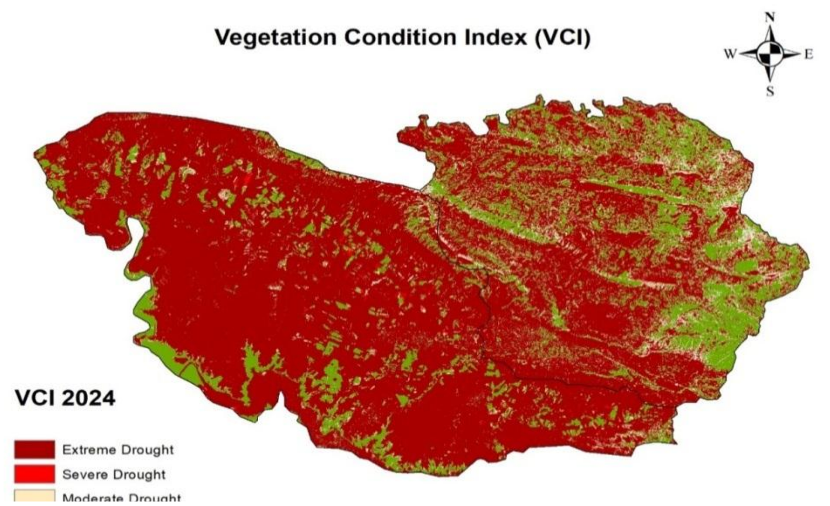

Figure 14: Vegetation Condition Index (VCI) range for the year 2024

By 2024, most of the areas were under extreme drought, Semel showed a higher concentration of extreme and severe drought areas compared to Duhok (See Figure 14), indicating it was more affected by vegetation stress and drought intensity. These changes reflect the increasing impact of drought over time and support the NDVI findings that showed vegetation decline during the same period.

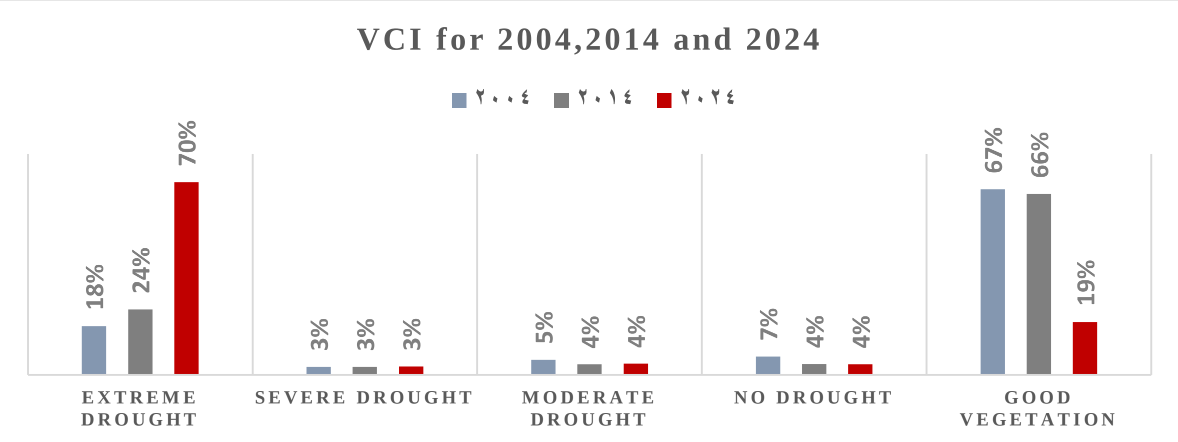

Figure 15: Comparison of Vegetation Condition Index (VCI) categories in 2004, 2014, and 2024 in Duhok and Semel Districts

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Change in percentage of land under each drought intensity level based on Vegetation Condition Index (VCI) in 2004, 2014, and 2024 in Duhok and Semel Districts. The chart illustrates a significant increase in areas affected by extreme drought, rising from 18% in 2004 to 70% in 2024. At the same time, the proportion of land with good vegetation conditions decreased from 67% to 19%, indicating a strong shift toward more severe drought conditions, particularly in Semel.

3.4.2 Standard Precipitation Index (SPI):

The SPI-12 (Standard Precipitation Index over a 12-month period) was utilized to analyze long-term drought trends in the study area from 2004 to 2024. This index adjusts annual precipitation based on the historical average and standard deviation, providing an objective framework for identifying the severity of both droughts and wet conditions.

Table 10: Standard Precipitation Index analysis study area from 2004 to 2024.

Years	SPI-12 Formula	Drought Category
2004	0	Near Normal
2005	0	Near Normal
2006	1	Moderately Wet
2007	-1	Moderate Drought
2008	-1	Moderate Drought
2009	0	Near Normal
2010	-1	Moderate Drought
2011	0	Near Normal
2012	0	Near Normal
2013	1	Moderately Wet
2014	1	Moderately Wet
2015	0	Near Normal
2016	0	Near Normal
2017	-1	Moderate Drought
2018	2	Extremely Wet
2019	0	Near Normal
2020	2	Extremely Wet
2021	1	Moderately Wet
2022	-2	Extreme Drought
2023	0	Near Normal
2024	-1	Moderate Drought

Among the 21 years examined, nine were classified as “Near Normal,” suggesting precipitation levels close to the historical mean. Six years (2007, 2008, 2010, 2017, 2022, and 2024) were labeled drought years with SPI values at or below –1. Notably, 2022 registered the harshest drought, categorized as “Extreme Drought” with an SPI value of –2. The remaining five drought years were identified as experiencing “Moderate Drought” with SPI values of –1.

Conversely, five years were marked by wetter-than-average conditions. Specifically, 2018 and 2020 were considered “Extremely Wet” with SPI values of 2, while 2006, 2013, and 2021 were rated as “Moderately Wet” with SPI values of 1.

3.5Relationship Between Vegetation Condition and Climatic Factors:

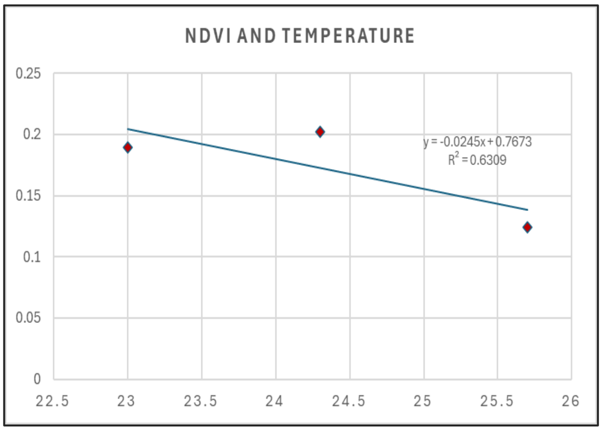
To analyze the relationship between vegetation condition and climatic factors, the mean NDVI values for the years 2004, 2014, and 2024 were extracted using the Zonal Statistics as Table tool in ArcGIS. This technique summarized pixel values within the study area zones to generate mean NDVI values. These were then used in a statistical analysis to assess their relationship with annual precipitation, temperature, and Vegetation Condition Index (VCI) values.

The table below shows the Mean NDVI values alongside total precipitation, average temperature and Vegetation Condition Index results for the year 2004, 2014 and 2024 for the study area:

Year	NDVI Mean	Total Annual Precipitation (mm)	Average Annual Temperature (°C)	VCI (% Good Vegetation)
2004	0.1893	533.2	23	67
2014	0.2018	733.4	24.3	66
2024	0.1243	400.8	25.7	19

Table 11: NDVI, Climatic Variables and Vegetation Condition Index results

Both Pearson correlation and simple linear regression were performed using SPSS. The Pearson correlation revealed a strong positive association between NDVI and precipitation ($r = 0.88$), a strong negative association with temperature ($r = –0.79$), and a very strong positive correlation with VCI ($r = 0.98$). These results suggest that NDVI tends to rise with increased rainfall and improved vegetation conditions, while it generally decreases with rising temperatures.



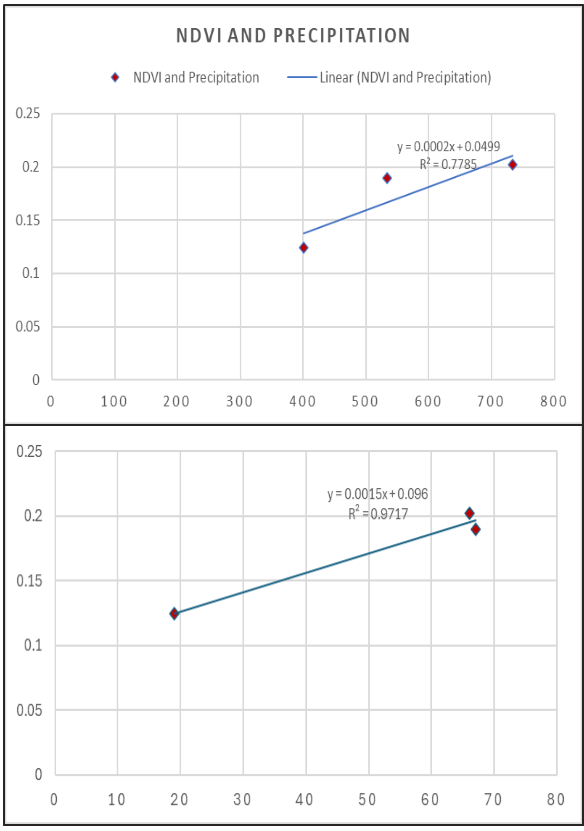


Figure 16: Pearson correlation between mean NDVI and climatic variables in Duhok and Semel Districts: (a) NDVI and total annual precipitation; (b) NDVI and average annual temperature; and (c) NDVI versus Vegetation Condition Index (VCI).

The findings of this research confirm that the landscapes of Duhok and Semel districts have undergone significant change between 2004 and 2024. NDVI and NDWI analysis revealed a steady decline in both vegetation cover and surface water over the past 20 years. NDVI-based land cover classification shows a sharp increase in barren and urban areas, expanding from 313.3 km² in 2004 to 1077.2 km² in 2024. During the same period, moderate vegetation areas declined from 1105.9 km² to 271.6 km², and dense vegetation dropped from 52.0 km² to 37.8 km². Sparse vegetation showed an increase from 820.5 km² to 948.0 km².

NDWI analysis confirmed a decline in surface water resources, with water covered areas shrinking from 103.1 km² in 2004 to 57.7 km² in 2024, a 44% reduction. These biophysical changes coincided with a decline in average annual precipitation from 533.2 mm to 400.8 mm and a rise in temperature from 23°C to 25.7°C over the same period. This shift toward a hotter and drier climate has reduced vegetation productivity and water retention capacity, particularly in lowland agricultural areas. Drought has placed increasing stress on vegetation and reduced the agricultural productivity of the Duhok and Semel districts between 2004 and 2024, as evidenced by both VCI and SPI analyses.

The Vegetation Condition Index (VCI) reveals a significant shift toward more severe drought categories over time. In 2004, 67% of the land area exhibited healthy vegetation (VCI > 50%), while only 18% experienced extreme drought conditions (VCI < 10%). By 2024, this trend had flipped: 70% of the region faced extreme drought, and just 19% maintained good vegetation health, indicating extensive stress across plant life. Semel District was notably more impacted, showing a greater occurrence of extreme and severe drought areas compared to Duhok.

The Standardized Precipitation Index (SPI-12) analysis corroborates these patterns. Over the 21-year period examined, six years were identified as drought periods with SPI values at or below −1. The most severe drought was recorded in 2022, with an SPI of −2, signifying an extreme drought. Other years (2007, 2008, 2010, 2017, and 2024) were marked as moderate droughts. The increasing concentration of drought years, especially after 2010, indicates a growing frequency and duration of drought events, compounding stress on both native vegetation and cultivated lands.

Survey responses revealed that many locals have observed noticeable environmental shifts, such as shrinking green areas, drier soil, and more degraded agricultural and grazing lands. Since a large portion of the population depends on agriculture and livestock, they are directly affected by these environmental changes. These observations are consistent with studies from other drought affected regions, which report similar consequences, including lower crop yields, greater economic instability, and forced changes in land use practices.

5. Patents

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Data Availability Statement: The datasets used and analyzed during this study are available from the corresponding author upon request.

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