Temporal variation of Tharthar Lake using time series analysis and Geomatics

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Abstract:

The study area is geographically located in the northwest of Salah al-Din Governorate and the north of Al-Anbar Governorate, approximately 120 km northwest of Baghdad. It lies within the administrative boundaries of Salah al-Din Governorate. The focus of the analysis is Lake Tharthar, Iraq's largest natural depression, located between latitudes 34°38'48"–33°34'55" N and longitudes 42°55'41"–43°40'53" E. results analyzes land cover changes over a 30-year period (1994–2024) using multiple remote sensing indices—NDVI, SAVI, NDWI, TCWI, and WRI—across a 14,266.38 km² area. The results highlight significant transformations in vegetation cover and water bodies. NDVI and SAVI data show a substantial decline in vegetation from 1994 to 2014, with a slight recovery by 2024. Bare land areas expanded notably until 2014, followed by a marginal decrease. Water bodies exhibit a consistent decrease in area across NDVI, SAVI, NDWI, and WRI, indicating a potential long-term drying trend. However, TCWI data reveal a sharp increase in water coverage in 2024, suggesting seasonal variation, hydrological interventions, or the index's higher sensitivity to surface moisture. These findings underscore the importance of using multiple indices for comprehensive environmental monitoring.

Keywords: NDVI, SAVI, NDWI, TCWI, WRI

Introduction:

Remote sensing indices such as the Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), Normalized Difference Water Index (NDWI), Thermal Condition Water Index (TCWI), and Water Requirement Index (WRI) have been widely used to monitor land cover changes, vegetation health, water availability, and hydrological dynamics over large spatial and temporal scales. These indices provide critical insights into environmental trends including deforestation, desertification, urbanization, and water resource fluctuations, which are essential for sustainable land and water management [9].

Lake Tharthar is an important model for studying temporal changes in artificial water bodies. The observed changes in water volume, temperature, and levels require continued attention from researchers and decision-makers to ensure the sustainability of water resources and protect the local environment [14]. Lake Tharthar has witnessed significant changes over the decades, whether in water volume, levels, or surface temperature, as a result of multiple factors such as climate change, urban expansion, and water policies [20]. A study by Rousta et al., [19] analyzed the climatic water balance of Lake Tharthar during the period from 1980 to 2014. The study showed that the relationship between rainfall and evaporation/transpiration directly affects water levels in the lake, leading to periods of drought or water surplus that impact the local environment and agriculture.

Ahmood et al., [3] used remote sensing and geographic information systems (GIS) techniques and their results showed that the surface temperature of Lake Tharthar varies seasonally, with temperatures rising during the spring and summer and falling in the fall and winter. These temperature changes affect the lake's ecosystem, including algal growth and the distribution of organisms. Rahi and Halihan [17] indicated that water bodies such as Lake Tharthar affect the levels of the Euphrates River. Changes in water levels in the lake cause similar changes in river levels, impacting irrigation and agriculture in the surrounding areas. Al-Jabri and Al-Maadidi [5] conducted a study using geographic information systems (GIS) and digital elevation models to analyze the topography and water volume of Lake Tharthar. The results showed that the model used was effective in representing the lake's topographical characteristics, with an accuracy of up to 98.3% in calculating areas and 99.99% in estimating water volume.

Hamza and AL-Razak, [10] focused on examining the topographic and hydrological characteristics of Lake Tharthar and its adjacent regions through the application of radar data and a Digital Elevation Model (DEM), both of which are essential datasets in the field of Geographic Information Systems (GIS). By employing the DEM as foundational input within GIS platforms, the study aimed to merge spatial data layers to generate comprehensive surface and hydrological insights for effective environmental and water resource analysis around the lake.

Geomatics has been widely used in representing spatial and temporal variation of land cover and land use especially spectral indices in different parts Iraq [23, 15, 2, 1, and 4]. In the meanwhile, these technologies have been used in different endeavors to express water use efficiency and management [6, 24, 16, 11, 7].

The objectives of this study could be briefed as quantify land cover changes over time, and to assess vegetation degradation and recovery patterns besides, evaluating changes in surface water extent and distribution.

Materials and Methods

1. Study Area Boundaries:

The study area is geographically located in the northwest of Salah al-Din Governorate and the north of Al-Anbar Governorate, approximately 120 km northwest of the capital, Baghdad, within the administrative boundaries of Salah al-Din Governorate.

Lake Tharthar is considered the largest natural depression in Iraq. It lies between latitudes (34°38'48" – 33°34'55") North and longitudes (42°55'41" – 43°40'53") East. In terms of satellite coordinates, it corresponds to Path 169 and Rows 36 and 37 of the Landsat satellite.

Figure (1): Map of Iraq showing the study area

Study Stages:

Field Study Stage: This stage included a visit to the study area to observe key features, particularly the nature of land use around the lake, with an emphasis on human activities and water utilization. The purpose of this fieldwork was to compare on-the-ground observations with satellite imagery interpretations.

Office Work Stage: his stage involved downloading satellite imagery of the study area for the purpose of processing, performing image clipping and applying spectral indices. It also included mapping, extracting the surface area of the water body in the region, and understanding its relationship with human activities around Lake Tharthar. Furthermore, climate data was analyzed to assess its impact on the lake's environment. Previous studies focusing on the geological, geomorphological, and hydrological aspects of the study area were also reviewed to establish a general overview of the region.

1: Downloading Satellite Imagery: Satellite images were obtained through the Earth Explorer website, a primary search interface that provides access to satellite data archived by the United States Geological Survey (USGS), especially Landsat data, which are essential for aerial data and elevation modeling used in map creation.

The process starts by creating a new account on the website, as its functions cannot be accessed without registration. Then, using the Search Criteria tab, the study area is specified either by entering its name or coordinates, or by manually selecting it. The Date Range option allows users to specify the desired time period for the imagery, and the Cloud Cover setting helps limit cloud presence. The Result Option is used to define the number of desired results.

In the Data Sets tab, which includes USGS archives (notably the Landsat section organized by group and processing level), the required satellite missions are selected. After clicking Results, suitable images can be previewed to ensure coverage of the study area, examine cloud coverage, and check metadata before downloading the image.

2: Remote Sensing Data Used in the Study: The downloaded raster data are in the form of digital images recorded by a sensor, consisting of rows and columns. The intersection of each row and column forms a pixel, representing a digital number captured from the electromagnetic radiation reflected by objects, stored as a satellite image (Abdu, 2013).

The study primarily relied on data from the American Landsat satellite, specifically Path 169 and Rows 36 and 37, which fully cover the study area. A total of eight satellite images were used, all taken in September of the years 1994, 2004, 2014, and 2024, as shown in Table (1). The compressed image files included spectral bands with wavelengths and spatial resolutions appropriate for the study's objectives.

Table (1): Satellite Images Used in the Study

Date	Path/Row	Sensor	Spacecraft ID	Years
15/9/1994	169/36 169/37	TM	Landsat 5	1994
2/9/2004	169/36 169/37	ETM+	Landsat 7	2004
22/9/2014	169/36 169/37	OLI	Landsat 8	2014
25/9/2024	169/36 169/37	OLI-2	Landsat 9	2024

3- Clipping and Merging of Satellite Imagery: The clipping process, particularly for delineating the study area, is considered one of the most important stages as it reduces data volume and limits processing and analysis to the area of interest. This in turn accelerates processing and minimizes the required time. The Clip operation was performed using the Extract by Mask tool, and the Merge operation was done using the Mosaic tool—both available in ArcGIS Pro under the Arc Toolbox.

4- Digital Processing of Satellite Imagery: The aim of digital image processing is to enhance visual interpretability by increasing the distinction between features, which facilitates easier visual interpretation of the satellite imagery. It also increases the amount of information that can be interpreted and extracted.

The processing was carried out using a series of mathematical algorithms implemented in ArcMap, based on the following equations:

a- Digital Processing for Landsat 5 (TM) and Landsat 7 (ETM+) Sensors (According to the Landsat 5–7 Data User Handbook):

The digital processing of imagery acquired by Landsat 5 (Thematic Mapper - TM) and Landsat 7 (Enhanced Thematic Mapper Plus - ETM+) follows the standard procedures outlined in the Landsat 5-7 Data User Handbook. These steps aim to convert raw digital numbers (DN) into physically meaningful values such as radiance or reflectance, which are essential for accurate analysis:

$$L_\lambda = \frac{LMAX_\lambda - LMIN_\lambda}{QCALMAX - QCALMIN} \cdot (QCAL - QCALMIN) + LMIN_\lambda \quad \text{.........(1)}$$

b- Conversion of Radiance to Top of Atmosphere (TOA) Reflectance

$$\rho_p = \frac{\pi \cdot L_\lambda \cdot d^2}{ESUN_\lambda \cdot \cos\theta_S} \quad \text{.....................(2)}$$

Where:

- ρp\rho_pρp = **Planetary reflectance** (unitless)
- π\piπ = **Mathematical constant**, approximately equal to 3.14159
- LλL_\lambdaLλ = **Spectral radiance** at the sensor aperture
- d2d^2d2 = **Square of the Earth–Sun distance** in astronomical units (AU)
- ESUNESUNESUN = **Mean solar exoatmospheric irradiance** (W/m²/µm)
- θS\theta_SθS = **Solar zenith angle**, in degrees

c- Digital Processing for the Landsat 8 (OLI) and Landsat 9 (OLI-2) Sensors, According to the Landsat 8–9 Data User Handbook

$\rho\lambda' = M^p * Qcal + A^p$ ……………..........(3)

- Conversion of Radiance to Top-of-Atmosphere Reflectance

$\rho\lambda = \frac{\rho\lambda'}{\sin(\theta SE)}$ ……………..........(4)

Where:

- ρλ\rho_\lambdaρλ = Top-of-atmosphere reflectance
- ρλ′\rho_\lambda'ρλ′ = Planetary spectral reflectance, without solar angle correction
- θSE\theta_{SE}θSE = Solar elevation angle

5: Spectral Indices:

a: Normalized Difference Vegetation Index (NDVI)

$NDVI = \frac{(NIR-Red)}{(NIR+Red)}$…………(5) [22]

b: Soil-Adjusted Vegetation Index (SAVI)

$SAVI = \left[\frac{(NIR-Red)}{(NIR+Red+L)}\right] \times (1 + L)$…………(6) [13]

c: Tasseled Cap Water Index (TCWI):

TCWI=(0.1509 ×Blue)+(0.1973 ×Green)+(0.3279 ×Red)+(0.3406 ×NIR)-(0.7112 ×SWIR1)-(0.4572 ×SWIR2)…………(7) [8]

d: Normalized Difference Water (NDWI)

$NDWI = \frac{(Green-Red)}{(Green+Red)}$…………(8) [18]

e: Water Ratio Index (WRI)

$WRI = \frac{(Green+Red)}{(NIR+SWIR1)}$…………(9) [21]

Results and Discussion

Analysis of Changes in the Normalized Difference Vegetation Index (NDVI):

The data presented in Table 2 provide an analysis of land cover changes based on the Normalized Difference Vegetation Index (NDVI) over the period from 1994 to 2024, focusing on three specific categories: Water, Barren Land, and Vegetation Cover, as detailed below:

Water Category: There has been a continuous decline in the water surface area from 2,280.08 km² (15.98%) in 1994 to 1,661.31 km² (11.64%) in 2024. This represents a reduction of approximately 4.34% of the total area over 30 years. This decline may be attributed to climate change, decreasing river or lake levels, or water depletion for agricultural or industrial purposes.

Barren Land: An initial increase followed by a slight decrease was observed. Barren land expanded from 10,838.57 km² (75.97%) in 1994 to a peak of 12,298.12 km² (86.2%) in 2014, then slightly decreased to 11,665.09 km² (81.77%) by 2024. The overall trend indicates that barren land expanded at the expense of both vegetation and water. The slight decline after 2014 may reflect attempts at land reclamation or replanting in certain areas.

Vegetation Cover: A sharp decline followed by partial recovery was noted. Vegetation area dropped from 1,147.73 km² (8.05%) in 1994 to its lowest point at 283.61 km² (1.99%) in 2014, then increased again to 939.98 km² (6.59%) in 2024. The decline between 1994 and 2014 reflects clear environmental degradation, likely due to drought, deforestation, or unregulated urban and agricultural expansion. The increase after 2014 may indicate efforts toward reforestation or improved environmental conditions.

In summary, the findings point to significant environmental degradation during the first two decades (1994–2014), characterized by a reduction in vegetation cover and expansion of barren land. After 2014, there are slight positive indicators of vegetation recovery and water stabilization. These changes highlight the urgent need for sustainable environmental resource management, enhanced vegetation restoration programs, and continuous monitoring of the impacts of climate change and human activities on the local environment. The results presented in Table 2 and Figure 2 demonstrate the monitoring of land cover changes based on the NDVI analysis for the study area.

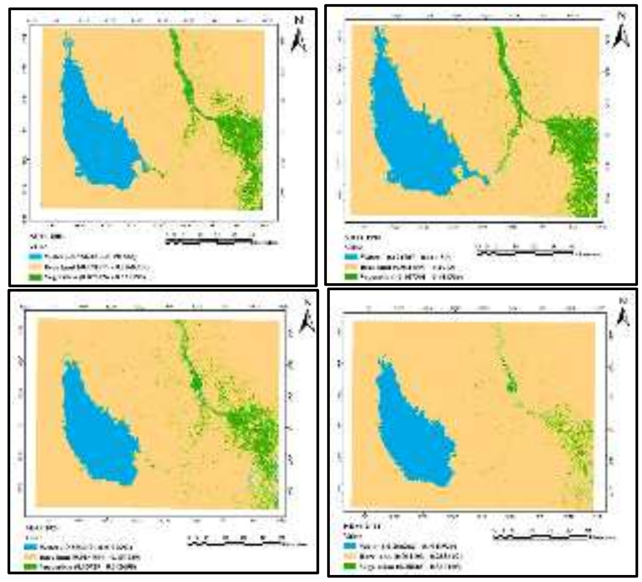

Figure 2. Detection of Changes in Vegetation Difference Index Distribution for the Years 1994, 2004, 2014, and 2024

Table 2. Spectral Indices Coverage Values, Area Percentages, and Land Cover Classification for the Years 1994, 2004, 2014, and 2024

Classes	NDVI 1994		NDVI 2004		NDVI 2014		NDVI 2024	
	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %
Water	2280.08	15.98	2068.33	14.5	1684.65	11.81	1661.31	11.64
Bear land	10838.57	75.97	11130.76	78.02	12298.12	86.2	11665.09	81.77
Vegetation	1147.73	8.05	1067.29	7.48	283.61	1.99	939.98	6.59
SUM	14266.38	100	14266.38	100	14266.38	100	14266.38	100

Classes	SAVI 1994		SAVI 2004		SAVI 2014		SAVI 2024	
	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %
Water	2279.82	15.98	2067.28	14.49	1682.2	11.79	1661.38	11.65
Bear land	10834.63	75.95	11136.78	78.06	11623.48	81.48	11665.43	81.77
Vegetation	1151.93	8.07	1062.32	7.45	960.7	6.73	939.57	6.58
SUM	14266.38	100	14266.38	100	14266.38	100	14266.38	100

Classes	NDWI 1994		NDWI 2004		NDWI 2014		NDWI 2024	
	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %
Non- Water	11970.34	83.91	12188.55	85.44	12488.78	87.54	12594.5	88.28
Water	2296.04	16.09	2077.83	14.56	1777.6	12.46	1671.88	11.72
SUM	14266.38	100	14266.38	100	14266.38	100	14266.38	100

Classes	TCWI 1994		TCWI 2004		TCWI 2014		TCWI 2024	
	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %
Non- Water	10753.68	75.38	10841.17	75.99	11502.72	80.63	7749.25	54.32
Water	3512.7	24.62	3425.21	24.01	2763.66	19.37	6517.13	45.68
SUM	14266.38	100	14266.38	100	14266.38	100	14266.38	100

Classes	WRI 1994		WRI 2004		WRI 2014		WRI 2024	
	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %	Area- Km2	Area %
Non- Water	11958.52	83.82	12187.74	85.43	12571.44	88.12	12578.69	88.17
Water	2307.86	16.18	2078.64	14.57	1694.94	11.88	1687.69	11.83
SUM	14266.38	100	14266.38	100	14266.38	100	14266.38	100

Analysis of Soil-Adjusted Vegetation Index (SAVI) Variability:

The data show the evolution of land use across four years (1994, 2004, 2014, and 2024) based on the SAVI index, which is used to assess vegetation cover while accounting for soil influence. The findings can be summarized as follows:

Water Bodies: The area of water bodies decreased from 2,279.82 km² in 1994 to 1,661.38 km² in 2024. The percentage dropped from 15.98% to 11.65%. This decline of about 4.33% over 30 years indicates a clear reduction in water levels, likely due to drought, climate change, or overuse of surface and groundwater resources.

Bare Land: Increased from 10,834.63 km² in 1994 to 11,665.43 km² in 2024. The percentage rose from 75.95% to 81.77%. This continuous increase reflects environmental degradation and desertification expansion, possibly caused by vegetation loss, reduced rainfall, or poor natural resource management.

Vegetation Cover: Decreased from 1,151.93 km² to 939.57 km², with the percentage falling from 8.07% to 6.58%. This decline of approximately 1.5% reflects a clear reduction in vegetation cover, indicating issues such as soil erosion, low rainfall, unsustainable urban or agricultural expansion, or overgrazing.

Thus, there is a consistent trend of environmental degradation, evident in the declining vegetation and water coverage and the expansion of barren land (desertification). Recommended actions include implementing vegetation restoration programs (such as afforestation and forest rehabilitation), improving water resource management, and adopting desertification control strategies. It is also crucial to continuously monitor environmental changes using remote sensing technologies and indices like SAVI. Table 2 presents the specific values of increase and decrease in this index, while Figure 3 illustrates the monitoring of SAVI changes throughout the study years: 1994, 2004, 2014, and 2024.

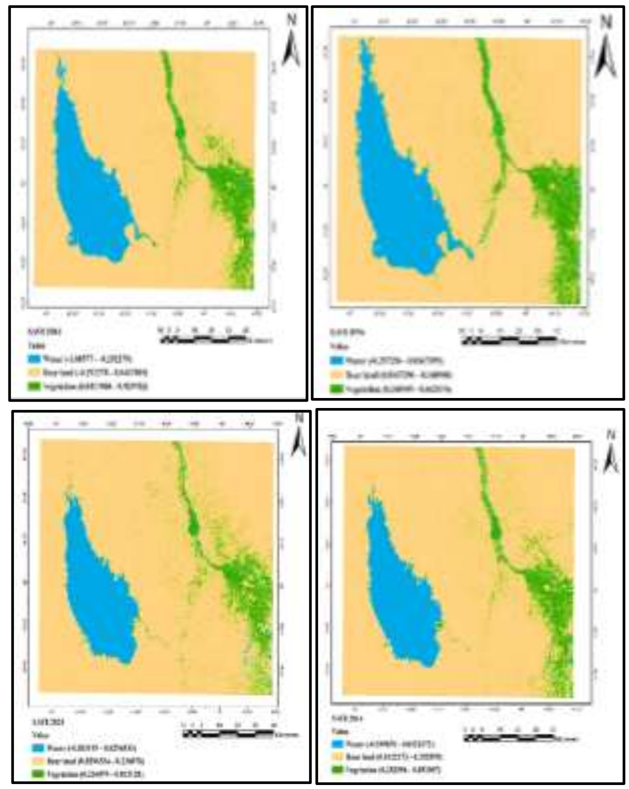

Figure 3. Monitoring Changes in the Soil-Adjusted Vegetation Difference Index Distribution for the Years 1994, 2004, 2014, and 2024

Analysis of Water Cover Variability Using NDWI:

The above results reflect changes in water and non-water areas between 1994 and 2024 based on the Normalized Difference Water Index (NDWI). The index classifies the area into two categories: water-covered areas and dry (non-water) areas. The general trend of these changes can be interpreted as follows:

There is a continuous increase in the **Non-Water category**, with the area rising from 11,970.34 km² (83.91%) in 1994 to 12,594.5 km² (88.28%) in 2024. The total increase was approximately 624.16 km² over 30 years. This reflects an expansion of dry land, urbanization, or degradation of water bodies (such as lakes or rivers), likely due to human activities or climate change.

The second category, **Water**, showed a continuous decrease, with the area shrinking from 2,296.04 km² (16.09%) in 1994 to 1,671.88 km² (11.72%) in 2024. The total decrease was about 624.16 km², equivalent to 4.37% of the total area. This decline indicates water recession, caused by drought, declining groundwater levels, dam construction, or urban and agricultural expansion. Figure 4 illustrates the monitoring of changes in this index for the years 1994, 2004, 2014, and 2024, respectively.

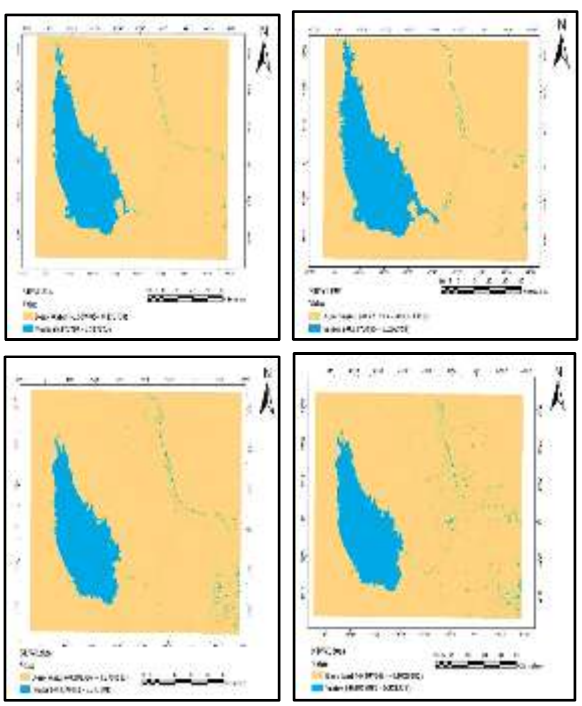

Figure 4. Monitoring Changes in the Normalized Difference Water Index (NDWI) Distribution for the Years 1994, 2004, 2014, and 2024

Analysis of the Water Cover Moisture Index (TCWI):

The attached data reflect changes in land use based on the TCWI (Tasseled Cap Water Index) during the period from 1994 to 2024. The land was divided into two categories: Water and Non-Water areas. The analysis shows:

Water Category: An interesting trend occurred over the thirty years, starting at 24.62% (3,512.7 km²) in 1994. It gradually decreased to 19.37% (2,763.66 km²) in 2014, then rose sharply to 45.68% (6,517.13 km²) in 2024. This decline until 2014 suggests drying or depletion of surface water, possibly related to climate change or excessive water use for agriculture and industry. The sharp increase after 2014 indicates water recovery due to improved climate conditions (such as increased rainfall), major water projects (like dam construction or water reclamation), or a rise in groundwater levels.

Non-Water Category: This category showed a continuous increase until 2014, from 10,753.68 km² (75.38%) in 1994 to 11,502.72 km² (80.63%) in 2014, then sharply decreased to 7,749.25 km² (54.32%) in 2024. This growth until 2014 reflects a shift from water-covered to dry land, possibly due to drought or urban and agricultural expansion. The significant drop in 2024 coincides with the increase in water areas, indicating a broad change in the water system or a return of dry land to its original state as wetlands or water-covered regions.

In summary, between 1994 and 2014, there was a clear contraction of water areas, reflecting environmental or human pressures on water resources. After 2014, a major environmental shift shows the return of large areas as water bodies, calling for investigation and understanding of the causes (natural or human-made) and the opportunity to utilize this change for sustainable development. It also highlights the importance of monitoring climate changes and government projects with significant impacts. Table 2 and Figure 5 present the results of change monitoring for the years 1994, 2004, 2014, and 2024.

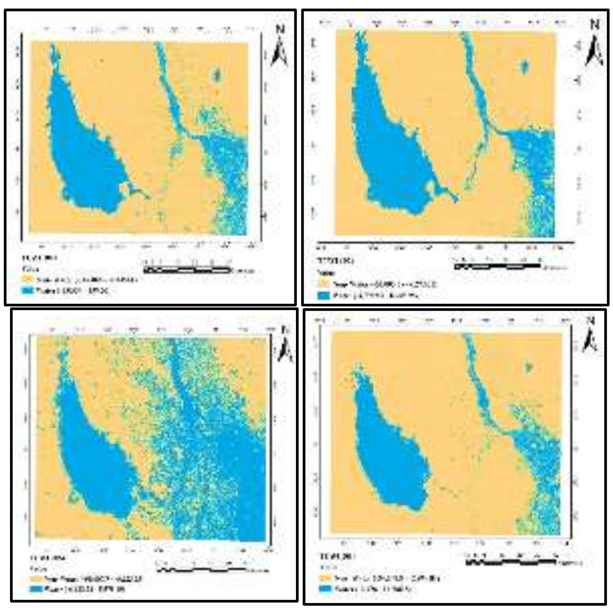

Figure 5. Water Cover Moisture Index (TCWI) for the Years 1994, 2004, 2014, and 2024

Analysis of the Water Requirement Index (WRI):

The data in Table 2 present an analysis of changes in the distribution of water and non-water areas based on the Water Requirement Index (WRI) during the period from 1994 to 2024. This index is used to estimate the abundance or scarcity of water and may reflect the capacity to meet water demand in different regions. The land was classified according to this index into:

Water Category: A gradual and steady decrease over the thirty years: 1994: 2,307.86 km² (16.18%), 2004: 2,078.64 km² (14.57%), 2014: 1,694.94 km² (11.88%), 2024: 1,687.69 km² (11.83%). This continuous decline indicates a shrinking of water-rich areas, either due to climatic changes (such as drought) or increased water consumption in agriculture and industry. The decrease became less severe after 2014, suggesting either stabilization or reaching a minimum threshold. The total decline in water areas from 1994 to 2024 is about 4.35% of the total area.

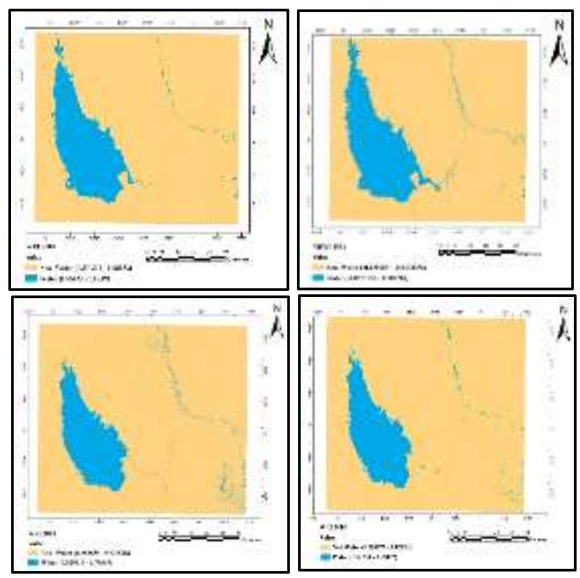

Figure 5. Water Requirement Index (WRI) for the Years 1994, 2004, 2014, and 2024

Non-Water Category: A continuous and clear increase from 11,958.52 km² (83.82%) in 1994 to 12,578.69 km² (88.17%) in 2024. This increase reflects the conversion of water-covered areas to dry land or a decline in surface water levels. The continuation of this trend may indicate potential environmental degradation, especially if no measures are taken to conserve or improve water resource management.

In summary, there is a clear trend of shrinking water resources and an increase in dry or water-deficient areas. This points to growing pressure on water resources and major challenges in managing future water demand. It is necessary to adopt sustainable water management plans that include improving water use efficiency, water harvesting, recycling, and protecting natural water sources. Figure 5 illustrates the monitoring of changes in this index for the years 1994, 2004, 2014, and 2024.

Time series analysis:

The given data for Lake Tharthar, covering changes in land cover and water area over 30 years (1994–2024), using five indices: NDVI, SAVI, NDWI, TCWI, and WRI. The analysis highlights trends and environmental implications.

NDVI (Normalized Difference Vegetation Index): Vegetation declined sharply from 1994 to 2014 (from 8.05% to 1.99%), likely due to drought or land degradation. A partial recovery in vegetation in 2024 (to 6.59%) is noticeable. Bare land increased significantly from 1994 to 2014, indicating vegetation loss. Water area steadily decreased, suggesting long-term water shrinkage (Table 3).

Table 3. Time series of NDVI changes through years of study

Year	Vegetation (%)	Bare Land (%)	Water (%)
1994	8.05	75.97	15.98
2004	7.48	78.02	14.50
2014	1.99	86.20	11.81
2024	6.59	81.77	11.64

SAVI (Soil-Adjusted Vegetation Index): Similar to NDVI, but minimizes soil brightness effects. Shows less drastic vegetation loss than NDVI, thanks to soil correction. Vegetation is relatively stable between 2014 and 2024. Water trends align with NDVI: steady decline. (table 4).

Table 4. Time series of SAVI changes through years of study

Year	Vegetation (%)	Bare Land (%)	Water (%)
1994	8.07	75.95	15.98
2004	7.45	78.06	14.49
2014	6.73	81.48	11.79
2024	6.58	81.77	11.65

NDWI (Normalized Difference Water Index): Consistent water area reduction, nearly 5% loss over 30 years. Reflects progressive desiccation of Lake Tharthar (Table 5).

Table 4. Time series of NDWI changes through years of study

Year	Water (%)	Non-Water (%)
1994	16.09	83.91
2004	14.56	85.44
2014	12.46	87.54
2024	11.72	88.28

TCWI (Tasselled Cap Wetness Index): Water percentage plummeted from 1994 to 2014. Sharp increase in 2024 (to 45.68%) may reflect: Flooding, Improved inflow or Algorithmic or sensor changes in TCWI analysis (Table 6).

Table 6. Time series of TCWI changes through years of study

Year	Water (%)	Non-Water (%)
1994	24.62	75.38
2004	24.01	75.99
2014	19.37	80.63
2024	45.68	54.32

WRI (Water Ratio Index): Very similar to NDWI, confirms reliable water area shrinkage. No significant recovery in 2024 (table 7).

Table 7. Time series of WRI changes through years of study

Year	Water (%)	Non-Water (%)
1994	16.18	83.82
2004	14.57	85.43
2014	11.88	88.12
2024	11.83	88.17

To summarize these data, trends could be shown as in table (8)

Table 8. Trends of increase and decrease in time series of the spectral indices

Index	Water Trend	Vegetation Trend	Notable Change
NDVI	↓ steady	↓ then ↑ slight	Vegetation crash in 2014
SAVI	↓ steady	Stable to slight ↓	More stable than NDVI
NDWI	↓ constant	N/A	Water decline confirmed
TCWI	↓ to 2014, ↑ 2024	N/A	Unusual surge in 2024
WRI	↓ steady	N/A	Aligns with NDWI

Conclusion:

The analysis of the spectral indices data (NDVI, SAVI, NDWI, TCWI, and WRI) from 1994 to 2024 reveals significant environmental changes in the study area. There is a clear decline in vegetation cover over the 30-year period, with a sharp reduction between 1994 and 2014, followed by a partial recovery by 2024. This trend indicates periods of environmental stress possibly due to drought, land degradation, and human activities, with some efforts or natural processes contributing to vegetation regrowth in recent years. Water bodies have consistently decreased in area across all indices (NDVI, SAVI, NDWI, WRI), highlighting a persistent reduction in surface water availability. This decline may be attributed to climate change effects, increased water extraction for agriculture and industry, and urban expansion. Interestingly, the TCWI index shows a sharp increase in water coverage after 2014, which could indicate changes in water management practices, improved precipitation, or restoration projects. Bare land areas have expanded notably, suggesting increasing land degradation and desertification risks. The growth of bare land at the expense of vegetation and water surfaces underscores the urgency of sustainable land management and conservation efforts. Overall, these findings emphasize the critical need for integrated environmental monitoring and proactive resource management to mitigate degradation, restore vegetation, and secure water resources in the face of climate variability and anthropogenic pressures.

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